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Evaluation and optimal design of electric vehicle charging infrastructure based on renewable energies in Iranian metropolises toward sustainable urban transportation

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Case Study

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Abstract

Given the critical challenges of air pollution and infrastructure limitations of distribution networks in densely populated metropolitan areas, this research focuses on developing localized strategies to improve sustainable consumption patterns. A case study of six major Iranian metropolises (Tehran, Mashhad, Isfahan, Karaj, Shiraz, and Tabriz) serves as the basis for analyzing these strategies. This study designs and conducts a techno-economic assessment of renewable-energy-based electric vehicle charging stations. Using HOMER Pro software, three scenarios are simulated and analyzed: (1) charging stations connected to the urban electricity grid, (2) an off-grid hybrid renewable system (solar, wind, storage), and (3) a hybrid system composed of photovoltaic panels, wind turbines, battery storage, and grid connection.

The results indicated that the third scenario, the on-grid hybrid system, offers significantly better economic and environmental performance. In this configuration, the Net Present Cost (NPC) fell within a negative range between $2.01 and $3.23 million, indicating capital recovery and project profitability. The Levelized Cost of Energy (LCOE) decreased to about $0.05/kWh, and annual carbon dioxide emissions were reduced by an average of over 1.5 million kg. These findings demonstrated that integrating solar and wind resources with battery storage in the form of smart microgrids not only ensures a reliable energy supply for charging stations but also reduces dependence on fossil-fuel-based power grids, improves economic efficiency, and significantly reduces air pollution in large Iranian cities. Therefore, the proposed model can be used as an effective solution for expanding electric transportation and achieving urban sustainable development goals.

Keywords

Charging Station Management and Optimization
Electric Vehicles
Iranian Metropolises
Renewable Energy
Urban Sustainable Transportation

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1. Introduction

Electric vehicles (EVs), due to their environmental advantages and high energy efficiency, are rapidly replacing conventional vehicles and have become a primary mode of transportation worldwide (Singh et al., 2023). The increasing popularity and acceptance of these vehicles have made the creation of a sustainable, efficient, and effective charging infrastructure crucial for the sustainable development of countries (Mohammed et al., 2024). However, the entry of this technology into markets that still benefit from fossil fuel subsidies faces challenges, including the lack of charging infrastructure, which is a major obstacle to this technological transformation. Moreover, the increasing penetration of EVs has raised concerns about their impact on electricity generation and distribution networks. Therefore, supplying the required power from renewable energy sources has become necessary (Kougias et al., 2020). In this regard, hybrid charging stations that integrate renewable energy with the conventional power grid offer a promising solution for providing reliable power without placing excessive strain on urban electricity networks (Kchaou-Boujelben, 2021). These stations not only ensure a dependable power supply but also contribute significantly to optimizing energy consumption, reducing grid load during peak hours, and ultimately fostering a greener and more sustainable urban environment (Manousakis et al., 2023).

With the increasing energy consumption in the transportation sector, the optimal management of this energy has become a major challenge for countries. The fast expansion of EV fleets further underscores the need for a scalable and efficient charging network, which, in itself, can impose substantial pressure on the national power grid. Since EV charging demand is directly tied to generation capacity and the stability of the electrical grid, ensuring a sustainable and flexible energy supply is vital for the long-term acceptance of this technology.

To address these challenges, integrating renewable energy sources into EV charging infrastructure is essential. Utilizing wind energy, solar photovoltaic systems, or a combination of these clean technologies can reduce dependence on fossil-fuel-based electricity generation, lower carbon emissions, and enhance grid stability (Singh et al., 2020). Additionally, using these resources can help mitigate energy imbalances and reduce issues arising from potential power outages, which may affect EV operational times and performance (Mohammed et al., 2024). Ultimately, transitioning toward EV charging powered by renewable energy represents a promising approach to aligning clean transportation with sustainable development goals and minimizing its environmental impacts (Schetinger et al., 2020).

With the increasing demand for electric vehicles in Iranian metropolises, there is significant pressure on the urban power grid. The lack of renewable energy infrastructure and storage systems leads to instability and higher energy procurement costs at charging stations. This research aims to determine the optimal combination of renewable resources (solar, wind, and battery) and the utility grid for a sustainable and economical energy supply at electric vehicle charging stations.

Main question:

How can a hybrid microgrid based on renewable energy be designed to supply the electricity required by electric vehicle charging stations at the lowest cost and with the greatest stability in Iranian metropolises?

Sub-questions:

1. How do climate variations (solar irradiation and wind speed) across six Iranian metropolises affect the technical and economic performance of the system?
2. Which combination of energy sources (solar, wind, storage, and grid) is optimal in terms of levelized cost of energy (LCOE) and reduction of CO_2 emissions?
3. What implications does the proposed optimal model have for energy policy and charging-infrastructure development in Iranian cities?

This research, through modeling six metropolises, introduces and verifies a hybrid configuration consisting of photovoltaic panels, wind turbines, battery storage systems, and grid connection as the optimal solution from technical, economic, and environmental perspectives.

2. Literature review

The global growth of electric vehicles has accelerated due to environmental concerns, technological advancements, and the need for clean transportation. The development of efficient charging infrastructure, particularly through the use of micro-grids and renewable energy sources, is crucial to support this trend. However, the variable and intermittent nature of renewable energy sources highlights the importance of hybrid systems (Pareek et al., 2020). Integrating resources such as solar energy, wind turbines, and energy storage systems provides the stability and reliability required for EV charging stations (Ibrahim et al., 2023).

Several studies worldwide have examined different aspects of this issue. Research conducted in Hawaii, USA (Singh & Kumar, 2023), the city of Jamshoro in Pakistan (Shaikh et al., 2022), four regions in Denmark (Boddapati, Kumar, Daniel, et al., 2022), four major cities in India (Boddapati, Kumar, Prakash, et al., 2022), and six locations with diverse geographical and climatic conditions in Nigeria (Boddapati, Kumar, Daniel, et al., 2022) has evaluated the application of hybrid renewable energy systems for electric vehicle charging stations, focusing on technical, economic, and environmental aspects. These studies frequently used software such as HOMER to simulate and optimize system design.

In addition to region-specific case studies, substantial research has also focused on management and optimization strategies for electric vehicle charging. For example, Japanese researchers (Takahashi et al., 2020) developed a priority-based charging strategy for managing EV charging stations in park-and-ride facilities, utilizing renewable energy sources and energy storage systems. Based on mixed-integer linear programming, their study yielded promising results in significantly reducing equipment costs. Another study (Kabir et al., 2020) also used a centralized system based on integer linear programming to minimize the cost of charging each EV, allowing for faster and more cost-effective charging.

Beyond technical considerations and station-level optimization, research has also addressed broader aspects of integrating electric vehicles with renewable energy resources. In this context, the authors of (Casella et al., 2022) presented a comprehensive review of the integration between the transportation sector and the smart grid, with an emphasis on EV management. The study by Zhao et al. (2022) emphasized the need to revise power system planning by considering the critical role of electric vehicles and renewable energy sources. In energy management, the research by Ouramdane et al. (2022) examined renewable energies, electric vehicles, and energy storage systems, with a focus on residential energy management rather than the commercial sector.

Overall, the literature indicates that hybrid systems based on renewable energy sources have strong potential to provide a sustainable and cost-effective power supply for electric vehicle charging stations. However, determining the optimal sizing of system components and managing associated costs remain key challenges that require further research. Table 1 presents a summary of related studies, their findings, and existing research gaps regarding the optimal design for meeting EV charging demand.

