

Policy Oriented Techno-Economic Evaluation of Off-Grid Electric Vehicle Charging Station Powered by Renewables

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Abstract

Electric vehicles play an important role in reducing the consumption of fossil fuel resources, adding much to mitigate environmental concerns like carbon dioxide and other pollutant gas emissions compared with internal combustion engine vehicles. Operation and maintenance charges are also at their lowest. However, they are required to charge batteries placed inside that propel the electric vehicle (EV) with the help of motors. Therefore, a charging infrastructure is required so that people can travel over longer distances without any hindrances in charging their EVs. The study aims to analyze the technical and economic parameters to integrate off-grid charging stations powered by renewable energy resources like solar, wind, and hydrogen in Islamabad the capital territory and Karachi, the biggest cities in Pakistan. As Pakistan ranks fifth in the Global Climate Risk Index, these resources help move up its number. The study employed HOMER software to design and obtain the proposed model and the data on solar irradiance and wind speed. Moreover, the study has performed a comparative analysis of these two big cities in Pakistan. This research provides valuable insights for policymakers and stakeholders planning for off-grid EV charging station infrastructure.

1. INTRODUCTION

Climate change imposes many challenges to humans in sustainable development [1]. Integration of Renewable energy resources in the national grid is crucial to meet energy demands in electricity, transportation, and hiking of fuel prices. Emissions from Pakistan's transportation sector are steadily increasing [2, 3]. It accounts for

28% of Pakistan's total greenhouse gas emissions, ranking second only to the power sector as the source of the greatest emissions. Pakistan's transport sector is one of the causes that affect the growth of its economy, as fuel is imported for energy generation and transport [4]. The adoption of renewable energy resources for energy generation and electric vehicles for

transport will somehow boost Pakistan's economy and mitigate the hazards caused by climate change due to greenhouse gas emissions. The limited number of charging stations is one of the reasons that affect the adoption of electric vehicles [5]. However, this issue can be solved by the integration of Public fast charging stations so that users feel no worry to travel long. The on-board and off-board chargers are used to charge an EV. The on-board chargers use an AC supply and convert it into DC for battery charging increasing the weight of an EV. However, off-board chargers directly supply DC power to charge the battery of an EV [3, 5]. The onboard chargers have a power level of 3.6 to 22 kW and a charging time of up to 11 hours. However, DC off-board chargers reduce the charging time with a power level of up to 350 kW [6].

The increasing demand for EVs and charging infrastructure impact the grid stability due to its varying and non-dispatchable load. Building an off-grid charging station for EVs will be less likely to impact the grid powered by renewable energy resources. The energy generation from solar and wind is non-dispatchable as solar relies on the availability of solar irradiance and in the same way wind power is dependent on the availability of wind speed. Therefore, the hybrid model to generate energy for EV charging will present a novel solution to the varying nature of solar and wind energy. Hydrogen gas due to its enormous chemical properties like less harmful but high calorific value is used in the cooling and heating of different processes. Liquid hydrogen is used as a fuel for rocket boosters [7]. The chemical energy of Hydrogen is converted into electrical energy with the help of fuel cells emitting oxygen and water as a bi-product without any other harmful gases or compounds. The energy generated by hydrogen fuel through fuel cells does not depend upon the availability of solar irradiance and wind speed. Hydrogen can be stored in large tanks and can be used as a fuel to generate electrical energy any time of the day. Hydrogen gas can be obtained using different processes like steam methane reforming, coal gasification, partial oxidation of hydrocarbon, biomass gasification, electrolysis, thermochemical, photochemical, and

photobiological. The process of electrolysis uses electricity to break down water into hydrogen and oxygen, where hydrogen can be stored for later use to generate clean electrical energy [8].

Most of the studies in the previous literature tested various equipment and devices to counterbalance the increasing energy demand. Author in West Bengal India proposed an on-grid system of hybrid energy resources to overcome the load demand of EVs. The study presents a Cost of Electricity (COE) of 0.085 \$/kWh for a base case grid-connected system. However, the COE decreased by 0.083 \$/kWh for different systems for on-grid PV. A study at Tharparkar, Sindh Pakistan compares the on-grid and off-grid systems based on COE. The results indicate a COE for the proposed system is Rs. 5/kWh and the grid-connected system is Rs.8/kWh [9]. In [10] the author presents a review of different components and technologies for EV charging, infrastructure, configurations of energy converters, their design, and standards. The author in [11] proposed different hybrid configurations to generate electrical energy under the expected demand of energy to be 2100 kWh/day. The study shows that among three hybrid configurations of PV-hydrogen, hydrogen-wind, and PV-wind the last configuration presents a COE of \$0.264/kWh with an Net Present Cost (NPC) of \$1.519 M [11].

