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Wind-to-Hydrogen Production Potential for Selected Sites in Pakistan

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ABSTRACT This paper provides a comprehensive assessment of wind energy potential for Hydrogen production under local conditions of Pakistan from the design, development and practical implementation perspectives. Simulations were performed for three sites—Bahawalpur, Sanghar and Gwadar using actual wind speed site data, recorded between 2016 and 2018, at intervals of 10 minute. For the selected sites, wind resource assessment was performed using the Weibull distribution function parameters, energy and wind-power density calculations at hub heights of 20m, 40m, 60m and 80m of the wind turbines. It was observed that Sanghar is the most suitable site for wind-to-Hydrogen production potential with power and energy density of 305.86 W/m^2 and 2665.81 kWh/m^2, respectively. From the implementation perspective, the Nordex N90/2500 wind turbine at an 80m hub height was found to be beneficial for Sanghar with a cost of energy of 35.21$/MWh (0.035$/kWh). The cost of Hydrogen using an electrolyzer for 7-year long-term investment was 2.29 k$/ton using Nordex N90/2500 turbine. Based on the available power density and land area, a general scheme for production of Hydrogen using electrolysis can be implemented with possibility of installation and commissioning of wind farms.

INDEX TERMS Economic assessment, hydrogen production, Weibull distribution, wind energy.

I. INTRODUCTION

Today world is facing the global challenge of climate change and temperature rise. The quest of finding a lasting solution to pollution-free clean air environment has led to the formulation of various policies and agreements like the Kyoto Protocol and Paris Agreement by all stake holders across the globe [1], [2]. Due to technological advancement in most developed countries, the demand for energy to sustain these buoyant economies such as extraction of gas Hydrogen and liquid Hydrogen from wind power and their techno-economic analysis, offshore oil and gas exploration has seen an upward trajectory in the last few decades [3]–[5]. Unlike developing countries, these giant economies have exploited various medium of energy generation to meet their demand during peak hours. In developing countries, the gap between the energy demand and supply is increasing because of the rapid growth in population, depletion of fossil fuel resources, high cost of oil and gas imports, the increase in energy costs and therefore trying to enhance energy efficiency and doing exergy, exergoeconomic and exergoenvironmental analysis [6], [7]. These observations are seen particularly in Bangladesh, India, Pakistan, Iran and some countries of Africa and Asia. An increasing trend has been observed in the utilization of green Hydrogen [8] in developing countries to cope with the energy crisis and preserving healthy environment with less Carbon pollution [9].

Depending upon the geographical location and local conditions, the most common resources of renewable energy in these countries include solar, wind, hydro and biomass along with sustainable development of Hydrogen from these resources. Feasibility study of six resources of renewable energy namely solar, municipal solid waste, biomass, micro-hydro, and geothermal for Hydrogen production was evaluated using fuzzy analytical hierarchy process, Fuzzy Delphi, and environmental data envelopment analysis (DEA)

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in [10]. It was concluded that production of Hydrogen can be made using wind energy. From available resources of renewable energy, wind energy is considered an integral part of various energy scenarios with the current worldwide installed power capacity of approximately 733.3 GW in 2020 [11]. In year 2020, renewable energy kept on growing exponentially. Moreover, solar and wind capacity increased 50% compared to any previous expansion [12]. Weather conditions play a vital role in the generation of wind power. These two parameters, wind speed and output power of wind turbines, have a cubic bond association and hence, the precise wind resource estimation for any site is considered significantly important [13], [14].

In [15] authors have provided current status of wind energy projects in general, but specifically the wind corridor of Jamshoro city in Sindh province of Pakistan and estimated parameters of Weibull distribution for Jamshoro at 50, 30 and 10m hub-height and determined wind energy potential. An overall status of Pakistan wind power plant projects is also provided. A recent study is done by authors in [16]. In this study authors have provided a through outlook on wind speed pattern of various sites, on wind energy deployment, its impact on environment and various technical challenges in adopting this source of renewable energy. Weibull distribution parameters for wind energy assessment for six locations (Gwadar, Jiwani, Karachi, Ormara, Pasni and Sonmiani Bay) in coastal belt of Sindh province in Pakistan is carried out in [17] and annual energy production, economic feasibility analysis, payback period estimation and cost of energy is determined. Different wind turbine technologies for power generation are proposed in the study. Similar studies were done in [18] for Hawke's Bay, in [19] for Hyderabad, in [20] for Babaurband, in [21] for Gharo and in [22] for Karachi sites situated in wind corridor of Sindh province of Pakistan. The land in Jhimpir area which is 127km away from Karachi, while traveling on Hyderabad motorway M-9 via nearby city Noori Abad, has been allocated initially for ten wind farms for power generation. Benchmark wind speeds for this site are estimated in [23]. The terrain of Jhimpir is hard and rocky and elevation of 40-50 m from sea level. Many companies later on got license for power generation and started installing their wind farms of 50 MW power output. The list of the companies working in Jhimpir is provided in [15]. All of these studies did not include production of Hydrogen from wind power. However, the installation of Vensys 62 was done at Thatta, Jhimpir, and operated by Zorlu Enerji Pakistan Ltd [24]. As can be seen in Table 6 in [24], wind resource capacity has a potential of 2.354 × 105 MW, that translates to production of around 45,000 tonnes of Hydrogen (considering a conversion value of 53 KWh per kg of Hydrogen).

Despite the increasing focus of research on electrical energy storage technologies, only a few industry scale storage facilities have been installed worldwide [25]. In this context, increasing research has focused on the environmental benefits of generating electrolytic Hydrogen using wind power as comparable to other methods of Hydrogen production [26]. The life-cycle assessment of wind-based electrolysis showed that 1 kg of CO_2 is emitted for the production of 1 kg of Hydrogen [27]. Based on this life-cycle assessment, wind-based electrolysis presents lower CO_2 emissions than other renewable energy systems [28], [29]. Mirza *et al.* [30] presented the complete road map to Hydrogen economy in Pakistan. The integration of Hydrogen economy with the society will lead to technological advancements in many fields, including transportation, power generation using renewable energy sources, and agriculture. For Hydrogen production through electrolysis, solar energy and wind energy are the most suitable renewable energy resources for electricity generation. However, the latter is more effective because of the lower levelized cost [31]. Olateju *et al.* [32] assessed the production of electrolytic Hydrogen for application in the oil sand bitumen upgrading industry in Western Canada. The results showed that the Hydrogen production cost is 7.84 USD/kg and is uncompetitive with respect to conventional fossil fuel Hydrogen pathways. Alavi *et al.* [33] carried out a feasibility assessment of wind energy for production of Hydrogen in Baluchestan and Sistan in Iran. The wind-power potential and Hydrogen production were assessed at five sites, and a maximum Hydrogen production of 39.82 tons per annum was observed. However, this study did not consider the technical and economic aspects in detail.

Al-Sharafi *et al.* [34] analyzed the Hydrogen and electricity production from solar and wind power in Saudi Arabia. The optimization results showed that the minimum levelized cost of energy is 0.609 USD/kWh, and the corresponding cost of the Hydrogen production is 43.1 USD/kg. Mostafaeipour *et al.* [35] investigated the wind energy capacity for Hydrogen production for car fuel in the Fars province of Abadeh city, Iran. For the selected site, the maximum annual electrical energy was 575.53 MWh and could meet the Hydrogen load of 22 cars per week. Rezaei-Shouroki *et al.* [36] selected 13 cities of Fars for the development of a wind farm for producing Hydrogen utilizing wind-power density estimates. It was concluded that Izad Khast city has the highest potential of Hydrogen production with an average of 21.9 tons/year using a 900-kW wind turbine. Ashrafi *et al.* [37] investigated the wind potential in detail using different variants of Weibull parameters for Hydrogen production in Iran. For the estimation of Weibull parameters, various methods were employed, namely: empirical method of Lysen, the power density method [38] and the standard deviation method.

Hydrogen production was depicted using Geographic Information Science maps. However, the study did not include economic aspects. In 2018, Gökçek and Kale [39] proposed an optimization-based scenario for Hydrogen fuel produced by PV-wind hybrid systems in Izmir-Cesme, Turkey. National Aeronautics and Space Administration surface meteorology and solar energy database were utilized for solar and wind potential assessment. The levelized cost of Hydrogen production was found to be 7.526-7.866 USD/kg under different system configurations.