Iran faces significant challenges, including electricity supply imbalances and environmental pollution caused by greenhouse gas emissions. Under these circumstances, transitioning toward clean energy, particularly through the expansion of electric vehicles, is crucial. EVs can help reduce air pollution, improve public health, and play a meaningful role in combating climate change. However, the primary challenge lies in establishing an efficient and sustainable charging infrastructure, one that relies on renewable energy sources, ensures grid stability, and imposes minimal environmental impact.

Table 1. Summary of the related literature, key findings, and existing gaps in the optimal design of electric-vehicle charging demand supply

Reference and year	Location	Goals	Algorithm/ tool	Results	Gaps
(Boddapati et al., 2022)	China	Electric vehicle strategy to improve electricity consumption and reduce charging costs	Optimization	Reduction in EV charging cost	No environmental analysis
(Kabir et al., 2020)		Minimizing the charging cost of each electric vehicle	Integer Linear Programming	Fastest EV charging at minimum cost	No environmental analysis
(Ouramdane et al., 2022)	France	Home energy management	MATLAB	Optimal micro-grid sizing; EV integration	Excludes the commercial sector
(AlHammadi et al., 2022)	United Arab Emirates	Determining the optimal size of electric vehicles through renewable energy sources	HOMER	Optimal micro-grid sizing for load demand; increased RES capacity, GHG reduction	Grid connection not assessed

Reference and year	Location	Goals	Algorithm/ tool	Results	Gaps
(Murat et al., 2020)	Turkey	Energy management system for electric vehicles installed in industrial zones	Monte Carlo Simulation	EV demands are met across various time periods	No financial/ environmental assessment
(Sayed et al., 2019)	Egypt	Energy management system for controlling power flow from renewable energy sources to electric vehicles	MATLAB/ Simulink	Good results in terms of technical performance and meeting load demand	No financial/ environmental assessment
(Al Wahedi & Bicer, 2022)	Qatar	Minimization of Energy Cost and Net Present Cost	Pro HOMER.	Optimal combination, sizing of charger components, and energy management strategy adoption	No environmental analysis
(Minh et al., 2021)	Vietnam	Optimal Configuration of Solar-Powered Electric Vehicle Charging Stations	HOMER Grid	Solar vs. grid energy share analysis and tariff sensitivity on LCOE	No environmental analysis; excludes other renewables
(Syed Mohammed et al., 2022)	India	Hydrogen Storage-Based Hybrid Systems for EV Charging Power Supply	HOMER	Net present cost (NPC) minimization	Relatively high LCOE
(Allouhi & Rehman, 2023)	Morocco	Hybrid RES Integration with EV Charging Platforms in Supermarkets	HOMER	Total operational cost minimization	No environmental analysis
(Baghaei et al., 2024)	Iran	Optimal Sizing of RES and Battery Storage in an EV Charging Station	GAMS/CPLEX	Economic cost and pollutant emission minimization	Grid connection not assessed
(Kang et al., 2023)	State of California, USA	Bi-Objective Optimization Model for Simultaneous CO2 and Peak Power Minimization	Python / CVXPY	18.9% CO2 reduction and 33% peak power decrease	No analysis of investment costs and infrastructure equipment
(Babar et al., 2025)	International Comprehensive Review	Fast Charging Station Operation Strategies: Techno-Economic Impact on Grid Integration with RES	MATLAB/ Simulink	Improved grid power quality parameters and performance	No environmental analysis
(Kotarela et al., 2024)	Greece	Techno-Economic & Environmental Assessment of Solar PV Fast Charger for 50% Diesel Fleet Replacement	PVGIS	3–6 year payback period; 100% direct CO2 emission reduction	Lack of grid/ storage integration impact study

The literature review reveals that most previous studies have either focused solely on technical and economic aspects or overlooked grid connection conditions and environmental analysis. The present study, through an integrated approach, fills the gaps identified in Table 1 because it (1) conducted a quantitative environmental assessment by calculating CO_2, NOx, and SO_2 emissions, (2) modeled different grid connection scenarios, and (3) provided a comparative analysis between six metropolises at a commercial scale. Thus, the present study provides a more comprehensive picture of the technical, economic, and environmental sustainability of electric vehicle charging stations in the urban context of Iran than studies that focused only on stand-alone systems. To address this challenge, the present study investigates the optimal configuration for charging stations by collecting energy consumption data and conducting a comprehensive techno-economic analysis using HOMER software. The results clearly show that the best model is a combination of solar panels, wind turbines, a battery storage system, and a grid connection. This model offers significant advantages over other approaches in terms of technology, economics, and the environment.

The ultimate goal of this study is to enhance sustainable transportation by improving the efficiency and environmental responsibility of electric vehicle charging stations. This research aims to achieve significant advances in the design and management of hybrid charging stations powered by renewable sources. The findings of this research can serve as a valuable guide for policymakers, urban planners, and energy activists, playing an important role in achieving global goals for sustainable transportation.

The key innovations of this research are as follows:

- Multidimensional approach: By considering technical, economic, and environmental dimensions, this study provides a relatively comprehensive picture of the challenges and opportunities associated with the transition toward sustainable electric transportation in Iran.
- Carbon reduction and global goals: Reducing carbon emissions, the proposed system significantly aligns with global sustainable development goals in clean energy, and can serve as a model for similar future projects.
- Hybrid charging integration: For the first time, the performance of hybrid charging stations (electric vehicles integrated with renewable energy sources) is examined in depth, representing a noteworthy innovation in sustainable transportation.
- Urban analysis: Focusing on six major Iranian metropolises (Tehran, Mashhad, Isfahan, Karaj, Shiraz, and Tabriz) enables a deeper understanding of climatic and infrastructural differences affecting the development of EV charging systems.

Given the gaps identified in previous studies and the need for a comprehensive techno-economic analysis of hybrid systems in Iran's metropolitan regions, the next section of the article is dedicated to explaining the research methodology and the proposed model. The structure of the article consists of five main sections: 1) Introduction and literature review: Presentation of the topic and a comprehensive review of previous research; 2) Materials and methods: Detailed explanation of the research methodology; 3) Proposed system architecture: Presentation of the proposed design for various scenarios; 4) Simulation results: Technical, economic, and environmental analysis of the findings; and 5) Conclusions and suggestions: Summary of the results and directions for future research.

3. Materials and methods

In this research, HOMER Pro software is employed for the optimal design and comprehensive analysis (technical, economic, and environmental) of electric-vehicle charging stations with an emphasis on renewable energy sources. Through simulation and optimization, the software identifies the most cost-effective system configuration based on indicators such as net present cost, unit energy cost, penetration of renewable energy sources, and sustainability. It ensures a highly reliable system with minimal cost, even under fluctuations in energy generation and load demand (Figure 1).

The selection of HOMER Pro is justified by its capability to perform multi-objective modeling and optimization of hybrid energy systems while simultaneously addressing technical, economic, and environmental dimensions. Additionally, HOMER Pro contains a globally validated database for climatic and technical parameters, which enhances the accuracy of the analysis compared to other available tools.