The study in Sub-Saharan Africa estimated the cost and size of a standalone hybrid energy system. The system was designed for 30 fuel-cell EVs and 70 battery-powered EVs. The study shows that the designed system produces 55.6 tons of hydrogen gas with 3.9 GWh of electrical energy per annum. The obtained results are COE is \$0.52/kWh, and NPC is \$6.53 M with an 8-year to be the payback period [12]. The study [13] compares the technical and economical parameters for backup power supplies based on hydrogen batteries. The obtained results indicate that the COE for the battery-only system is \$ 2.68/kWh. However, the COE for a hybrid battery-hydrogen system is \$0.626/kWh.

A study at Jamshoro, Sindh Pakistan was conducted which compares the technical and economical parameters of an EV charging station

powered by a Hybrid solar PV-hydrogen-based system for an off-grid system. The 1750kWh/day and 180 kW are the expected demand and peak load for EVs. The study gives a COE of \$0.379/kWh with an NPC of \$3.08 M for an Off-grid PV-hydrogen and battery hybrid system. However, with the proposed system the obtained COE and NPC are \$0.432/kWh and \$3.58 M [14]. A case study in a rural area presents a hybrid system to produce electricity comprising solar, distributed generation, and wind in Omans' Sultanate. The study's objectives were to reduce greenhouse gases and lessen gasoline use. The ETAP and HOMER software have been used to model the proposed design. The study outcomes show that up to 3.38 times the use of gasoline has been reduced and the proposed system has a

COE of \$0.257/kWh with an NPC of \$14.09 [15].

In [16] the feasibility of technical and economic parameters of an on-grid PV systems for EVs were evaluated. Due to high solar potential, the location of Ngawi Indonesia was selected. The study reveals that the COE and NPC of the designed system are \$0.21/kWh and \$68134.8 for the expected load of 343 kWh. In the author has explained infrastructure and numerous key roles in designing sustainable EVs. Furthermore, the optimal siting for EVs connected with the grid has been fully explained. **Table 1** represents more literature relevant to this study.

Table 1: Past literature on EVs charging stations powered by renewables

Reference	Location	Configuration	COE (\$/kWh)
[17]	Morocco	Solar-Battery	0.280
[18]	Fiji	Solar-Battery-Wind	1.15
[19]	North America	Solar-Fuel Cell	0.77
[20]	Iran	Grid-Solar-Wind	0.214
[21]	Bangladesh	Solar-Battery-Wind	0.470
[22]	South Africa	Solar-Hydro-Wind	0.197
[23]	Sarawak Malaysia	Solar-Fuel Cell	0.355
[24]	Central India	Solar-Wind-Fuel Cell	0.505
[25]	Bozcaada Turkey	Solar-Wind-Fuel Cell	0.685
[26]	North of Cameroon	PV-Diesel Generator-Battery	0.576
[6]	Pakistan (Hyderabad, Lahore, Quetta, Peshawar)	Solar, Wind, Fuel Cell	(0.567,0.517, 0.485,0485)

Based on the above literature, a vast amount of work has been done to find optimal designs with their sizes to meet the increasing load demand of EVs and energy needs. Different designs are proposed with decreasing COE, and greenhouse house gasses to meet energy demands in many countries. In the same, manner Pakistan has the potential to generate 64 GW of electricity from solar and 50 GW from wind energy with its current load demand of only 48 GW [27]. It will play a key factor in reducing harmful greenhouse gas emissions, reducing the import of gasoline required for conventional energy generation, meeting the increasing load demand for EVs, and

contributing to sustainable development goals. Therefore, this study intends to fill a significant vacuum by looking into the integration of off-grid solar, hydrogen, and wind-powered EV charging stations in Islamabad and Karachi. This study aims to find the ideal size and cost parameters for sustainable EVs charging infrastructure by examining the effects of geographical location, climate conditions, and variable renewable energy output on system performance and economics. The research shows the feasibility and optimization of hybrid renewable energy systems for EV charging by developing a hypothetical load demand model and utilizing simulation

tools such as HOMER software. The findings may give significant insights to policymakers, energy sector stakeholders, and decision-makers in facilitating the transition towards environmentally friendly transportation options in Pakistan, eventually helping.

2. Research Methodology

This study employed HOMER software to perform a techno-economic analysis of an off-grid electric vehicle charging station fueled by renewable energy resources. The software is a helpful tool because it emphasizes cost-efficiency while also delivering insightful perspectives on energy asset harmonization [28]. The **Figure 1** represents the flowchart of how HOMER software optimizes.