Ayodele and Munda [40] investigated the economic feasibility for the production of green Hydrogen using wind energy and water electrolysis at five different locations in South Africa. The simulation results showed that the maximum Hydrogen production was 226.82 metric-tons with an annual storable compressed Hydrogen content of 598 m3. Sensitivity analysis concluded that the wind speed significantly affected Hydrogen production and its associated viability. Chade *et al.* [41] analyzed the wind turbine-diesel-electrolyzer system for Hydrogen production by considering the example of Grimsey Island and showed that the proposed system was economically feasible with a payback period of 4 years for the optimal system configuration. Douak and Settou [42] presented methods for production of Hydrogen using wind energy in Algeria. Wind resource assessment was performed using the Weibull probability distribution function. The results showed that the minimum cost of Hydrogen production was 1.214 USD/kg. A comprehensive review of Hydrogen production from renewable energy from the economic perspective is presented in Table 1.

Thus, numerous studies have focused on the potential of Hydrogen production via electrolysis using wind energy. However, from deployment perspective, it is essential to consider all techno-economic aspects of wind power utilization for wind-to-Hydrogen production and realization. Moreover, there is a clear research gap, in previous works, between the actual wind resource assessment, technical and economic aspects of Hydrogen production and implementation strategies. This study considers the case study of Pakistan and estimates the Hydrogen production based on the potential of wind energy resources of three selected sites. The novelty of this study is that for the first time, to the best of our knowledge, a study has focused on estimate of Hydrogen production from wind energy resource assessment and most economically relevant wind turbine technologies with promising payback for Sanghar, Gwadar and Bahawalpur sites. Although, there is an existing study for the production of renewable Hydrogen using wind energy in Sindh, Pakistan that includes various sites, namely: Talhar, Keti Bandar, Baghan, Gharo, DHA Karachi, Jamshoro, Nooriabad, and Golarchi [54], however, the authors did not find any published work of this kind for our selected sites. This study will act as catalyst for oil-dependent nations having wind energy resources for Energy and Hydrogen production. The summary of our contribution for selected sites of Pakistan in this perspective is highlighted as follows;

- Wind resource assessment through Weibull Distribution
- Calculation of power and energy densities for these sites.
- Selecting the best choice of wind turbines
- Calculation of levelized cost of energy and payback period.
- Estimation of cost of Hydrogen production using wind-to-Hydrogen energy conversion system
- Exploration of possible pathways for distribution of Hydrogen from production sites

The rest of the paper is organized as follows. Section II provides the conceptual framework for current research work. Section III contains data analysis of the sites and subsequent wind resource assessment. Section IV outlines techno-economic assessment of integrating wind turbines for power generation their payback period. In Section V a model for Hydrogen production is provided and cost analysis is carried out with Hydrogen delivery options for a given transport radius. Section VI gives a good account of discussion on results and paper is concluded in Section VII.

II. RESEARCH FRAMEWORK

Knowledge regarding the characteristics of wind regimes of the selected site is important to provide an overview of the economic viability of the locations for electric power generation and subsequent utilization for Hydrogen production from water electrolysis. A schematic diagram of the proposed research framework is shown in Fig. 1. In the following sections we will first do a wind resource assessment for electricity generation through selection of the most suitable wind energy conversion system followed by investigation for a Hydrogen production model and then at the end life-cycle cost analysis through break-even analysis.

III. WIND DATA ANALYSIS FOR WIND RESOURCE ASSESSMENT

We analyzed satellite data for the period of $2000 - 2010$ and existing ground data, and the initial results indicate a good wind regime in the country, as shown in Fig. 2(a) [55]. The selected sites with their geographical details are shown in Table 2 and shown on a GIS map in Fig. 2(b). Temporal wind speed data recorded for the selected sites for two years with 10 min intervals have been preprocessed by converting it into daily and monthly mean wind speeds at heights of 20m, 40m, 60m, and 80m.

Wind speeds for Pakistan are classified into various classes according to the National Renewable Energy Laboratory (NREL) wind map as shown in Fig. 2(a) [55]. Using this classification, it could easily assess the wind regime of different provinces of Pakistan. Because of global growth in the production of power from wind energy, various studies have been conducted in the last two decades with an aim to statistically model the potential of wind and its frequency distribution in many countries. This frequency distribution approach can help simply predict the energy output of a typical wind-energy-conversion system. Various methods have been tested for fitting the measured wind speed data to a target probability distribution function (PDF) for a given location over a period of time, typically on a monthly or yearly basis. However, choosing the best PDF that fits the wind speed distribution is a challenging task.

Some of the most widely adopted distribution functions include the Weibull and Rayleigh distributions to characterize wind speed patterns for a given location under consideration. The two parameter Weibull distribution has been considered in this study because it has been found to fit a wide variety of

TABLE 1. Economic aspects of production of hydrogen.

Ref.	System details	Hydrogen Cost(USD/kg of H_2)
[43]	Directly coupled PV-PEM electrolyzer	7.94
[44]	Combined PV modules and parabolic trough collectors with SOEC electrolyzer	5.23
[45]	Solar thermal power integrated with alkaline electrolyzer	2.89
[45]	PV modules with alkaline electrolyzer	7.22
[46]	Grid assisted PV-PEM electrolyzer	6.1
[47]	Electrolyzer powered by wind turbine	3.1
[48]	Wind turbine and alkaline electrolyzer	2.53
[49]	Electrolyzer powered by wind turbine	8.5
[50]	Electrolyzer powered by wind turbine	4.34
[51]	Electrolyzer powered by wind turbine	3.37
[52]	Wind turbine-electrolyzer-PEM fuel cell	5
[53]	SOEC electrolyzer using geothermal energy for water preheating	1.84
[53]	Geothermal plant with CO_2 as working fluid and alkaline electrolyzer	8.24

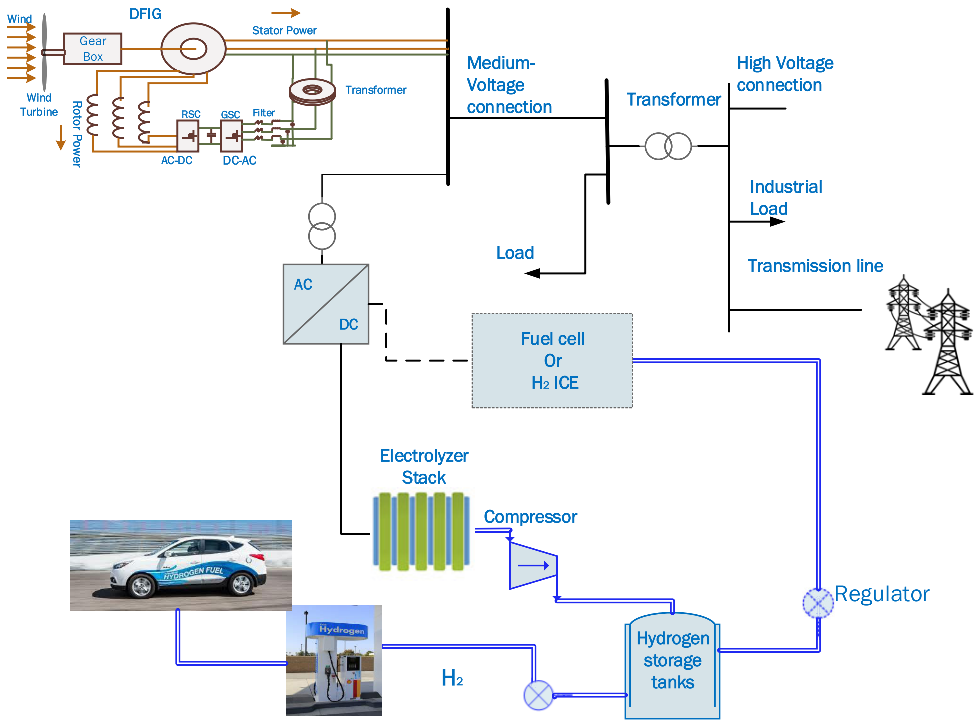


FIGURE 1. Conceptual schematic diagram of the wind-Hydrogen plant.

TABLE 2. Site data and its geographical coordinates.