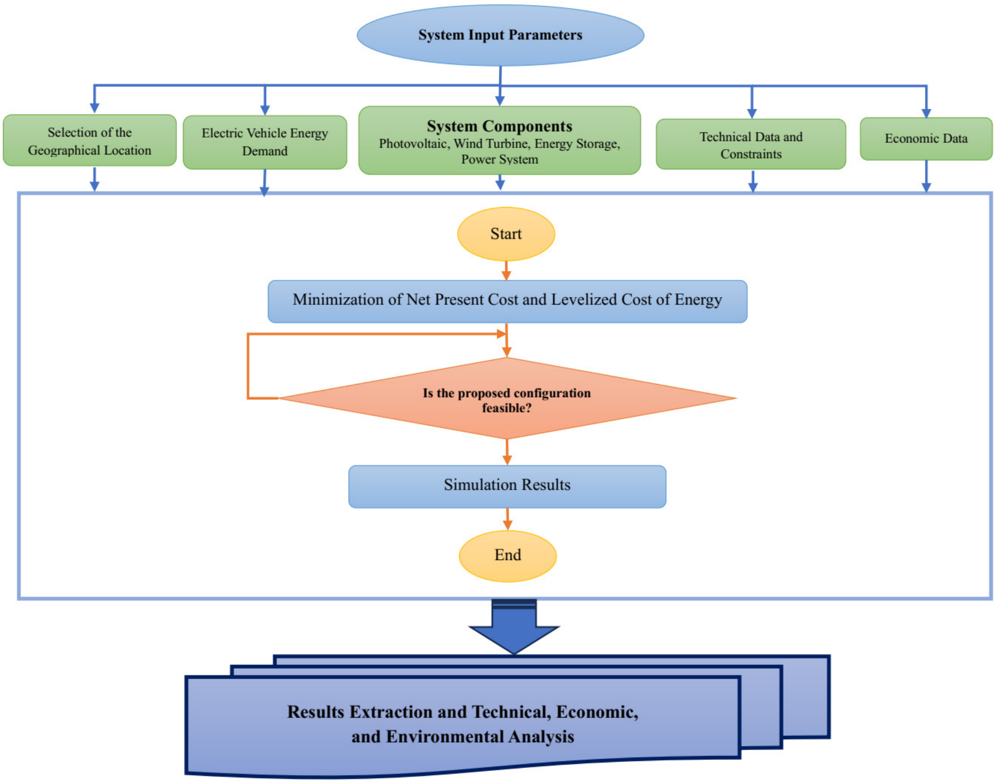


Figure 1. Micro-grid optimization flow of electric vehicle charging stations

3.1. Meteorological data

In this study, six metropolises (Tehran, Mashhad, Isfahan, Karaj, Shiraz, and Tabriz) were selected as candidate locations for establishing electric-vehicle charging stations. The required meteorological data for assessing renewable energy potential, including solar and wind information (illustrated in Figures 2 and 3), were obtained from the NASA database. These data play a crucial role in optimizing renewable energy generation and conducting technical, economic, and environmental analyses of the system at each location.

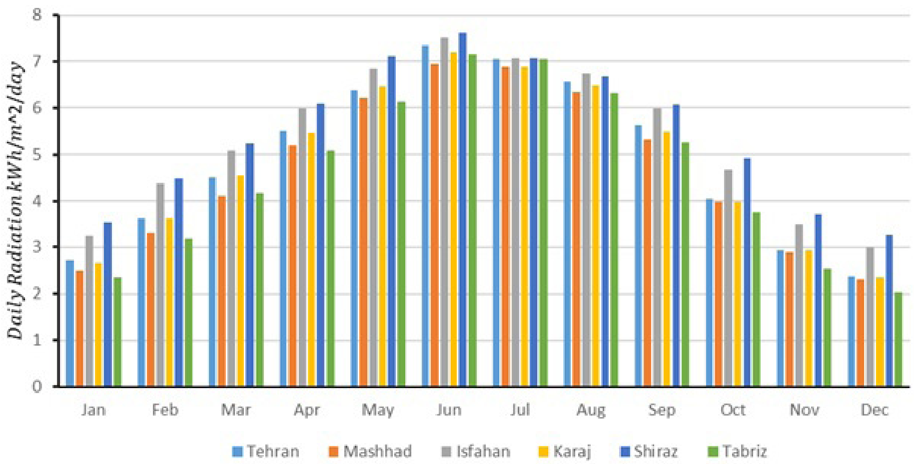


Figure 2. Solar irradiation levels in the selected sample regions

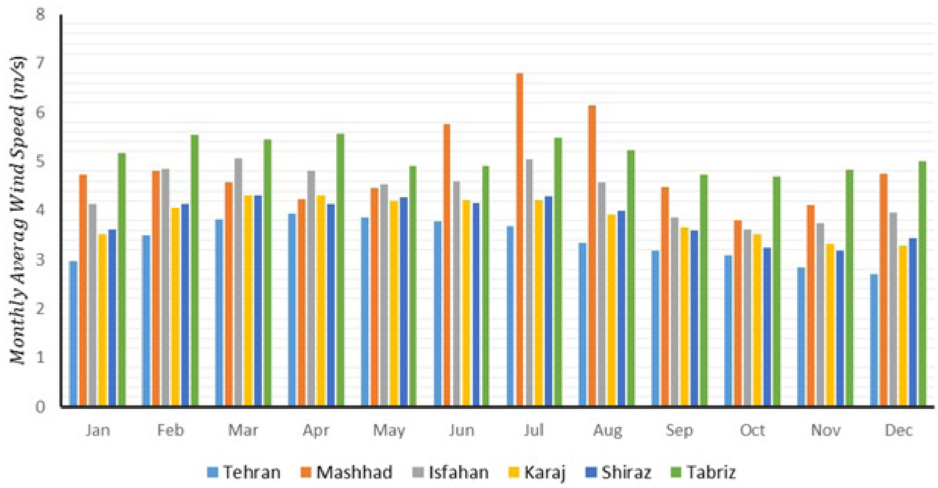


Figure 3. Wind speed levels in the selected sample regions

3.2. Electric-vehicle charging demand

Given the limited availability of accurate EV charging-demand data in the country, this study models the load demand based on a set of assumptions. It is assumed that each urban fast-charging station serves 100 electric vehicles per day, and each requires an average of 30 kWh of energy for charging (considering charging from 20% to 80% in 20 minutes for EVs equipped with 100-kWh battery packs). Accordingly, the total daily energy demand is estimated at 3000 kWh.

Due to the absence of field data on daily EV charging habits in Iran, the demand data used in this model were adopted from studies conducted in countries with similar climatic and consumption characteristics (including Qatar). Although these data may partially represent practical conditions in Iran, collecting real-world data on travel patterns and user charging behavior will be essential in future research to obtain more generalizable results (Al Wahedi & Bicer, 2020).

The assumed daily charging demand of 30 kWh per EV in this study is based on the following facts:

- Most EVs fall within the medium-size category, with battery capacities around 100 kWh, which represents the upper bound for this class (Allouhi & Rehman, 2023).
- According to reference hourly demand patterns (AbdElrazek et al., 2025), most EV drivers on the move tend to seek a charging station when their battery's state of charge (SoC) drops to around 20%, aiming to reach a SoC level of 80% within approximately 20 minutes.

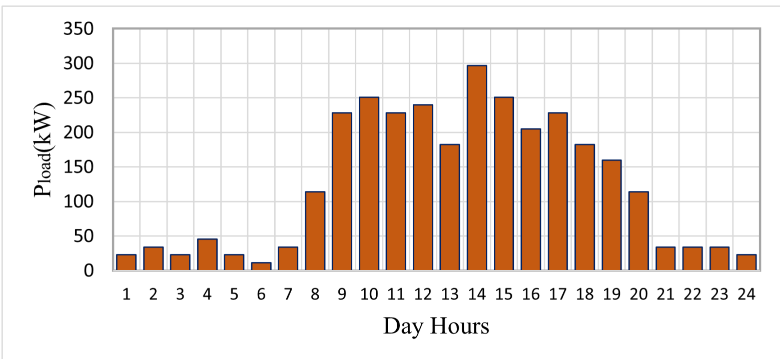


Figure 4. Average daily load profile of the case study

To account for possible fluctuations in demand, variability parameters, including 20% variability in charging duration, 10% daily variability, and 15% time-step variability, were incorporated into the model (Dejkam & Madlener, 2025). This approach enables the model to simulate a wide range of user charging patterns and reflect a more accurate load profile. Based on the reference hourly demand patterns

(AbdElrazek et al., 2025), the daily charging-demand profile follows the shape illustrated in Figure 4. Overall, despite the lack of detailed urban data, this modeling approach provides a reasonable estimate for planning the EV charging station.