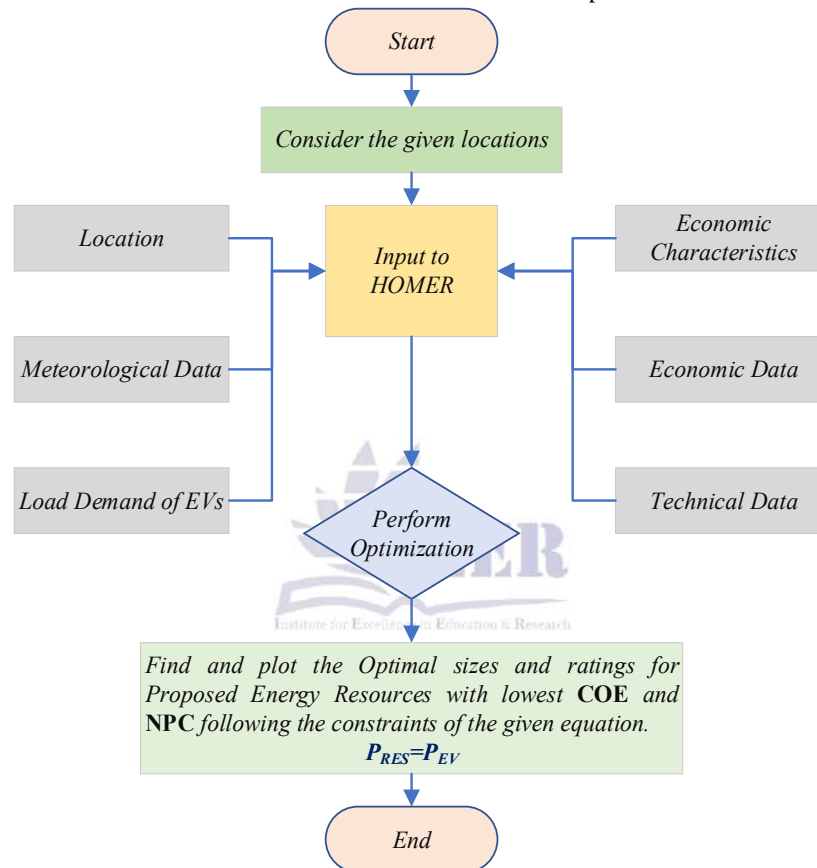


Figure 1: Flowchart of methodology used in this study

The HOMER software needs a specific amount of data for specified locations for solar, and wind. Global Horizontal Irradiance (GHI), temperature data, and wind speed. Moreover, the specified ratings of required components and specified load data are necessary for HOMER optimization. HOMER software is primarily used to calculate the economic feasibility analysis for any proposed design of renewable energy resources. HOMER software optimizes these parameters following the constraints of load and generation [29]. These economic parameters

include COE, NPC, inflation rate, nominal and real discount rates, payback period of the proposed design, and profitability index. The main concerns of this study are COE, and NPC of the proposed design. The COE can be calculated using **Equation 1**. The LCOE is the ratio of the total annual capital cost of the system to the total energy supplied by the system to load [28].

$$COE = \frac{C_{annum\ total}}{E_{annum\ total}} \quad (1)$$

Where,

C_{annum} = Total annual cost of the system (\$/year)

$E_{annum\ total}$ = Total annual energy served to the load (kWh/year)

Moreover, the time after which the investor earns some profit for its investment in any project is termed as payback period. The feasibility of the project can be seen in how much the payback period is, lower value of the payback period enables the investor to earn profit early. The payback period is the ratio of initial capital to annual savings. The value of the payback period is calculated using Equation 2 and annual savings can be calculated using Equation 3.

$$\text{Payback period} = \frac{\text{Initial Capital}}{\text{Annual Saving}} \quad (2)$$

$$\text{Annual Saving} = \text{Electricity Generation per Year} \times \text{Fix rate} \quad (3)$$

Where,

Fix rate = feed-in-tariff/kWh

The net present cost of an EV charging Station is the difference between the present value of capital expenditures and lifetime costs (including operation and maintenance cost, initial capital, and the revenue generated over the lifetime of

the project). Equation 4 is used to calculate NPC [30, 31].

$$C_{NPC} = \frac{C_{annual,load}}{CRF(i, R_{project})} \quad (4)$$

Where,

C_{NPC} = Net Present Cost

$C_{annual,load}$ = Total annual cost of the project (\$/kWh)

CRF = Capital Recovery Factor

i = Real Interest/ Discount Rate (%)

$R_{project}$ = Project Lifetime (years)

In this study, the two big cities of Pakistan Karachi and Islamabad are selected. Karachi is the coastal region of Pakistan having an altitude of 24.86, a longitude of 66.99 with a GPS of 24° 51' 39.4776" N, and 6° 59' 25.8036" E is rich in wind power and GHI resources these resources can be extracted to generate a surplus amount of energy as seen in Figure 2 and Figure 3. In the same way, Islamabad the capital territory of Pakistan located at 33.6844°N 73.0479°E in Margalla Hills Near Faisal Mosque has a vast amount of solar and wind potential. This study examines the techno-economic analysis for the integration of off-grid EV charging stations supplied with solar, wind, and hydrogen energy.