Site	Longitude	Latitude	Province	No of Data Samples	Data Time Period
Bahawalpur	$71°41'56.03''E$	$25°19'35.97''N$	Punjab	115645	01/04/2016 – 06/30/2018
Sanghar	$69°2'15.12''E$	$25°48'57.26''N$	Sindh	65965	01/12/2016 – 30/11/2017
Gwadar	$60°20'46.95''E$	$25°16'47.30''N$	Balochistan	50910	01/12/2016 – 30/11/2017

wind speed data [56], [57]. At a specific wind farm, the available electricity generated by a wind turbine generator system depends on the mean wind speed, its skewness, standard deviation, and kurtosis. Considering the data location, data sample size, goodness of fit test, and statistical inference criteria, one estimation method can demonstrate better performance than other methods [58]. In this study, a comparison of four different estimation methods is proposed for selected sites to estimate the Weibull parameters. The deviation of estimated results from Weibull Distribution from the measured values of wind speed and their effect on annual energy produced by wind turbines is also examined. The yearly energy estimate is further utilized to calculate the cost of electricity per kilo watt hour and production of Hydrogen using water electrolysis. The amount of Hydrogen generated is used for long-term, midterm, and short-term cost of Hydrogen estimate for economic feasibility of the installation of wind turbines at various sites. The research framework is based on the flowchart given in Fig. 3.

A. WIND RESOURCE ASSESSMENT OF SELECTED SITES

The distribution pattern of wind speed data can be investigated using two statistical estimators, namely: skewness[1] and kurtosis.[2] These statistical expressions are defined as follows [60], [61];

$$skewness = \frac{1}{T-1}\Sigma_{i=1}^{T}\frac{(v_i-\bar{v})^3}{\sigma^3} \tag{1}$$

$$kurtosis = \frac{1}{T-1}\Sigma_{i=1}^{T}\frac{(v_i-\bar{v})^4}{\sigma^4} - 3 \tag{2}$$

where v_i, $\bar{v}$, and σ are the wind speed (m/sec) at *ith* observation, mean, and standard deviation of wind speed respectively. T is the number of non-zero instances in wind speed data. Wind characteristics for selected sites are listed in Table 3.

B. ESTIMATION OF WEIBULL PARAMETERS

The Weibull PDF [60], $f(v)$ is shown in Eq. (3).

$$f(v) = (\frac{k}{c})(\frac{v}{c})^{k-1}exp(\frac{-v}{c})^k \tag{3}$$

Here c and k are scale and shape factor respectively. Several numerical methods can be used to estimate the parameters of the Weibull PDF [62]–[64] using wind speed data. Some of these numerical methods include the graphical method (GM), empirical method (EM), energy pattern factor (EPF) and the maximum likelihood estimate (MLE) [65]–[68].

1) GM

The cumulative distribution function(CDF), $F(v)$ is given by Eq. (4).

$$F(v) = 1 - exp(\frac{-v}{c})^k \tag{4}$$

Taking natural logarithms twice, we get Eq. (5), which is linear in the parameters to be fit. Given the plot of $ln[-ln\{1-F(v_i)\}]$ versus $ln(v)$, c is computed from y-intercept and k equals the slope of the plot.

$$ln[-ln\{1-F(v_i)\}] = -klnc + klnv_i \tag{5}$$

2) EM

Justus *et al.* [69] suggested this method, according to which, the empirical k and c are defined by Eq. (6) and (7) respectively. The gamma function is defined by Eq. (8).

$$k = (\frac{\sigma}{\bar{v}})^{-1.086} \tag{6}$$

$$c = (\frac{\bar{v}}{\Gamma(1+\frac{1}{k})}) \tag{7}$$

[1]Skewness describes the symmetrical characteristic of the data sequence.
[2]Kurtosis is a measure of whether the data are light-tailed or heavy-tailed with respect to a Gaussian distribution.

$$\Gamma(X) = \int_0^\infty t^{x-1}e^{-t}dt \tag{8}$$

3) EPF

The EPF method was suggested by [70] and is governed by Eq. (9).

$$E_{pf} = (\frac{\overline{v^3}}{\bar{v}^3}) \tag{9}$$

k parameter calculated by EPF method is given by Eq. (10) and c parameter is given by Eq. (7).

$$k = 1 + (\frac{3.69}{(E_{pf})^2}) \tag{10}$$

4) MLE

The fitting of parameters k and c requires numerical iterations. This method uses a likelihood function of wind speed time series data. Parameters k and c are estimated using the following two equations (Eq. (11) and Eq. (12) derived in [71] and also suggested by [72].

$$k = \left(\frac{\sum_{i=1}^{T} v_i^k \ln(v_i)}{\sum_{i=1}^{T} v_i^k} - \frac{\sum_{i=1}^{T}\ln(v_i)}{T}\right)^{-1} \tag{11}$$

$$c = \left(\frac{1}{T}\sum_{i=1}^{T} v_i^k\right)^{\frac{1}{k}} \tag{12}$$

C. STATISTICAL ERROR INDICATORS

Statistical error indicators (root mean square error(RMSE), mean absolute percentage error (MAPE), relative root mean square error (RRMSE), and coefficient of correlation are used as error functions for performance analysis [71]. Mathematical formulation of these parameters is provided below, with P_{WB} and P_M being the power density from Weibull function and actual measured data, respectively.

1) RMSE

$$RMSE = \sqrt{\frac{1}{T}\Sigma_{i=1}^{T}(P_{i,WB}-P_M)^2} \tag{13}$$

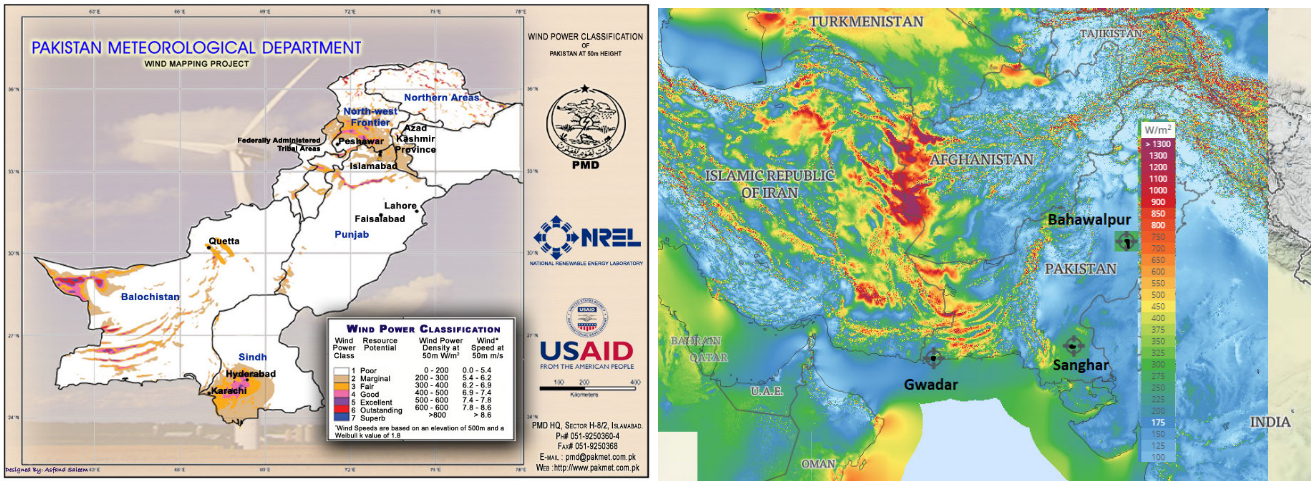
RMSE provides short-term performance of these models. Smaller $+ve$ values indicates the closeness of match between actual data P_M and estimated power density P_{WB}.