To ensure accuracy and reproducibility of the simulations, the technical specifications of system components—including the types of solar panels, wind turbines, batteries, and converters—along with their investment, maintenance, and replacement costs, are presented in Table 2. This table displays all technical and economic parameters of the charging station components used in the simulation.

Table 2. Technical and economic specifications of charging station components and economic indicators

Photovoltaic module (generic flat plate PVU)		Battery (kinetic battery model)	
Rated capacity	1kW	Rated capacity	1kWh
Investment cost	320$/unit	Investment cost	300$/unit
Maintenance cost	2.5$/year	Replacement cost	300$/unit
Lift time(years)	25	Efficiency	85%
Wind turbine (Generic U)		Maintenance cost	5$/year
Rated capacity	3kW	Lift time(years)	15
Investment cost	750$/unit	Converter (Context SW2524)	
Replacement cost	680$/unit	Rated capacity	1.0 kW
Maintenance cost	20$/year	Investment cost	250$/unit
Lift time(years)	20	Replacement cost	250$/unit
$v_{cut\text{-}in}$	3(m/s)	Maintenance cost	0$/year
$v_{cut\text{-}out}$	20 (m/s)	Efficiency	97%
v_r	9 (m/s)	Lift time(year)	15
Discount rate		15%	
Inflation rate		12%	
Project lifetime		25 years	

4. System architecture proposed for the scenarios

The present study proposes a fast-charging station with a hybrid configuration (solar, wind, storage, and grid) to supply the daily fast-charging demand of electric vehicles (Figure 5). In this model, EVs are powered by renewable energy sources whenever they are available. Any excess generated energy is either stored in the battery bank or fed into the grid. When weather conditions are unfavorable for renewable energy production, the system relies on stored energy or electricity from the grid. Therefore, the station's batteries are designed to meet the minimum storage and backup requirements.

Additionally, the use of the utility grid is incorporated to reduce storage costs and enable revenue generation through the sale of surplus energy produced by the system.

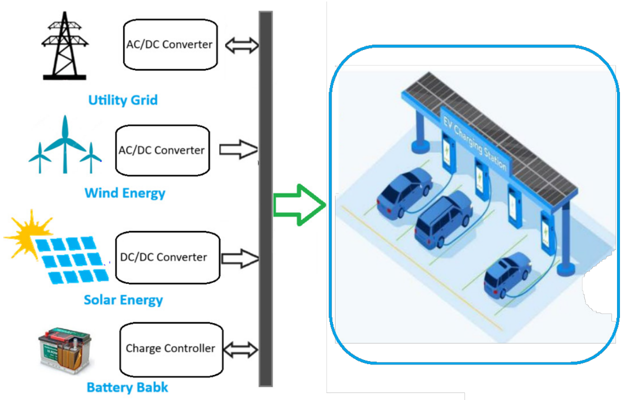


Figure 5. Structure of the proposed hybrid micro-grid

This charging station can operate in five different modes to optimally meet the charging demand of electric vehicles:

Mode 1 (pure renewable): When sufficient solar and wind energy is available, the station operates entirely on renewable sources and disconnects from the grid.

Mode 2 (grid mode): When renewable resources are unable to generate enough electricity (nighttime, cloudy days, or low-wind periods), EV charging is supplied by the grid.

Mode 3 (hybrid mode): When renewable energy covers part of the demand, charging is supplied simultaneously from both renewable sources and the grid. The grid's contribution is adjusted according to renewable generation to maintain the required charging power.

Mode 4 (selling to grid): When no vehicles are present or when the demand is lower than the available generation, the excess renewable energy is sold back to the grid.

Mode 5 (battery backup): In the event of a grid outage or lack of renewable-energy production (due to weather conditions or technical failures), backup batteries power the station. These batteries are sized to meet only the minimum charging requirements, to minimize investment costs.

The photovoltaic system is selected as the primary energy source due to Iran's advantageous geographical conditions and the declining cost of solar technology. A wind turbine is also included to cover periods when solar energy is unavailable. The output of both systems is used to charge vehicles and to store energy in the battery bank. Additionally, energy-storage systems are employed to ensure an uninterrupted power supply, even in the absence of wind or sunlight.

4.1. Solar photovoltaic (PV) system modeling

The output power of a photovoltaic (PV) panel depends on solar irradiance, absorption capacity, panel surface area, and panel temperature. Solar irradiance has a probabilistic nature, and therefore the corresponding output power is intermittent. The output power of the PV system can be calculated using Equation (1) (Gol & Ščasný, 2023):

$$P_{PV} = Y_{PV} \times f_{PV} \times \frac{G_T}{1000} \times [1 + \alpha(T_C - T_{STC})] \qquad (1)$$

where G_T is the total solar irradiance incident on the PV panels, Y_{PV} is the rated (nominal) power of the PV panels, f_{PV} is the PV power derating factor, α is the temperature coefficient, T_C is the PV cell temperature, and T_{STC} is the cell temperature under standard test conditions (STC) (25 °C). The cell temperature is estimated as follows:

$$T_C = T_a + \left(\frac{NOCT - 20}{800}\right) \times G_T \qquad (2)$$

where T_a is the ambient temperature in degrees Celsius, and NOCT is the nominal operating cell temperature, typically ranging between 45°C and 47°C.

4.2. Wind turbine system modeling

Wind turbines convert the mechanical energy generated by the impact of wind on the blades into electrical energy. The output power of a wind turbine, ($P_{WT}(t)$), is a function of wind speed and is described by Equation (3).

$$P_{WT} = \begin{cases} 0, & v \le v_{cut-in} \quad or \quad v \ge v_{cut-out} \\ P_r\left(\frac{v^3 - v_{cut-in}{}^3}{v_r{}^3 - v_{cut-in}{}^3}\right), & v_{cut-in} < v \le v_r \\ P_r, & v_r < v \le v_{cut-out} \end{cases} \qquad (3)$$

where v_r, v_{cut-in}, $v_{cut-out}$ and represent the rated wind speed, cut-in wind speed, and cut-out wind speed, respectively. P_r denotes the output power at the rated wind speed (v_r) (Figure 6). To determine the wind speed at the turbine hub height based on the measured wind speed, Equation (4) is used (Riayatsyah et al., 2022).

$$v_h^t = v_{ref}^t \times \left(\frac{h}{h_{ref}}\right)^{\gamma} \quad (4)$$

where h represents the turbine hub height, and v_w^{ref} is the measured wind speed at the anemometer height h_{ref}. The parameter γ ranges from 0.10 (for flat terrain) to 0.25 (for forested or tree-covered areas).