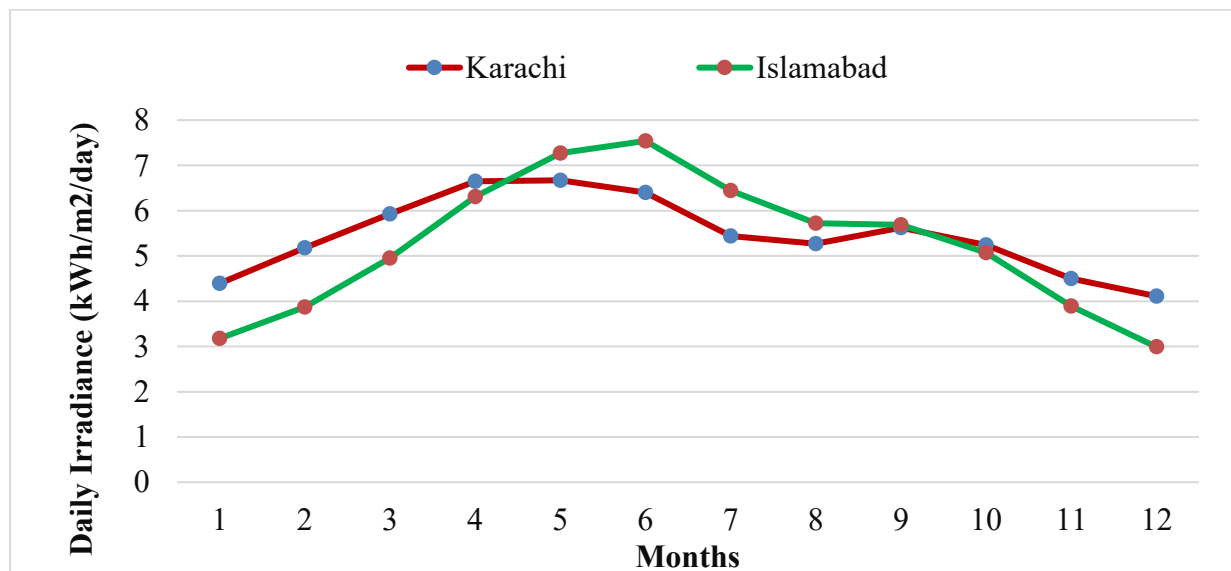


Figure 2: Average Solar Irradiance at selected locations

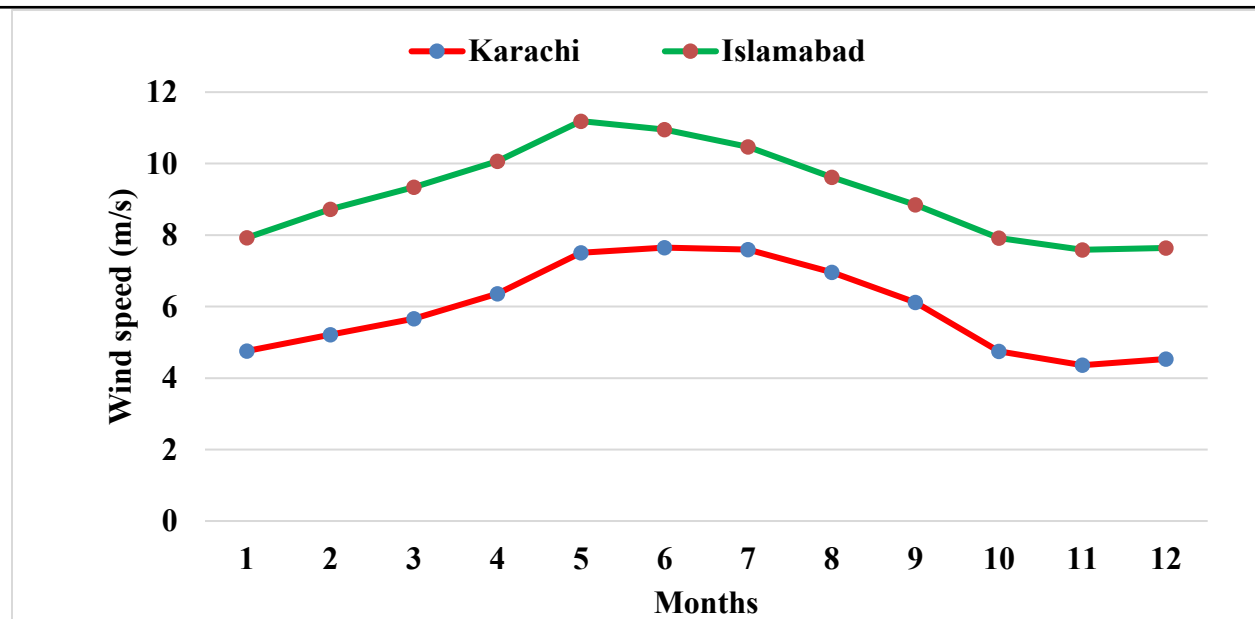


Figure 3: Wind Speed at selected locations

Table 2 shows the parameters used for Solar PV. In this study, LONGi solar LR6-72 is used having 18.1% efficiency under nominal conditions. The selected solar type has \$ 10/kW of maintenance cost and 640 /kW of replacement and capital. The Equation 5 calculates the output power of solar PV arrays [12, 28, 29].