2) MAPE

$$MAPE = \frac{1}{T}\Sigma_{i=1}^{T}|\frac{(P_{i,WB}-P_M)}{P_M}| \tag{14}$$

3) RRMSE

$$RRMSE = \frac{\sqrt{\frac{1}{T}\Sigma_{i=1}^{T}(P_{i,WB}-P_M)^2}}{\frac{1}{T}\Sigma_{i=1}^{T}(P_M)} \tag{15}$$



(a) (b)

FIGURE 2. **(a) Wind resource map of Pakistan based on NREL. (b) GIS map of sites (Gwadar, Sanghar and Bahawalpur) [59].**

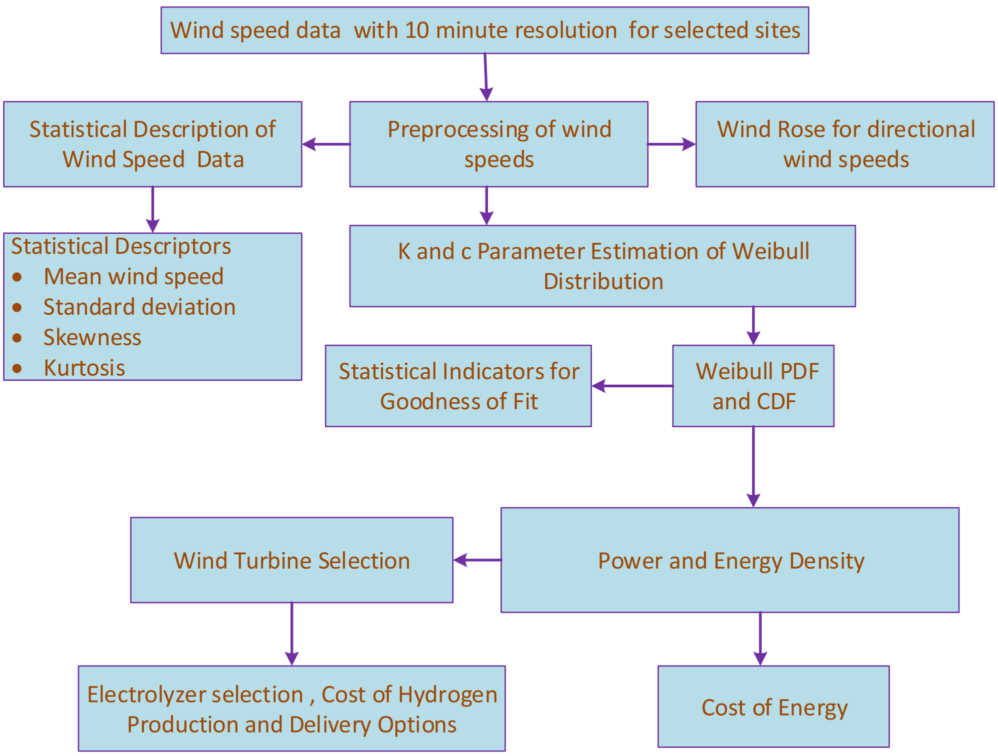


FIGURE 3. **Research Methodology.**

The range of accepted values of RRMSE to determine the accuracy of our model is given below [72], [73]:

Usually RRMSE $\leq$ 10% is considered excellent and RRMSE $\geq$ 30% indicates poor performance.

4) COEFFICIENT OF CORRELATION (*R*)

$$R = \frac{\Sigma_{i=1}^{T}(P_{i,M} - P_{i,WB})^2}{\Sigma_{i=1}^{T}(P_{i,M} - P_{avg,WB})^2} \tag{16}$$

R can measure the strength of the correlation between the control and simulated values. Higher R values indicate better model performance [74]. The value of R is between 0 and 1.

5) DIEBOLD-MARIANO TEST FOR STATISTICAL ACCURACY

This method is used in inferential statistics to determine if apriori hypothesis is correct by computing a test statistics. The error between the actual data sequence y and prediction model $\hat{y}_n^i$ can be written as follows for two forecasts:

TABLE 3. Statistical characteristics of winds for selected sites.

Site	height	mean speed(m/sec)	std.(m/sec)	skewness	kurtosis
Bahawalpur	20m	3.92	2.18	0.80	3.94
	40m	4.59	2.34	0.70	3.93
	60m	4.60	2.12	0.02	2.00
	80m	5.48	2.93	0.45	2.98
Sanghar	20m	4.99	2.55	0.56	2.80
	40m	5.65	2.74	0.39	2.73
	60m	6.20	2.98	0.23	2.45
	80m	6.51	3.21	0.15	2.24
Gwadar	20m	4.23	2.59	0.72	2.87
	40m	4.61	2.63	0.64	2.93
	60m	4.79	2.67	0.61	2.97
	80m	4.98	2.80	0.58	2.94

$e_n^i = y - \hat{y}_n^i, i = 1, 2$. We define a loss function $F(e^i)$ to indicate prediction accuracy [75]. In general, the loss function can be defined in two ways, as follows: Square error loss:

$$F(e_n^i) = (e_n^i)^2 \tag{17}$$

Absolute deviation error loss:

$$F(e_n^i) = |e_n^i| \tag{18}$$

The DM statistic is represented using Eq. (19).

$$DM = \frac{\frac{1}{N}\Sigma_{n=1}^{N} F(e_{n+h}^2) - F(e_{n+h}^1)}{\sqrt{\frac{s^2}{N}}} \tag{19}$$

s^2 represents the variance of $F(e_{n+h}^2) - F(e_{n+h}^1)$. Two hypotheses are developed here.
$H_0 : F(e_{n+h}^2) = F(e_{n+h}^1)$ and
$H_1 : F(e_{n+h}^2) \neq F(e_{n+h}^1)$.
Here h is the prediction step size and is taken as 1. The null hypothesis H_0 represents that the prediction performance of the two models are same, that is, the two predictions are not significantly different. In contrast, the other hypothesis H_1 represents a significant difference in the predictive performance of the two models. The level of statistical significance is set to α and the critical value of the test is $Z_{\alpha/2}$. If $|DM| \succ Z_{\alpha/2}$, the null hypothesis H_0 could be rejected, and if $|DM| \prec Z_{\alpha/2}$, there is not enough evidence to show that a significant difference occurs between the two models. It is further assumed that DM follows a normal distribution with zero mean and unit variance i.e. $N(0, 1)$. We used four estimating models in our current study. We will run the DM test for these methods for their statistical accuracy.

D. WIND POWER DENSITY ESTIMATION

There are two methods to calculate Wind-power density (power per unit area)in $\frac{W}{m^2}$ using either measured wind speed data [76] or using the two parameters estimated for Weibull distribution function [77] at the given site.

1) WIND POWER DENSITY USING MEASURED DATA

$$\frac{P}{A} = \frac{1}{2n}\rho\Sigma_{i=1}^{n} v^3 = \frac{1}{2}\rho\overline{v^3} \tag{20}$$

where P is power(kW) and A is the swept area of wind turbine blades. ρ is air density taken as $1.225\ kg/m^3$.

2) WIND POWER DENSITY ESTIMATE USING WEIBULL PARAMETERS

The k and c values of Weibull Distribution estimated from the four statistical methods (GM, EM, EPF, and MLE) are used to get an estimate of wind power density.

$$\frac{P}{A} = \frac{1}{2}\rho\int_0^\infty v^3 f(v)dv = \frac{1}{2}\rho c^3\Gamma(1 + \frac{3}{k}) \tag{21}$$

3) CAPACITY FACTOR AND ANNUAL ENERGY PRODUCTION

Capacity factor (CF) [78] as given by Eq. (22) is highly dependent on k and c parameters and rated, $cut-in$ and $cut-out$ wind speeds of selected wind turbine. Most of the practical values for CF lie between 20% and 40% depending on site conditions and the technology of the wind turbine.

$$CF = \frac{exp[-(\frac{v_{cut-in}}{c})^k] - exp[-(\frac{v_r}{c})^k]}{(\frac{v_r}{c})^k - (\frac{v_{cut-in}}{c})^k} - exp[-(\frac{v_{cut-out}}{c})^k] \tag{22}$$

Here, v_{cut-in} is the cut-in wind speed, v_r is the rated wind speed, and $v_{cut-out}$ is the cut-out wind speed of the selected wind turbine. The annual energy production, E_{out} for each wind turbine can be calculated using its rated power, P_r, and capacity factor, CF.

$$E_{out} = CF.P_r.8760 \tag{23}$$

IV. ECONOMIC ASSESSMENT

A. WIND TURBINE SELECTION FOR PROPOSED SYSTEM

After careful wind resource assessment, we have a good estimate of how much power can be generated from wind energy. The next phase is to select wind turbines to achieve this goal. Therefore a thorough analysis is done for the most suitable wind turbines from top list of manufacturers. The prices for wind turbines are declining because of a competitive and ever-increasing energy market and advancements in technology. The generation cost of electricity (USD/kWh) is heavily dependent on geo-political factors of the country and current tariffs enforced by regulatory authorities. Various costs that are involved in this process are capital cost, investment cost, operation and maintenance cost. Capital cost is mainly affected by interest rate and period of loan. Further expenditures of the wind energy conversion project involve prevailing prices for land acquisition, installation, planning, licensing and connection to grid. The operation and maintenance costs include the sum of operation and maintenance cost of each subsystem. This usually involves cost of repair, insurance and administration of spare parts. An in-depth economic analysis is carried out regarding wind turbine selection and finally three wind turbines i.e. DeWind D4/48, DeWind D6, and Nordex N90/2500 are recommended in this work. The wind speed and corresponding power characteristics of the selected wind turbines are listed in Table 4. A certain portion of generated wind power can be fed to utility grid to meet the energy demand of the region whereas a fixed share of remaining power can be consumed by the electrolyzer for Hydrogen production. Various topologies based on power electronics modules to control active and reactive power, voltage and harmonics, dynamic economic dispatch and wind farm layout are possible [79], [80].