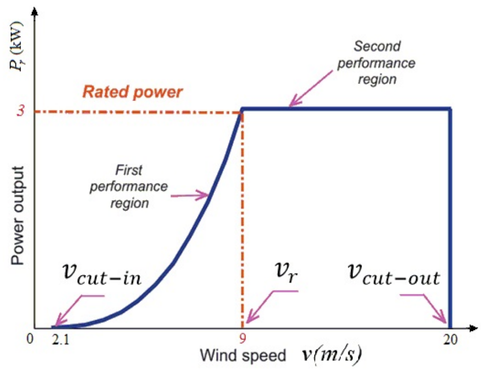


Figure 6. power curve of the wind turbine as a function of wind speed

4.3. Energy storage system (battery bank) modeling

Depending on the level of generated power and the load demand, the battery bank can either be charged or discharged. The input power of the batteries can take positive or negative values depending on whether they are in charging or discharging mode (Buestan-Morales et al., 2024) (Equation 5).

$$P_B(t) = P_{WT}(t) + P_{PV}(t) - P_L(t)/\eta_{inv} \quad (5)$$

In this equation, $P_L(t)$ represents the total load demand at time t, and η_{inv} denotes the inverter efficiency. If P_B (t)=0, the battery bank capacity remains unchanged.

For $P_B>0$, the surplus generated power is used to charge the battery bank (and for $P_B<0$, the deficit in generated power is supplied by discharging the batteries). The new battery bank capacity can then be determined using Equation (6).

$$SOC_B(t) = SOC_B(t-1) \times (1-\sigma) \pm P_B(t) \times \eta_b \quad (6)$$

In the above equations, $SOC_B(t)$ and $SOC_B(t-1)$ represent the state of charge of the batteries at times t and t–1, σ respectively. The parameter σ denotes the battery self-discharge rate, and η_{inv} and η_b refer to the inverter efficiency and battery efficiency, respectively.

To ensure proper battery performance and to preserve its useful lifetime, two constraints are applied to the charging and discharging processes: when the battery reaches its maximum capacity, charging must be stopped, and when it reaches its minimum capacity, discharging must be stopped.

$$SOC_{min} \le SOC \le SOC_{max} \quad (7)$$

To prevent a reduction in the useful lifetime of each battery, the constraints presented in Equation (8) are applied to the charging and discharging processes.

$$E_{batmin} = (1 - DOD) \times E_{batmax} \quad (8)$$

E_{batmax} and E_{batmin} represent the upper and lower allowable limits for the energy stored in each battery, and D denotes the permissible depth of discharge (DoD) for each battery.

4.4. Economic evaluation

In this study, the net present cost (NPC) of the entire system and the levelized cost of energy (LCOE) are used as the two main criteria for the economic assessment of renewable energy–based power generation systems (Al Wahedi & Bicer, 2022).

Cost of system components

The total cost of the k-th component of the system includes the following elements: the initial cost (IC_k) (including purchase, installation, and commissioning), the replacement cost (Rep_k), the operation and maintenance cost ($O\&M_k$), and the residual value (RV_k). The total expenditure for the k-th, denoted by (TUC_k), is determined using the following equation:

$$TUC_k = IC_k + Rep_k + O\&M_k - RV_k \quad (9)$$

To convert the initial cost into an annualized cost, the capital recovery factor (CRF) is used (Equation 10).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad i = \frac{i' - r}{1+r} \quad (10)$$

where i’ is the real interest rate, r is the annual inflation rate, n is the system lifetime, and n_k is the lifetime of component k. In this study, the nominal interest rate and expected inflation rate are assumed to be 15% and 12%, respectively.

The annualized initial cost of component k is determined using the following equation:

$$AIC_k = IC_k \times CRF \quad (11)$$

The annual replacement cost of component k is also calculated according to Equation (12).

$$ARep_k = Rep_k \times \sum_{m=0}^{\left[\frac{n}{n_k}\right]-1} \frac{1}{(1+i)^{m \times n_k}} \quad (12)$$

The salvage value of component k is presented in Equation (13).

$$ARV_k = RV_k \times \sum_{m=1}^{\left[\frac{n}{n_k}\right]} \frac{1}{(1+i)^{m \times n_k}} \quad (13)$$

Therefore, the annual cost of component k will be as follows:

$$ATUC_k = AIC_k + ARep_k + OM_k - ARV_k \quad (14)$$

To calculate the net present cost of component k, Equation (15) is used:

$$NPCU_k = ATUC_k / CRF(i، k) \quad (15)$$

The net present value (NPV) of the entire system, which represents the sum of all costs and revenues over the project's lifetime discounted to their present values, is calculated using the following equation:

$$NPC = \sum_k NPCU_k \quad (16)$$

The levelized cost of energy (LCOE), also known as the unit cost of electricity over the lifetime of a system, is one of the significant indicators for comparing the cost-effectiveness of different energy technologies. LCOE is calculated as the ratio of the total annual cost to the total annual useful energy production. These economic formulas are fundamental to the optimization algorithm and play a crucial role in determining the most cost-effective and efficient configuration for a hybrid energy system (Islam et al., 2023):

$$LCOE = \frac{\sum_k ATUC_k}{\sum_t^{8760} P_{WT}(t) + P_{PV}(t)} \quad (17)$$

4.5. Environmental analysis

The expansion of electric vehicles and growing concerns over climate change underscore the need for a clean and sustainable energy supply for this fleet. In this context, standalone microgrids that supply charging stations using renewable energy sources have emerged as an effective solution for reducing the carbon footprint of electric transportation.

To accurately assess the environmental benefits of these microgrids, the emission factors of conventional power plants in the country are first calculated based on their generation capacity, fuel type and consumption, and operational parameters. Then, by applying weighted averaging according to the electricity produced by each plant and considering the total energy generated from fossil fuels, hydropower, and wind sources nationwide, the emission factors of the main pollutants are determined.

Based on the references (Nazari et al., 2009) and (Mousavi & Sadatinejad, 2021), the emission factors for fossil-fuel power plants in the country are calculated as follows:

- CO_2: 640 g/kWh
- SO_2: 2.75 g/kWh
- NO_x: 2.4 g/kWh

These values provide the basis for estimating gas emissions when electricity is supplied from the grid, which relies predominantly on fossil fuels.

5. Findings

The main power grid in its current state is facing an energy imbalance, which will be exacerbated if electric vehicles are developed. At the same time, air-pollution levels are already unfavorable. Therefore, the use of electric vehicles and the use of renewable energy sources of electric vehicle stations is proposed, which, in addition to supplying the electricity required by electric vehicle charging stations, can create a very favorable situation in terms of the environment. It is even possible to inject energy into the main power grid during periods when the production of renewable resources exceeds the consumption of charging stations.

To examine the development of urban electric transportation, six major metropolises were selected as case studies, and comprehensive technical, economic, and environmental analyses were conducted for various scenarios.

To more accurately simulate the current condition of the urban grid, a scenario incorporating scheduled load, shedding periods during peak-demand hours in summer and winter was included. These outages are modeled as follows:

- Summer: From June 5 to September 6, on working days, from 13:00 to 15:00.
- Winter: From December 6 to March 5, on working days, from 18:00 to 20:00.

This simulation approach enables a more realistic representation of grid performance under peak-load conditions and during potential planned outages

5.1. Scenario 1

In this scenario, the electric vehicle charging stations rely entirely on the urban power grid. Such dependence can be problematic given the serious challenges currently facing the national electricity network. Issues such as supply–demand imbalance (leading to blackouts), aging infrastructure (causing energy losses and frequent outages), and reliance on fossil fuels (with environmental and public-health consequences) all contribute to grid instability.

Adding the load of EV charging stations to this already strained grid would impose additional pressure and further complicate the existing situation. The same grid conditions are assumed for all metropolitan areas included in the study. Table 3 summarizes these conditions, including the annual energy purchased from the grid, the amount of unmet energy, the percentage of power unavailability, and the quantity of pollutants emitted to supply electricity for each charging station per year.