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_p (T_c - T_{c,STP})] \quad (5)$$

Where,

Y_{PV} = the PV array's rated capacity

f_{PV} = the percentage of PV derating.

G_T = the incident of solar radiations

$G_{T,STC}$ = the incident radiations under standards test conditions

α_p = the power coefficient at a temperature (%/°C)

T_c = the cell temperature of the PV array

$T_{c,STP}$ = the cell temperature under standard conditions (25°C)

Table: 2 Technical parameters of solar PV [29]

Parameters	Value
Model	LONGi solar LR6-72
Capacity	350 W
Efficiency	18.10%
Lifespan	25
Type	Flat Plate
Weight	26.5 kg
Operating Temperature	47 °C
Coefficient of Temperature	-0.41 %/°C

Table 3 represents the different parameters of wind turbine used in this study. A wind turbine works opposite of ceiling fan. A wind turbine converts the power available in wind into

mechanical energy, whereas a coupled generator extracts the mechanical power of the turbine and converts it into electrical energy. As solar power is available only in the daytime, therefore wind

power is combined with it to supply energy during the night. The power extracted from the wind depends on the area of rotor blades, the velocity of the wind, the hub height of the wind turbine, and the density of the wind, which is affected by the hub height. In this study, the “Lagerwey LW30/250” model of a wind turbine is selected under a hub height of 50 m with a unit capacity of 250 kW [6]. The HOMER uses **Equation 6** to calculate the feasible hub height and wind speed to optimize the economic parameters. In the same way **Equation 7** is used by HOMER to calculate the power curve of any type of wind turbine.

$$U_{hub} = U_{anem} \times \left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \quad (6)$$

Where,

α = the power law exponent

Z_{hub} = hub height (m)

Z_{anem} = height of an anemometer

U_{anem} = wind speed at anemometer height (m/s)

U_{hub} = wind speed at height of wind turbine (m/s)

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right) P_{WTG,STP} \quad (7)$$

Where,

P_{WTG} = the output power of wind turbine (kW)

$P_{WTG,STP}$ = the output power of wind turbine at STP (kW)

ρ = real density of air (kg/m³)

ρ_0 = the density of air at STP (1.225 kg/m³)

Table: 3 Technical Parameters of Wind Turbine [6]

Parameters	Value
Manufacturer	Wind energy solutions
Capacity	250 kW
Lifespan	25 years
Rotor Diameter	30 m
Hub height	50 m
Rated wind speed	13 m/s
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Total number of blades	2

The process of splitting water into hydrogen and oxygen using electricity is termed an electrolysis process and the device is known as electrolyzer. In this study, an electrolyzer uses some power from solar PV arrays to convert water into hydrogen and oxygen. The obtained hydrogen is termed green hydrogen because it uses renewable energy resources solar. The proton exchange membrane electrolyzer is used having an efficiency of 85% with a 15-year lifespan [12]. The amount of pressure required to compress hydrogen for storage is 30 Bar [13]. The HOMER software uses **Equation 8** to calculate the power consumed by an electrolyzer [32].

$$P_{EZ} = \frac{m_{H_2} HHV_{H_2}}{\eta_{H_2}} \quad (8)$$

Where,

η_{H_2} = total efficiency of an electrolyzer

m_{H_2} = mass flow rate at which the Hydrogen is produced by an electrolyzer (kg/s)

HHV_{H_2} = heating value of hydrogen fuel (MJ/kg)

P_{EZ} = DC power of an electrolyzer (W)

Moreover, **Equation 9** is used to calculate the expected Hydrogen produced by the Electrolyzer.

$$R_{hydrogen} = \frac{I_{ele} \times \eta_f \times N_c}{2F} \quad (9)$$

Where,

$R_{hydrogen}$ = rate of Hydrogen production

I_{ele} = current of the electrolyzer

N_c = the number of consecutive cells in the electrolyzer

F = Faraday's Coefficient

η_f = Faraday's efficiency

Hydrogen brings numerous chemical properties, and when used as a fuel emits no harmful gases and it is a highly flammable gas. Hydrogen gas can be stored in tanks and used as fuel at any time of the day. Hydrogen is stored in tanks at 30 bars. This study considers \$ 435/kg as its

replacement and capital cost. The heating value of hydrogen is three times that of any other hydrocarbon e.g. 28000 kcal/kg. **Table 4** shows the configuration of components employed in this study.

Table 4: Configuration of hydrogen, electrolyzer, fuel cells, and converter [13, 14, 31, 32].