Nordex N90/2500 wind turbine having double-fed induction generator (DFIG) technology is designed for name plate capacity of 2500 kW at generation voltage of 660 V with operating frequency of 50 Hz or 60 Hz. These turbines have good performance in variable wind speed regions. The DeWind D4/48 and D6 turbine models have rated powers of 600 kW and 1250 kW, respectively. at 40m and 60m hub heights, a 690-V generation voltage and DFIG design. DFIG technology utilizes rotor-side and grid-side power electronics based controllers for maximum energy capture under variable wind speeds with a tight harmonic control at the output. The characteristics of these wind turbines are compared in detail in [73].

B. COST OF ENERGY

Improvements in technology, regional manufacturing processes, and competitive supply-chains have led to a continuous reduction in the wind turbine prices. According to the data given in a report of the International Renewable Energy Agency (IRENA) 2021, global weighted-average total installed cost and average turbine prices are steadily falling since 2010. However there is an increased trend in capacity factor. Chinese wind turbine prices have fallen drastically for projects commissioned in 2020 [81]. The cost trend according to IRENA report is shown in Fig. 4.

In order to estimate the energy purchase cost (EPC), the National Electric Power Regulatory Authority (NEPRA) of Pakistan has considered many different reports published around globe such as report by IRENA [81], Bloomberg and other sources for wind energy project tariff determination. It finalized that average wind turbine prices in different parts of the world were below USD 0.70 million per MW in 2019 [82]. These reports also forecast the gradual reduction in turbine prices in coming years. Many other factors were considered in estimating EPC besides wind turbine costs such as local manufacturing cost, cost of land and labor etc. However in its report it argued that the cases of different countries can not exactly be mapped to Pakistan because of different market trends, local manufacturing condition, tariff regimes, performance evaluation and economic factors of other countries. The global trend in decrease of wind turbine prices and corresponding decline in EPC are attributed to competition among turbine manufacturers. Turbines are manufactured with different rotor diameters, hub heights and power generation capacity of turbine etc. Installation costs also vary due to different wind farm layouts, cost of the land with varying terrains, transportation cost, labor cost and level of target performance desired etc. Considering the international trends of reduction in capital cost for onshore wind energy projects and incorporating local geo-political factors for a developing country like Pakistan, NEPRA approved recently (August 18, 2020) cost of approximately USD 50 million per 50 MW for Iran-Pak Wind Power (Pvt.) Ltd (IPWPPL) wind project at Deh Kohistan, District Thatta, Sindh [82]. The details of various project cost components such as EPC, project development cost (PDC), insurance during construction (IDC), financing and fee charges, Karachi Inter-bank Offered Rate (KIBOR) and London Inter-bank Offered Rate (LIBOR) used, can be found in the IPWPPL NEPRA report. The Authority also carefully examined previously determined costs for various wind power projects to approve the new costs in their final decision aligned with the global market trends.

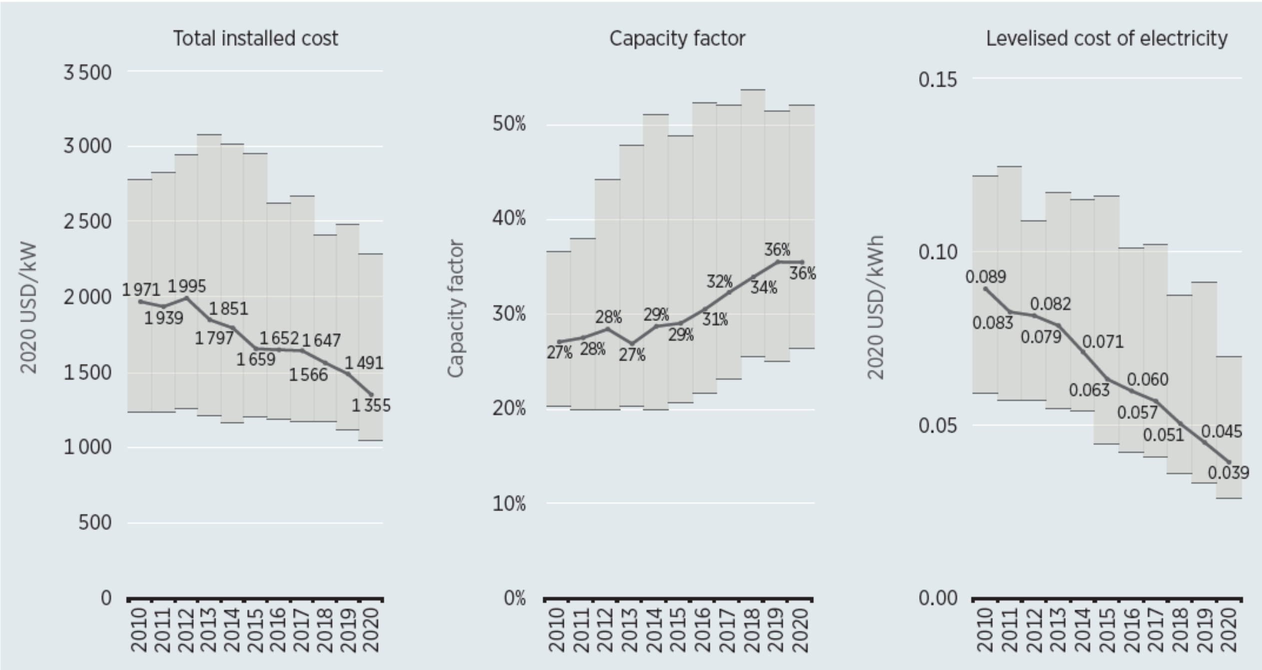
As per the NEPRA, the approved cost of a wind projects in Pakistan, taking the example of IPWPPL and IRENA report [81], we considered wind power project cost as 1 million USD/MW (USD 1000/kW) [82]–[85] to take into account the local site and country specific conditions. Hence, to estimate the investment cost C_{inv} in the current study, we considered 1000 USD for each kW of nominal capacity of the wind turbine. The present value cost (PVC) or the cost of the kilowatt-hour (kWh) of energy was evaluated based on the following assumptions:

1) The investment cost (C_{inv}) consists of the price of wind turbines plus the cost of civil works, installation, land rent, and the connection cables to the grid and is taken as 1 million USD/MW.
2) Operation, maintenance and repair costs (C_{omr}), which are related to the general inflation rate, were considered to be 3.5% of the investment cost.
3) According to Pakistan's economic indicators given by Trading Economics, Karachi interbank interest rate (KIBOR) (I) and inflation rate (r) were considered to be 10.5% and 9.5%, as of November 2020.
4) The wind turbine lifetime (n) is assumed to be 20 years.
5) A scrap value (S) of 10% of the investment cost (machine and civil work costs) was chosen.

With these assumptions, the cost of energy per kWh can be calculated using the total energy output, E_{out}, from the wind turbine for its lifetime and PVC from [85], [86] using

TABLE 4. Power and wind speed characteristics of selected wind turbines.

Turbine model	Rated Power(kW)	$v_{cut-in}(m/sec)$	$v_r(m/sec)$	$v_{cut-out}(m/sec)$	Hub Height(m)	Rotor Diameter(m)	$C_{inv}(USD)$
Dewind D4/48	600	2.5	11.5	23	40	48	600000
Dewind D6	1250	3	13	23	60	64.3	1250000
Nordex N90/2500	2500	3	13	25	80	90	2500000



Source: IRENA Renewable Cost Database.