Table 3. Details of the proposed system for supplying power to EV Charging stations through the urban power grid

Term	Unit	Value
Energy Purchased	kWh/yr	1,041,435
Unmet Electric Load	kWh/yr	53,565
Capacity Shortage	%	5.38
Emission Carbon Dioxide	kg/yr	658,187
Emission Sulfur Dioxide	kg/yr	2,854
Emission Nitrogen Oxides	kg/yr	1,396

5.2. Scenario 2

In the proposed scenario, a configuration consisting of photovoltaic panels, wind turbines, and battery storage is considered to achieve the lowest possible electricity cost. The unit capacities of each microgrid component used in the charging stations, the amount of energy generated from renewable sources, and the economic analysis of this configuration are presented in detail in Table 4.

Table 4. Details of the proposed system for supplying power to EV charging stations using renewable energy sources, categorized by metropolises

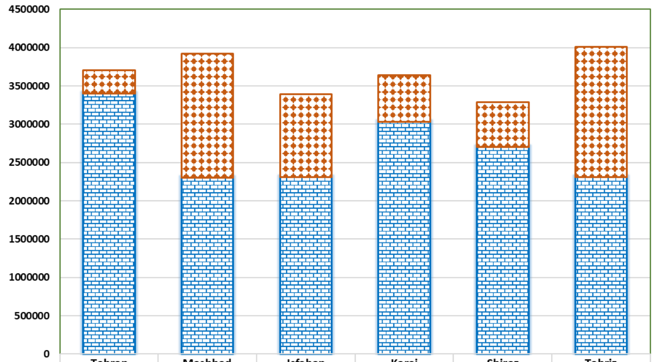
Term \ City	Tehran	Mashhad	Isfahan	Karaj	Shiraz	Tabriz
Rated Capacity of PV units (kW)	2116	1504	1320	1905	1545	1529
Rated Capacity of WT units (kW)	834	1215	1149	948	918	1101
Rated Capacity of Battery bank units (kWh)	2639	1802	1524	2238	1956	1829
Rated Capacity of Converter units (kW)	407	387	369	418	411	384
PV Energy Production (kWh/yr)	3402401	2299542	2307238	3035482	2702159	2310429
WT Energy Production (kWh/yr)	302792	1619502	1086106	607841	582919	1702765
Excess Electricity (kWh/yr)	2540328	2774743	2246278	2488899	2129673	2878275
Total NPC ($)	3267106	2678726	2483400	2933312	2729554	2380222
Levelized COE ($/kWh)	0.166	0.136	0.126	0.149	0.139	0.121

In this scenario, the optimal capacity of each component is determined based on achieving the minimum total net present cost. The load demand is assumed to be identical across all metropolises, with the highest net present cost observed in Tehran and the lowest in Tabriz. This difference arises from the higher annual average wind speed in Tabriz (5.12 m/s) compared to Tehran (3.39 m/s). Consequently, the proposed wind-turbine capacity in Tabriz is 24% more than in Tehran, and wind-energy generation in Tabriz is

82% greater than in Tehran. Moreover, the cost per kilowatt-hour of energy in Tabriz is estimated to be 27% less than in Tehran.

The contribution of each renewable source to total energy production in the selected metropolis is shown in Figure 7. Tehran has the highest photovoltaic energy production, while Mashhad has the lowest; conversely, Tabriz exhibits the highest share of wind-energy generation, with Tehran having the lowest.

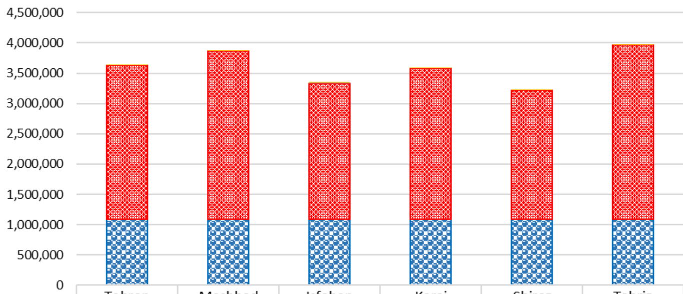
The combined use of renewable resources in microgrids results in a smoother energy generation profile and consequently reduces the need for energy storage systems. The simulation results confirm this observation; for example, the required battery-bank capacity in Tehran is reported to be 2.2 times that of Tabriz.



	Tehran	Mashhad	Isfahan	Karaj	Shiraz	Tabriz
WT Energy Production (kWh/yr)	302792	1619502	1086106	607841	582919	1702765
PV Energy Production (kWh/yr)	3402401	2299542	2307238	3035482	2702159	2310429

Figure 7. The share of each renewable source in energy production in selected metropolises

Further details regarding the annual energy consumption, surplus energy generation, and unmet load per year for the renewable micro-grid feeding scenario are shown in Figure 8.



	Tehran	Mashhad	Isfahan	Karaj	Shiraz	Tabriz
Capacity Shortage (kWh/yr)	12,041	11,974	12,037	12,027	12,026	12,033
Unmet Electric Load (kWh/yr)	7,330	6,978	4,957	6,511	5,887	6,065
Excess Electricity Load (kWh/yr)	2,540,328	2,774,743	2,246,278	2,488,899	2,129,673	2,878,275
Consumption(Load) (kWh/yr)	1,087,670	1,088,022	1,090,043	1,088,489	1,089,113	1088935

Figure 8. Annual energy consumption, surplus energy generation, and unmet load in scenario 2 for selected metropolises

Figure 9 illustrates the total net present cost for the six selected cities, along with the percentage of surplus energy produced by the microgrid. The results show that Tabriz has the lowest cost and the highest surplus energy generation, whereas Tehran has the highest cost and Shiraz has the lowest surplus energy generation. These differences arise from variations in renewable energy potential among the metropolises and the inherently variable nature of renewable resources.

As shown in Figure 9, managing surplus renewable energy generation, particularly when production exceeds the charging station demand, is a fundamental challenge. The results indicate that, on average, 68.4% of the renewable energy is surplus and wasted. This energy loss, caused by the intermittent and uncontrollable nature of renewable resources, leads to a mismatch between generation and consumption. The main reasons for this mismatch include:

- The high installed generation capacity required to

ensure system reliability,
- The inherent fluctuations of renewable sources (e.g., solar irradiance and wind speed), and
- The irregular charging behavior of EV users.

All these factors produce significant economic and environmental implications.

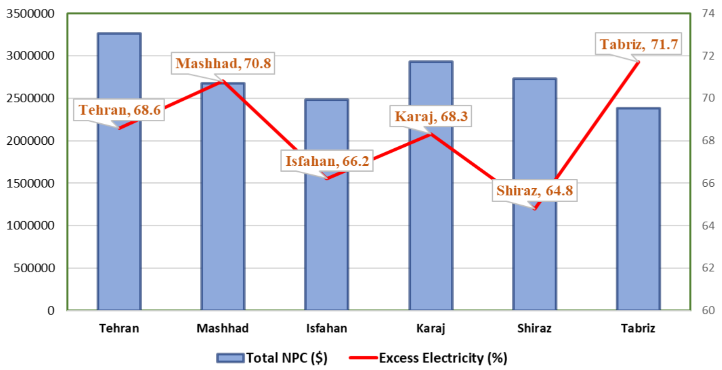


Figure 9. Total net present cost and percentage of surplus energy generation for the six studied cities

To address this energy waste, two main strategies are available: reducing generation capacity and increasing storage capacity. Although reducing generation capacity decreases surplus energy, it may not lead to an optimized total present value cost (TPVC), as during peak demand periods, the system may be unable to fully meet charging requirements. On the other hand, increasing storage capacity enhances system reliability, but the high upfront and maintenance costs of storage, if not carefully analyzed economically, can increase the TPVC.