Equipment	Fuel cell	Electrolyzer	Hydrogen Tank	AC-DC Converter
Model/Type	PEMFC	PEM	Storage	Generic system converter
Unit capacity	1 kW	1 kW	1 kg	1 kW
Efficiency	45%	85%	-	95%
Lifespan	40,000 h	15 years	25	15 years

Fuel cells use the process of redox reaction in which hydrogen as a fuel with ambient oxygen is converted into electricity and water as a biproduct [31]. The fuel cell was first created in 1839 by Sir William Grone called a Gas Battery. Among different types of Fuel cells like Proton Exchange Membrane Fuel cells, Direct Methanol Fuel cells, Alkaline Fuel Cells, Solid Oxide Fuel cells, Phosphoric Acid Fuel Cells, and Molten Carbonate Fuel cells the PEMFC have greater efficiency of 40-50%. **Equation 10** is used to calculate the power generated by the fuel cell.

$$P_{FC} = N \times V_{FC} \times I_{FC} \quad (10)$$

Where,

P_{FC} = power produced by the fuel cell

N = number of fuel cells in the stack

V_{FC} = output voltage of fuel cell

I_{FC} = Current in fuel cell

Moreover, **Equation 11** calculates the output voltage of the fuel cell

$$V_{FC} = E \times V_{act} \times V_{con} \times V_{\Omega} \quad (11)$$

Where,

V_{FC} = Activation voltage

V_{con} = concentration voltage

V_{Ω} = Ohmic voltage

E = Fuel cell internal voltage

The charging time of an EV depends on the rate at which the power is flowing from the source to the EV. The charging time will be low if power flows faster to charge the battery placed in the EV. The power converters in Superfast chargers reduce the charging time because of their high efficiency. **Equation 12** is used to determine the efficiency of power converters. **Figure 4** represents the types of converters used in literature to reduce the charging time of an electric vehicle.

$$P_{out} = P_{in} \times \eta_{con} \quad (12)$$

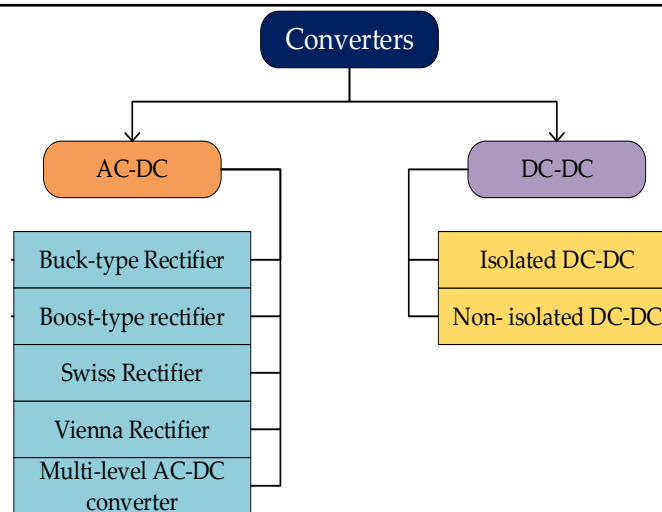


Figure 4: Types of power converters used in EVs

3. Results and Discussion

In this study two different cities of Pakistan were selected to integrate off-grid EV charging stations. **Figure 5** represents the design of charging station power sources. The model depicts a system of hybrid renewable energy, which combines wind and solar energy to store and to use hydrogen and fuel cells. The WES250 wind turbine produces AC power thus feeding electricity in the Electric Load 1 or through the Converter that

makes it DC. The LR6-72 solar PV panels supply DC power which also supplies the load or goes to the Electrolyzer. Its Electrolyzer that generates hydrogen by using surplus electricity and this hydrogen is stored in the Hydrogen Tank. The stored hydrogen is returned to electricity, to assist the load in the case of requirement, by the Fuel Cell (FC). Such arrangement allows efficient use of renewable energy and hydrogen consisting of backup and medium energy storage.

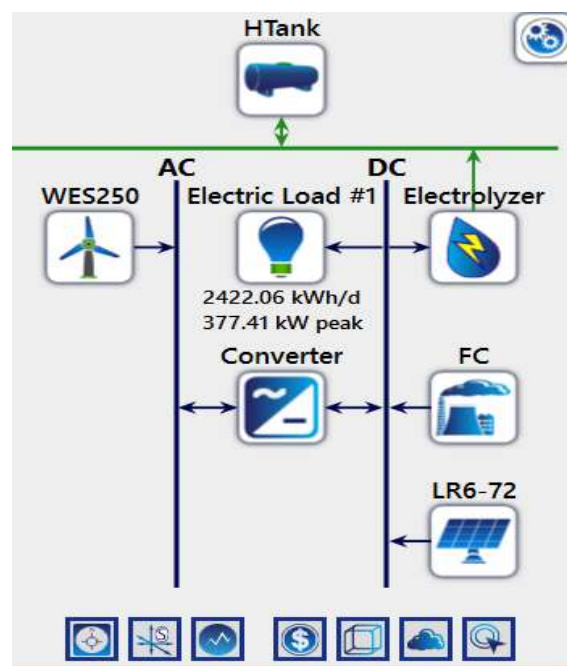


Figure 5: Block diagram of solar-wind-hydrogen hybrid charging station

The hourly load patterns of EVs that are displayed on 24H of a day is shown in **Figure 6**. The blue bars show the load in kilowatts (kW) and a small constant load of 36 kW occurs in the early morning hours, and the late-night hours. At 8 AM, its load starts sharply increasing till 240 kW when the load is between 9 AM to 4 PM showing that there is a high EV charging demand as people drive for their work locations at the usual daytime. Load decreases slowly after 4 PM, candles in the evening there will be fewer EVs that will be charged. The red dotted line indicates the total or mean exponentially increasing load pattern at any point through the day.