FIGURE 4. Wind power generation costs in 2020. Source: [81].

the Eq. (24).

$$CoE = \frac{PVC}{E_{out}} \tag{24}$$

$$PVC = C_{inv} + C_{omr}[\frac{1+I}{r-I}][1-(\frac{1+I}{1+r})^n] - S(\frac{1+I}{1+r})^n \tag{25}$$

$$PVB = UAB\frac{(1+DR)^n - 1}{DR(1+DR)^n} \tag{26}$$

$$DR = \frac{1+r}{1+I} - 1 \tag{27}$$

where UAB is the uniform annual benefit, which is mainly obtained using the selling CoE, n is the number of years, and DR is the discount rate. UAB is determined by using the energy output and purchase tariff of wind energy in Pakistan. Purchase tariff value of 7.4756 cent/kWh is taken in this study. DR is the discount rate given by Eq. (27) [85]. Beak-even analysis can be performed using Eq. (24)-(26), and the payback period for the wind turbine can be estimated.

V. HYDROGEN PRODUCTION

In this section, a system model is presented that can be used for generating Hydrogen from wind energy conversion system(WECS). The WECS utilizes double-fed induction generator (DFIG) wind turbines, AC-DC/DC-AC converters with their grid-side and rotor-side controllers (GSC and RSC), an electrolyzer, and a fuel-cell option. An embedded control system is responsible for controlling the DC bus voltage of the converter using a PID controller and its associated pulse width modulated (PWM) signal for a buck-boost converter.

The DC bus voltage can be further regulated using another DC–DC converter that supplies the desired DC voltage to the electrolyzer. The amount of Hydrogen produced depends on the energy yield from the wind turbine E_{out}, efficiency of the converter, η, and the energy consumed by the electrolyzer during the electrolysis process,E_{el}. The efficiency of a standard AC-DC converter ranges from 85% to 95%, and the energy consumed by electrolyzer E_{el}. varies between 5 and 6 kWh/Nm^3. Assuming the efficiency of the electrolyzer is linearly proportional to the energy supplied and that all losses have been considered, Eq. (28) can be used to calculate the amount of Hydrogen, aH_2, produced [42], [87].

$$aH_2 = \frac{\eta \times E_{out}}{E_{el}} \tag{28}$$

The detailed dynamic model of WECS, electrolyzer, power electronics module, and the associated control is provided in [33]. One kilogram of Hydrogen is equal to 11.13 Nm^3 [88]. The Hydrogen generated from different sources are dependent on many factors, such as the size of the wind turbine installed, and the weather profile that affects wind speeds. Because of the intermittent nature of wind energy, the DC bus voltage fed to the electrolyzer needs to be controlled. Therefore, the operational life of the electrolyzer is considered to be seven years in this study, and the results are correspondingly generated for short-term, midterm, and long-term Hydrogen production A good speed of wind, along with excess power, can be fed better to the electrolyzer. When wind speeds are low or there are no winds at all, a fuel-cell system can enhance the reliability of the system. The proposed scheme is shown in Fig. 5 and its associated power flow controller is shown in Fig. 6.

A. COST OF ELECTROLYZER

The most crucial component of the integrated hybrid system for Hydrogen production is the electrolyzer, whose cost has three main parts, e.g., capital cost, operation and maintenance (O&M) cost, and replacement cost. The capital cost is affected by the amount of Hydrogen produced, electrolyzer efficiency, CF, and the electrolyzer unit cost. The annual O&M cost and replacement costs are assumed to be 2% and 25% of the initial investment cost. The cost of the electrolyzer, $C_{electrolyzer}$ is formulated as follows [89],

$$C_{electrolyzer} = \frac{aH_2 \times E_{th,elec} \times C_{electrolyzer,pu}}{8760 \times CF \times \varphi} \tag{29}$$

where $E_{th,elec}$ is the theoretical specific energy consumed by the electrolyzer assumed to be 5 kWh/Nm^3 (or 55.6 kWh/kg), $C_{electrolyzer,pu}$ is the unit cost of the electrolyzer, which is taken as 384 USD/kWe in accordance with the target values mentioned in [84], CF is the capacity factor, and φ is the electrolyzer efficiency, which is approximately 75% for an alkaline electrolyzer.

B. COST OF HYDROGEN PRODUCTION

This cost of Hydrogen cH_2 is formulated as follows:

$$cH_2 = \frac{C_{electrolyzer} + CoE}{aH_2 \times n} \tag{30}$$

where $C_{electrolyzer}$ is the capital, operating, and maintenance cost of the electrolyzer; CoE is the cost of energy in USD; aH2 (kg/yr) is the annual Hydrogen production; and n represents the project lifetime. For long-term investment that would result in lower cost of Hydrogen production, it is economically feasible to install large-scale wind farms on the selected sites. DFIG based WECS coupled with electrolyzers and fuel cells for back-up, can be utilized in such an arrangement.

VI. DISCUSSION ON RESULTS

A. WIND RESOURCE ASSESSMENT

The Wind Resource Assessment has been done over wind speed data collected by World Bank under Energy Sector Management Assistance Program (ESMAP)] [90], [91] project for three locations selected in this study. Data set contains diurnal wind speed with 10-min intervals, direction of wind and atmospheric conditions say temperature, humidity and pressure. From this data, the mean wind speeds on monthly basis were calculated at four heights of 20m, 40m, 60m and 80m.

1) MONTHLY MEAN WIND SPEEDS

The mean wind speeds calculated on monthly basis for the selected sites are presented in Fig. 7(a) to Fig. 7(c).

Fig. 7(a) represents the monthly mean wind speed for Bahawalpur site for a time span of more than two years i.e., April 2016 to June 2018. It is evident that there is a seasonal wind speed variation. During a time span from March to August, a trend of higher wind speeds occurs with peaks in April and August. The peaks of average monthly wind speed at heights of 20m, 40m, 60m and 80m are 4.61, 5.29, 5.75, and 6.10 m/s, respectively. The annual average wind speeds for four heights are 3.57, 4.35, 4.83, and 5.16 m/s, respectively. During a span of September to February, a trend of lower wind speeds occurs with minimum values of 2.54, 3.18, 3.49, and 3.63 m/s, respectively for the four heights. With the wind-power classification given in Fig. 2(a), this site can be considered as marginal to fair, with a wind-power class performance of two or higher.

Fig. 7(b) represents the monthly mean wind speed for Sanghar site for a time span of more than two years i.e., June 2016 to October 2017. During a time span from April to August, a trend of higher wind speed occurs. The peaks of average monthly wind speed at heights of 20m, 40m, 60m and 80m were 7.32, 8.04, 8.6, and 9.08 m/s, respectively and the annual average wind speeds were 4.91, 5.68, 6.28, and 6.65 m/s, respectively. During a span of October to January, a trend of lower wind speed occurs with minimum values were 3.01, 3.83, 4.33, and 4.59 m/s for the four heights. With the wind-power classification given in Fig. 2(a), this site can be considered as fair to good with a class designation between three and four.

Fig. 7(c) represents the monthly mean wind speed for Gwadar site for a time span of more than two years i.e., November 2016 to October 2017. During a time span from March to June, a trend of higher wind speed occurs. The peaks of average monthly wind speed at heights of 20m, 40m, 60m and 80m were 4.87, 5.46, 5.74, and 5.95 m/s, respectively and the annual average wind speeds were 5.57, 6.50, 7.12, and 7.56 m/s, respectively. During a span of June to September, a trend of lower wind speed occurs with minimum values were 3.09, 3.63, 3.92, and 4.10 m/s for the four heights. With the wind-power classification given in Fig. 2(a), this site can be considered as marginal with class designation between two or higher.