By eliminating reliance on fossil-fuel power plants, microgrids supplying EV charging stations prevent the annual emission of approximately 700.8 tons of CO_2, 3 tons of SO_2, and 2.6 tons of NO_x per station. This not only decarbonizes transportation, improving air quality and public health, but also enhances grid resilience and reduces dependence on fossil fuels. Therefore, deploying such microgrids represents an effective investment in supporting EV adoption, reducing air pollution, and achieving environmental goals, ultimately charting a clear outlook toward a cleaner and more sustainable future in the energy and transportation sectors.

Thus, balancing costs, reliability, and surplus generation constitutes a complex optimization challenge. Achieving the minimum TPVC requires a precise multi-criteria analysis of technical and economic aspects, including generation costs, storage costs, and the value of wasted energy. The ultimate goal is not merely reducing surplus energy, but minimizing energy losses and achieving the economic optimization of the system, to sustainably supply power to EV charging stations.

5.3. Scenario 3

In the third configuration, electric vehicle charging stations, consisting of solar photovoltaic panels, wind turbines, and energy storage systems, are connected to the urban power grid. This hybrid system can store excess energy or inject it into the national grid. By utilizing the existing urban infrastructure, this approach offers advantages such as improved efficiency, lower costs and emissions, and enhanced reliability.

The nominal capacity of the microgrid components, the annual energy generated from renewable resources, the amount of energy purchased from and sold to the urban power grid, surplus energy, the percentage of energy supplied to charging stations from solar, wind, and grid sources, as well as the internal rate of return and payback period for each of the studied metropolitan areas, are presented in Table 5.

Based on optimization results for the six metropolises, the EV charging stations obtain a significant portion of their energy from solar power. Among them, Tehran (with 87.2%) has the highest share of solar energy, while Tabriz (with 56%) has the lowest. Conversely, Tabriz leads in wind energy utilization with the highest share (41.3%), whereas Tehran records the lowest share at 7.8%.

Overall, 96% of the total energy required by these stations is supplied through renewable resources, and only 4% is purchased from the urban power grid (as shown in Figure 10). Another noteworthy point is that 68.3% of the renewable energy generated, equivalent to 2346 MWh per year, is surplus to the needs of each station and is sold back to the urban grid.

These findings highlight the high efficiency of clean energy–based charging systems and their strong potential to support the stability and sustainability of the urban power grid.

Rows 10 to 11 of Table 5 present the relative share of each energy source (solar, wind, and grid) in the total annual generation for each city. The differences in the share of renewable resources among the cities arise from the climatic characteristics of each region.

Table 5. Power supply for electric vehicle charging stations using a hybrid micro-grid of renewable energy sources and the urban power grid

Term \ City	Tehran	Mashhad	Isfahan	Karaj	Shiraz	Tabriz
Rated Capacity of PV units (kW)	2116	1504	1320	1905	1545	1529
Rated Capacity of WT units (kW)	834	1215	1149	948	918	1101
Rated Capacity of Battery bank units (kWh)	297	202	286	281	310	199
Rated Capacity of Converter units (kW)	1648	1180	1038	1498	1235	1174
PV Energy Production (kWh/yr)	3,403,118	2,299,643	2,306,727	3,034,993	2,702,752	2,310,836
WT Energy Production (kWh/yr)	302,792	1,619,502	1,086,106	607,841	582,919	1,702,765
Energy Purchased (kWh/yr)	194,820	148,949	140,608	163,599	163,313	111,585
Energy Sold (kWh/yr)	2,552,211	2,748,975	2,249,885	2,480,993	2,161,456	2,805,990
Excess Electricity (kWh/yr)	160,100	162,522	125,041	147,428	117,644	162,384
PV Production (%)	87.2	56.54	65.3	79.7	78.4	56
WT Production (%)	7.76	39.8	30.7	16	19.6	41.3
Grid Purchases (%)	4.99	3.66	3.98	4.3	4.74	2.7
IRR (%)	30	42	41	32	36	31
Simple Payback (yr)	3.3	2.4	2.5	3.1	2.8	3.3

In the central areas (Isfahan, Tehran, and Karaj), solar irradiance is the dominant factor in energy supply, and the contribution of wind energy is relatively low. In the northeastern region (Mashhad), the climate is dry with moderate average wind speeds. In contrast, in the northwestern and southern cities (Tabriz and Shiraz), the share of wind energy is higher due to greater average wind speeds.

This climatic diversity results in different optimal configurations for each city, providing the proposed model with strong spatial adaptability.

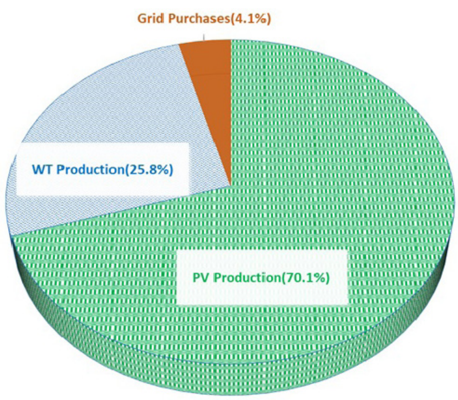


Figure 10. The share of energy supply sources for charging stations

By shifting the operational focus from energy storage to injecting surplus energy into the grid (a comparison of Scenario 2 and Scenario 3), the storage system capacity is reduced by 87%, while the capacity of the bidirectional converter increases by 69% to accommodate this function.

Table 6 shows the annual reduction of greenhouse gas emissions resulting from electricity generation by the proposed renewable hybrid system in EV charging stations across the six metropolises. Due to its high environmental compatibility and flexible, efficient power supply, this system demonstrates the best performance.

A notable result is the zero emissions of pollutants such as carbon monoxide, unburned hydrocarbons, and particulate matter, since the system contains no fossil-fuel generators or combustion-based units, and surplus electricity is fed into the urban grid. Overall, the system represents an environmentally efficient and sustainable solution for EV charging stations.

This system plays a significant role in reducing pollution by eliminating approximately 2342.4 tons of CO_2 annually for each charging station, a quantity that reaches nearly 58 million tons over a 25-year project lifetime! Additionally, it reduces 8.9 tons of SO_2 emissions and 10 tons of NO_x emissions annually.

Table 6. Details of greenhouse gas emission reductions resulting from the construction of electric vehicle charging stations

	Tehran	Mashhad	Isfahan	Karaj	Shiraz	Tabriz
Carbon Dioxide (kg/year)	2,371,782	2,508,253	2,171,413	2,331,414	2,102,829	2,568,705
Sulfur Dioxide (kg/year)	8,894	9,406	8,143	8,743	7,886	9,633
Nitrogen Dioxide (kg/year)	10,154	10,738	9,296	9,981	9,003	10,997

With this approximate annual reduction of 2342.4 tons of CO_2 per charging station, the environmental impact is substantial. Over a 25-year lifespan, the cumulative avoided emissions approach 58 million tons! Furthermore, the system annually mitigates 8.9 tons of sulfur dioxide and 10 tons of nitrogen oxides.

Table 7 presents a comparative overview of key performance indicators for each scenario. The results reveal considerable differences in the economic cost, levelized cost of energy, and carbon emissions among the three scenarios evaluated for EV charging stations in the six metropolises.

In Scenario 1, representing the baseline condition where no renewable energy is integrated and the system depends entirely on the conventional grid, the net present cost (NPC) is equal across all cities and relatively low (1.41 million USD). However, the levelized cost of energy (LCOE) is relatively high (0.075 USD/kWh), and the carbon emissions are extremely high (approximately 658,000 kg of CO_2 per year). This scenario clearly reflects:

- full dependence on fossil fuel–based grid electricity, and
- a complete lack of environmental benefits or sustainability.