The optimization results of this study are shown in **Table 5** that invents a relationship between renewable energy systems in Karachi and Islamabad by comparing the systems based on

energy mix, generation and economic performance of the system at Gulshan-e-Hadeed Phase 2 Karachi and at the Faisal Mosque Islamabad in Pakistan. Both systems are mainly based on the solar power with Islamabad recording a little higher solar input by 93.2% against 89.1% of Karachi because of the good solar panel orientation or irradiation as seen in **Figure 7(a)**. Nevertheless, Karachi provides a better wind potential which provides 6.91% of its generation by wind but in Islamabad it only gains 1.48%. Although both systems produce well over 10 million kWh/year, they both use less than 900,000 kWh/year, leaving more than 9 million kWh/year as unused, giving a possible indication that energy could be stored or exported to the grid or increasing load of EVs will not affect the stability of the design.

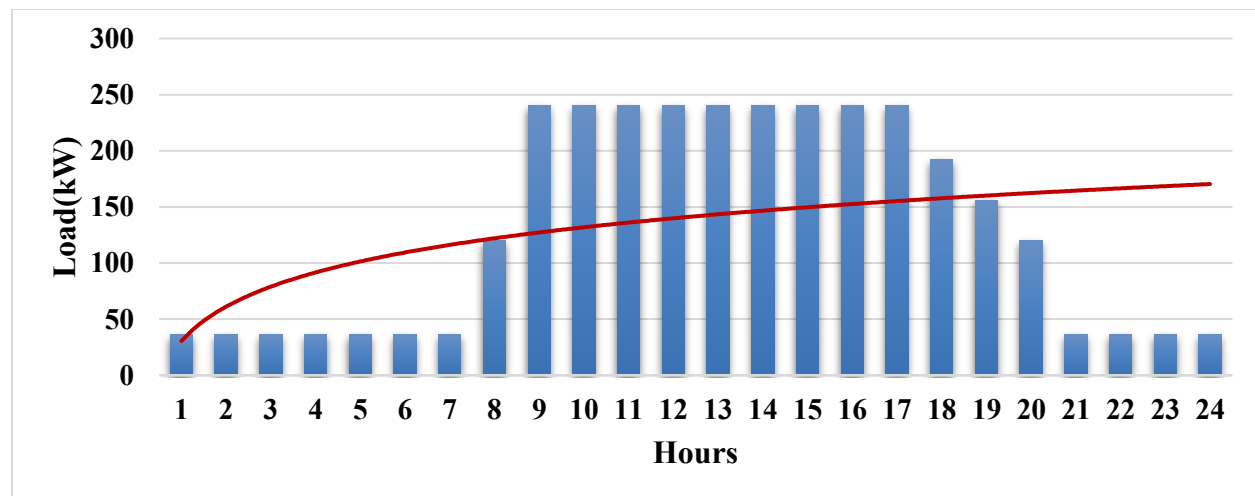


Figure 6: Daily average load profile

Table 5: Comparative results of selected locations

Location	% Generation from each Source	Power Generated (kWh/yr)	Power Consumed (kWh/yr)	COE (\$)	Excess Power (kWh/yr)	NPC (\$M)
Karachi Gulshan-e-Hadeed Phase 2	89.1% Solar, 4% Fuel Cell, 6.91% Wind	10065998	884025	0.270	9158100	3.08
Islamabad Faisal Mosque	93.2% Solar, 5.33 Fuel Cell, 1.48 Wind	10031406	884074	0.3388	9146921	3.872

The system of Karachi is more economical with a lower COE of 0.270 /kWh and a Net Present Cost (NPC) of 3.08 million dollars when compared with the higher COE of 0.3388 /kWh and the Net Present Cost (NPC) of 3.872 million dollars of the Islamabad system as seen in **Figure 7(b)** This implies that the hybrid model in

Karachi is more cost effective with an improved ratio between solar and wind. Therefore, although the two systems have the potential to be extremely renewable, location-wise and in terms of resources combination, Karachi exhibits an improved performance and expense.