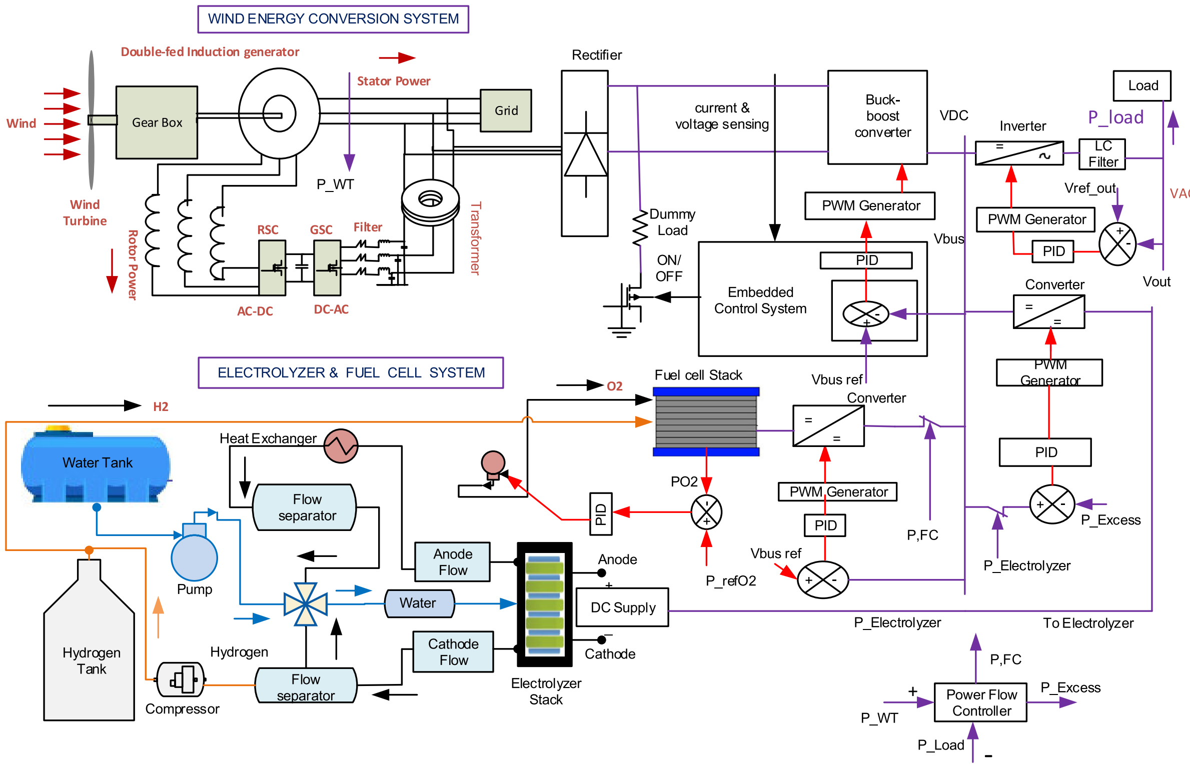


FIGURE 5. Implementation strategy for wind-to-Hydrogen production. An integrated WECS coupled with an electrolyzer and a fuel cell through power electronic modules.

2) DIURNAL WIND SPEEDS

The mean wind speeds calculated on daily basis for the selected sites are presented in Fig. 8(a) through Fig. 8(c). As given in Fig. 8(a), the daily variations for Bahawalpur site lies between 3.26 to 5.87 m/s at heights of 20m, 40m, 60m and 80m. The wind speeds decreased at 1 AM till noon and then started to increase until midnight. For Sanghar and Gwadar, different wind speed patterns were observed, as shown in Fig. 8(b) and Fig. 8(c). These patterns show that Sanghar has a trend of higher wind speed, while Gwadar shows peaks at 11AM to 1PM.

3) ESTIMATED WEIBULL PDF AND CDF

The estimated Weibull PDFs and recorded wind speed data were analyzed for Bahawalpur, Sanghar and Gawadar for fitness and shown in Fig. 9 through Fig. 11 at heights of 20m, 40m, 60m and 80m. The Weibull parameters are estimated by four different techniques. From the figures, it is evident that at a height of 20m, the wind frequency probabilities are equal to 18%, 15%, and 17% at 5, 5.5, and 2.5 m/s wind speeds for Bahawalpur, Sanghar, and Gwadar respectively. The maximum wind probabilities varies at 40m by 17%, 14%, and 16% with 5, 5.25, and 2.5 m/s wind speeds, at 60m by 18%, 14%, and 16% with 5, 7.10 and 3.5 m/s wind speed and at 80m by 13.5%, 13%, and 15% with 5, 6.25, and 2.5 m/s wind speeds.

Next, the cumulative distribution function (CDF) of the corresponding Weibull PDFs are shown in Fig. 12 for these sites at heights mentioned before. This CDF is another useful statistical indicator in describing the probabilities of wind speeds as far as cut-off and cut-in wind speed.

4) WIND ROSE DIAGRAMS OF SELECTED SITES

Installation of wind farms depends on the wind direction at that particular site. The wind direction and mean wind speed help in generating the wind frequency rose (%) diagram. The wind directions were recorded by sensors installed at heights of 58.5m and 78.5m and the corresponding wind rose plots, presented in [83], [84], are reproduced here. Fig. 13 through Fig. 15 represents the wind rose plots of the selected sites. These rose diagrams indicate the direction in which particular wind speed blows (north = N, east = E, south = S, west = W) with the frequency of occurrence. The prevailing wind directions for Bahawalpur are N, S, SSW, and NNW (Fig. 13), that for Sanghar is W (Fig. 14), and those for Gwadar are WSW and SSW (Fig. 15). The same wind directions also carry the most energy content.

5) ESTIMATED K AND C WEIBULL PARAMETERS

The estimated Weibull parameters namely k and c with their values at four different heights for the selected sites are given in the Table 5. The results from EM, EPF, and MLE are closely matched with each other. However, the results of the GM differ from all three methods mentioned earlier. At a height of 80m, Table 5 showed that the representative k and

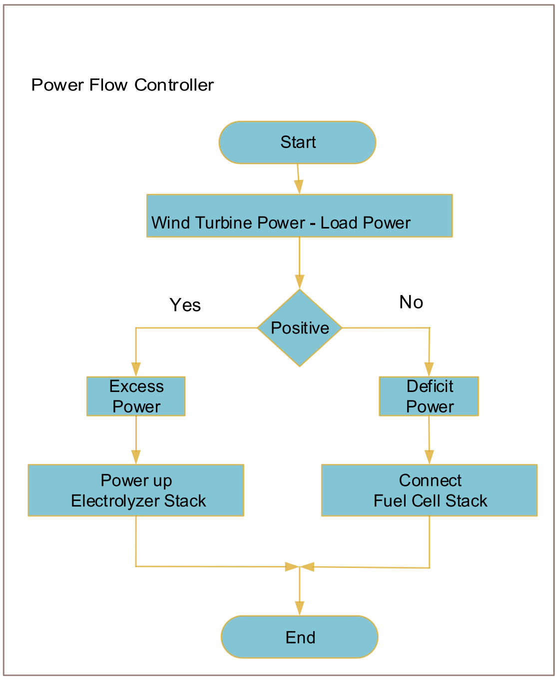


FIGURE 6. Flow chart of the power controller of the proposed system.

c values using MLE were 1.92 and 6.16 for Bahawalpur, 2.12 and 7.34 for Sanghar, and 1.84 and 5.61 for Gwadar, respectively. Similarly, the values at heights of 20m, 40m and 60m depending on site and estimation method can be taken from Table 5.

6) GOODNESS OF FIT OF STATISTICAL PARAMETERS FOR SELECTED SITES

The statistical indicators for goodness of Fit are mentioned in Table 6. These indicators are used to compare the measured wind power and the calculated wind power from Weibull parameters using EM, EPF and MLE methods. The most frequent indicators for goodness of Fit are RMSE, RRMSE, MAPE, and correlation coefficient (R). Lowest RRMSE values are achieved with EM, EPF and MLE methods which represents the best accuracy and therefore better performance. However when GM method is used to calculate the Weibull parameters, based on RRMSE value the performance is worst. In case of R the best match between measured and estimated values occur at unity. Comparing to MLE, the EPF method has the lowest MAPE values at heights of 40m and 60m. MLE showed better performance than the other two methods because it achieved the lowest values for MAPE for Sanghar site where turbine installations at 40m, 60m, and 80m are more suitable. Table 6 clearly shows that GM has the highest RMSE values, whereas the other three methods show better error statistics (small error values). GM is not included for the Diebold-Mariano (DM) test due to its poor performance [85]. We performed the DM test for the remaining three estimator models (EM, EPF, and MLE); the results are tabulated in Table 7. We used the estimated PDFs of the fitted methods to obtain the error statistics given in Eq. (19)