Table 7. Comparison of key indicators across the scenarios

Term/City		Tehran	Mashhad	Isfahan	Karaj	Shiraz	Tabriz
NPC ($) (Net Present Cost)	Scenario 1	1.41M	1.41M	1.41M	1.41M	1.41M	1.41M
	Scenario 2	3.27M	2.68M	2.48M	2.93M	2.73M	2.38M
	Scenario 3	-2.33M	-3.03M	-2.27M	-2.34M	-2.01M	-3.23M
LCOE($/kWh) Levelized Cost of Energy	Scenario 1	0.0750	0.0750	0.0750	0.0750	0.0750	0.0750
	Scenario 2	0.166	0.136	0.126	0.149	0.139	0.121
	Scenario 3	0.0532	0.0522	0.0501	0.0533	0.0445	0.0515
Emission (kg/yr) Carbon Dioxide	Scenario 1	658187	658187	658187	658187	658187	658187
	Scenario 2	0	0	0	0	0	0
	Scenario 3	-1489871	-1643216	-1333063	-1464612	-1262827	-1702864

In Scenario 2, which typically represents the use of renewable resources without bidirectional energy exchange with the grid, investment costs increase, and the NPC ranges from $2.3 to $3.2 million, while carbon emissions drop to zero. Although this scenario is environmentally attractive, its relatively high energy cost (LCOE up to $0.166 in Tehran) indicates the need for further economic optimization.

In contrast, Scenario 3 delivers the best overall results. In this scenario:

- The NPC becomes negative, meaning the system not only recovers its investment but also generates economic profit.
- The cost of energy production decreases to about 0.05 USD/kWh.
- Carbon emissions become negative, indicating that the stations not only avoid pollution but also help reduce national emissions by feeding surplus clean energy back into the grid.

Among the cities analyzed, Tabriz and Mashhad exhibit the strongest economic and environmental performance.

Overall, this analysis demonstrates that implementing Scenario 3 is the most sustainable and efficient option for developing electric vehicle charging infrastructure in Iran's metropolises.

6. Sensitivity analysis of economic parameters

To evaluate the economic robustness of the proposed model against macroeconomic fluctuations, the impact of two key parameters, nominal interest rate and inflation rate, was analyzed by applying a ±20% variation. The results of this sensitivity analysis are presented in Table 8.

Table 8. Sensitivity analysis of economic parameters

Term	City / Nominal Discount Rate	Tehran	Mashhad	Isfahan	Karaj	Shiraz	Tabriz
NPV ($) (Net Present Value)	12%	3.79M	4.65M	3.56M	3.76M	3.23M	4.91M
	15%	2.33M	3.03M	2.27M	2.34M	2.01M	3.23M
	18%	1.42M	2.01M	1.45M	1.45M	1.24M	2.16M
LCOE($/kWh) Levelized Cost of Energy	12%	0.0438	0.0445	0.0402	0.0400	0.0374	0.0436
	15%	0.0532	0.0522	0.0501	0.0533	0.0445	0.0515
	18%	0.0638	0.0609	0.0583	0.0633	0.0526	0.0635
	Inflation Rate						
NPV ($) (Net Present Value)	9.6%	1.54M	2.14M	1.56M	1.54M	1.34M	2.30M
	12%	2.33M	3.03M	2.27M	2.34M	2.01M	3.23M
	14.4%	3.44M	3.03M	3.26M	3.43M	2.94M	4.51M
LCOE($/kWh) Levelized Cost of Energy	9.6%	0.0620	0.0595	0.0569	0.0616	0.0513	0.0619
	12%	0.0532	0.0522	0.0501	0.0533	0.0445	0.0515
	14.4%	0.0454	0.0459	0.0415	0.0461	0.0387	0.0450

Nominal interest rate:

As the primary discount rate, the nominal interest rate has a direct impact on the net present value (NPV) and the levelized cost of energy (LCOE). A 20% decrease in the interest rate results in an 89.3% increase in NPV and an 18.1% reduction in LCOE, indicating improved profitability under favorable financial conditions. Conversely, a 20% increase in the interest rate results in a 36% reduction in NPV and an 18.9% increase in LCOE.

Annual inflation rate:

A 20% reduction in inflation results in a 31.5% decrease in NPV and a 15.9% decrease in LCOE. A 20% increase in inflation results in a 35.5% rise in NPV and a 13.8% decrease in LCOE.

Overall, NPV exhibits the highest sensitivity to the nominal interest rate, as a 20% change in this parameter leads to nearly a 90% fluctuation in NPV. In summary, the proposed model remains economically stable under ±20% variations in macroeconomic parameters, although its profitability is more vulnerable to changes in the interest rate.

7. Conclusion

Energy crises and environmental challenges have become major concerns for policymakers worldwide. In this context, electric vehicles play a key role in sustainable transportation by reducing carbon footprints and offering substantial environmental benefits. Charging these vehicles using renewable energy not only contributes to the sustainability of the electricity grid but also enhances the reliability and environmental performance of charging systems.

This study explored how renewable energy sources, such as solar and wind, can be integrated with electric vehicle charging stations. The main objective was to design a sustainable and reliable system that enables EV charging with clean energy. Achieving this integration requires consideration of EV energy demand patterns, renewable energy generation capacities, and battery storage systems.

The findings of the study demonstrated that the proposed systems, consisting of solar panels, wind turbines, a battery system, and a connection to the municipal power grid, provide the highest technical and economic efficiency for ensuring a sustainable electricity supply to EV charging stations. The resource share analysis showed that solar energy accounts for 70.4% and wind energy for 25.4% of the total energy supplied to the stations, while only 4% of the required energy is purchased from the grid under low renewable-generation conditions. This energy mix ensures a highly reliable power supply. It enables the annual production of 2,346,106 kWh of surplus energy (equivalent to 68.3% of total renewable energy generated), which can be sold to the national grid, creating an additional economic advantage. Furthermore, the proposed systems significantly reduce greenhouse gas emissions, particularly by cutting more than 2,342 tons of CO_2 annually per charging station, thereby offering substantial environmental benefits. Overall, the results clearly demonstrated that hybrid renewable energy charging systems not only achieve desirable economic performance but also strengthen urban grid stability, reduce environmental pollutants, and improve energy resilience indicators. Thus, they represent an effective step toward developing green and smart charging infrastructure in Iran's major metropolitan areas.

Despite challenges such as seasonal variability in renewable generation, precise system design and the use of advanced energy management technologies, including smart grids, are essential to ensure reliability and optimal energy management. Successful implementation requires a comprehensive approach that incorporates economic, environmental, and social factors. Future research should focus on the impact of EV charging on power grids and on developing strategies to optimize this integration, thereby enhancing the sustainability of electric transportation systems.

7.1. Recommendations

Due to the lack of access to real-world data on EV load profiles in the region, this study relied on data from neighboring countries. Future research should focus on developing a dynamic load model that considers various types of electric vehicles and chargers, as well as the differences between residential, educational, and industrial locations. The greatest barrier to installing high-capacity solar charging stations is the availability of open space. Limited land, especially in densely populated urban areas, makes selecting suitable locations for solar infrastructure a challenging task. Therefore, identifying appropriate sites must involve more detailed analysis, both in terms of physical space and accessibility to renewable energy resources.

Authors' Contributions

This article was prepared by a single author, who holds 100% contribution to the work.

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Conflict of Interest

The author declares no conflicts of interest.

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