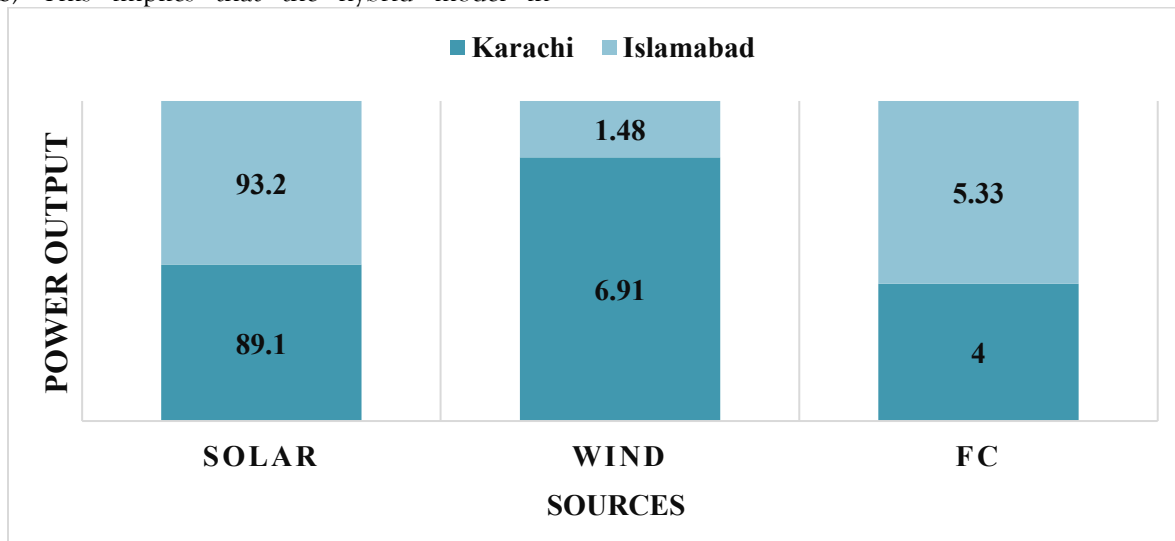


Figure 7(a): Power output of selected locations

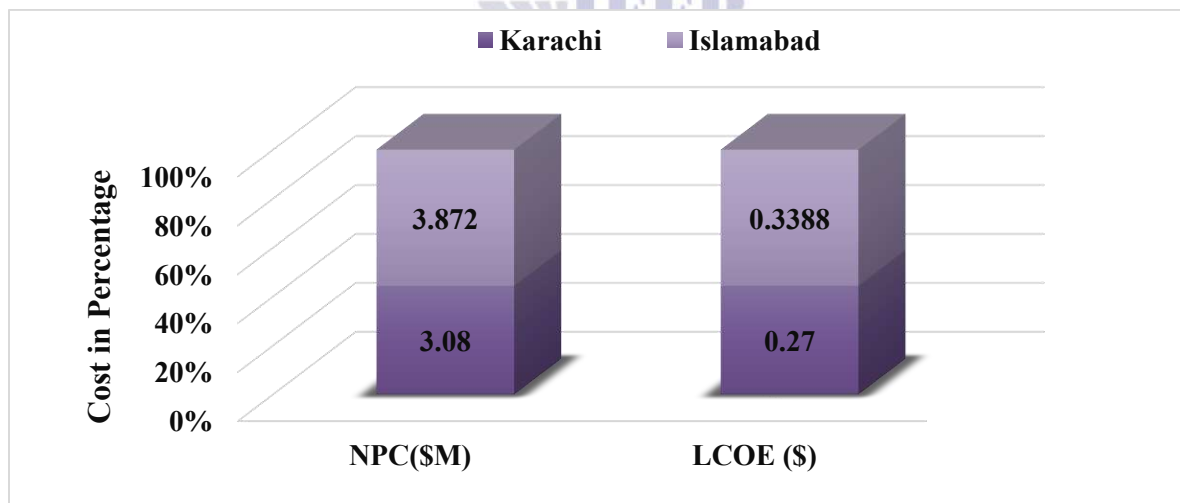


Figure 7(b): Cost output of selected locations

Figure 7(a,b): Cost and Power Output at the Selected Location

4. Conclusion

This paper highlights the feasibility of off-grid hybrid renewable energy systems (solar-wind-hydrogen) for EV charging stations in Islamabad and Karachi, which leads to a significant reduction in fossil fuel dependence and

emissions. Although Islamabad has a greater solar irradiance (93.2% solar share), the potential wind is higher in Karachi (6.91% wind share) hence its system is more economical even with the lesser LCOE (\$0.270/kWh vs. \$0.3388/kWh) and NPC (\$3.08M vs. \$3.872M). The amount of

surplus energy generated in both systems is very large (>9 million kWh/year). This is indicating the possibility of integration into the grid, hydrogen storage or even more EV charging ports may be installed will bring no power stability issues. The optimization of the hybrid model applied in Karachi showcases the best economic performance that the city highlights, the necessity of the location-bound renewable energy strategies. Such conclusions are useful for policymakers in creating sustainable EV infrastructure in Pakistan. Additional studies need to be done to investigate the production of high-level energy storage to improve efficiency and reliability of the system including hybrid battery-hydrogen. Also, further locations of such a study in other parts of Pakistan would probably facilitate the implementation of a country level renewable-powered EV charge network.

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Data Availability Statement

The data that support the findings of this study are available within the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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