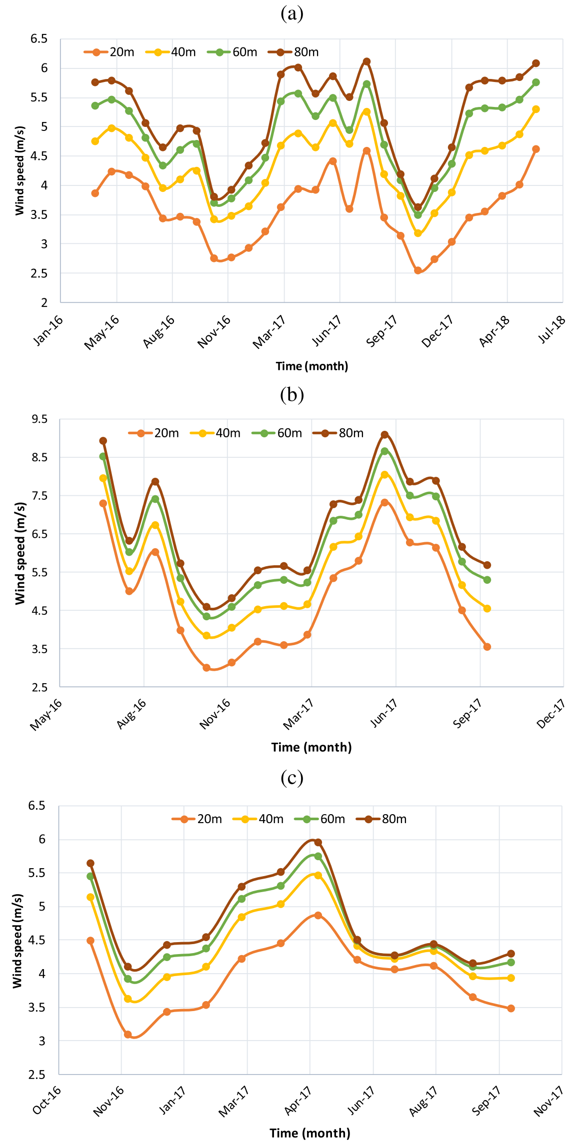


FIGURE 7. Monthly mean wind speed with various hub heights at a) Bahawalpur b) Sanghar and c) Gwadar sites.

and used the square error loss function from Eq. (17) to calculate the values of the DM test. The result showed that PDF closely follows Weibull statistics. When compared with the true Weibull function obtained from the histogram data, DM test can be applied to verify if the fits are statistically significantly different.

According to the DM test results for Bahawalpur, at 60m, based on the square error loss function, DM values, i.e., 10.624, 12.97, and 17.83, are greater than the $Z_{\alpha/2}$ value of 1.96. Thus, hypothesis H_0 can be rejected at the 5% level of significance. This means that the observed differences between the forecasting performances of all three methods for a height of 60m for Bahawalpur are significantly different. Therefore, hypothesis H_1 is accepted. The results for a height of 80m also show that the three methods used for Bahawalpur are statistically different; thus, hypothesis H_1 can be accepted at a 5% level of significance. The same argument can be used

TABLE 5. Estimated k and c parameters of Weibull distribution for selected sites.

Site	Height	GM		EM		EPF		MLE	
		k	c	k	c	k	c	k	c
Bahawalpur	20m	2.07	4.14	1.89	4.42	1.86	4.41	1.84	4.40
	40m	2.48	4.92	2.07	5.18	2.04	5.18	2.05	5.18
	60m	2.27	5.22	2.32	5.19	2.37	5.19	2.29	5.18
	80m	2.16	5.84	1.97	6.18	1.99	6.18	1.92	6.16
Sanghar	20m	2.33	5.38	2.07	5.63	2.06	5.63	2.06	5.64
	40m	2.30	6.24	2.19	6.37	2.20	6.37	2.17	6.37
	60m	2.21	6.93	2.21	7.00	2.24	7.00	2.19	6.99
	80m	2.15	7.27	2.15	7.35	2.20	7.35	2.12	7.34
Gwadar	20m	1.84	4.43	1.70	4.74	1.70	4.74	1.69	4.75
	40m	1.96	4.94	1.84	5.20	1.84	5.20	1.82	5.20
	60m	1.98	5.19	1.88	5.41	1.89	5.41	1.87	5.41
	80m	1.98	5.33	1.87	5.61	1.87	5.61	1.84	5.61

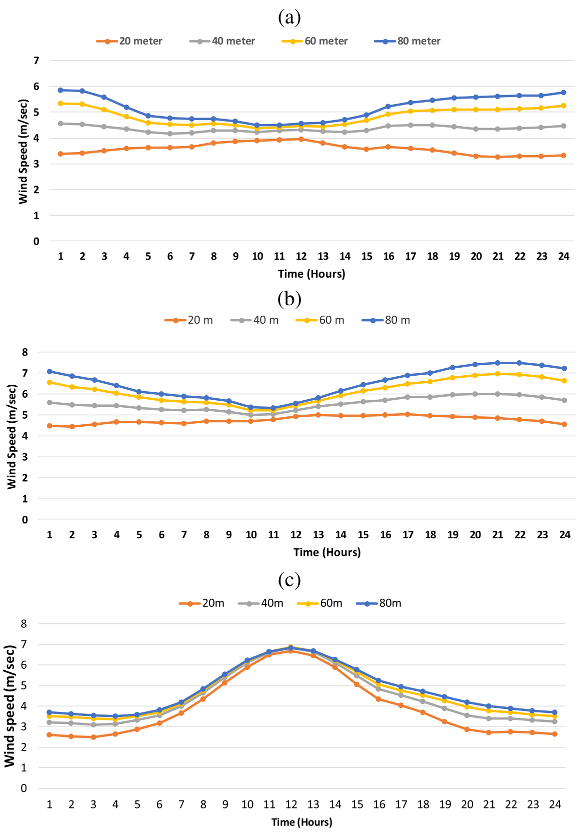


FIGURE 8. Daily mean wind speed with various hub heights at a) Bahawalpur b) Sanghar and c) Gwadar sites.

for the Sanghar and Gwadar sites. Results for heights of 60m and 80m indicate that the three methods used are statistically different. Thus, hypothesis H_1 can be accepted at a 5% level of significance. The last column in Table 7 provides the statistical conclusions regarding accepting hypothesis H_1 for the three methods adopted to estimate the parameters for these sites.

7) POWER DENSITY AND ENERGY DENSITY

The measured and estimated values of wind-power density are mentioned in Table 8. In order to calculate the annual wind energy density, the power density must be multiplied by the total number of hours in a year i.e., 8760 hrs. From Table 8, it is evident that the actual and estimated values are quiet close. For all sites, the highest values of annual wind energy densities are at the height of 80m. Further, Table 8 illustrate that Sanghar has the highest power density compared to the other two sites. Power densities calculated in Table 8 are compared with wind-power classification shown in Fig. 2 and in Table 11. It is evident that Sanghar is relatively a good site, while Gwadar and Bahawalpur sites belong to marginal wind-power classes.

8) ANALYSIS OF COST OF ENERGY AND PAYBACK PERIODS

For all calculations, the conversion rate considered was 1 USD = 168.19 Pakistani Rupee (on September 11, 2021). Capacity factors are calculated according to Eq. (22) using estimated k and c Weibull parameters given in Table 5. The annual energy yield is then calculated using Eq. (21) and calculated values are listed in Table 10. Considering the electricity costs given in Table 10 it is evident that cost varies from one site to another site.

If DeWind D4/48 is used, the lowest CoE is 37.03 USD/MWh for Sanghar (Table 10). If DeWind D6 is used, then the cost is 40.56 USD/MWh for Sanghar (ref. to Table 10). Therefore, it is evident that DeWind D4/48 turbines are promising options for these sites. Selecting Nordex N90/2500 wind turbines for Sanghar is a better option than DeWind D4/48. The CoE for Nordex N90/2500 is 35.21 USD/MWh for Sanghar. Payback periods can be calculated from Fig. 16 and the values are listed in Table 9. Using 2500 kW Nordex N90 could be more economical for wind-farm installation due to its higher CF of 25.73% among all sites. Another reason is that the payback period of Nordex N90/2500 is smaller (6 years) compared with that of DeWind D6, which is 7 years. Nordex N90/2500 is more economically beneficial for its lifetime and will result in less CoE per MWh. Irfan Ullah in [91] and Shahnawaz Farhan Khahro in [21] suggested that Nordex N90/2300 can be selected for installation in Gharo and Keti Bandar areas of Sindh in Pakistan. Therefore, all economic indicators suggest that Nordex N90/2500 is a good choice for the sites selected in our current work. DeWind D4/48 and Nordex N90/2500 are therefore, suitable wind turbines for installation of wind farms.

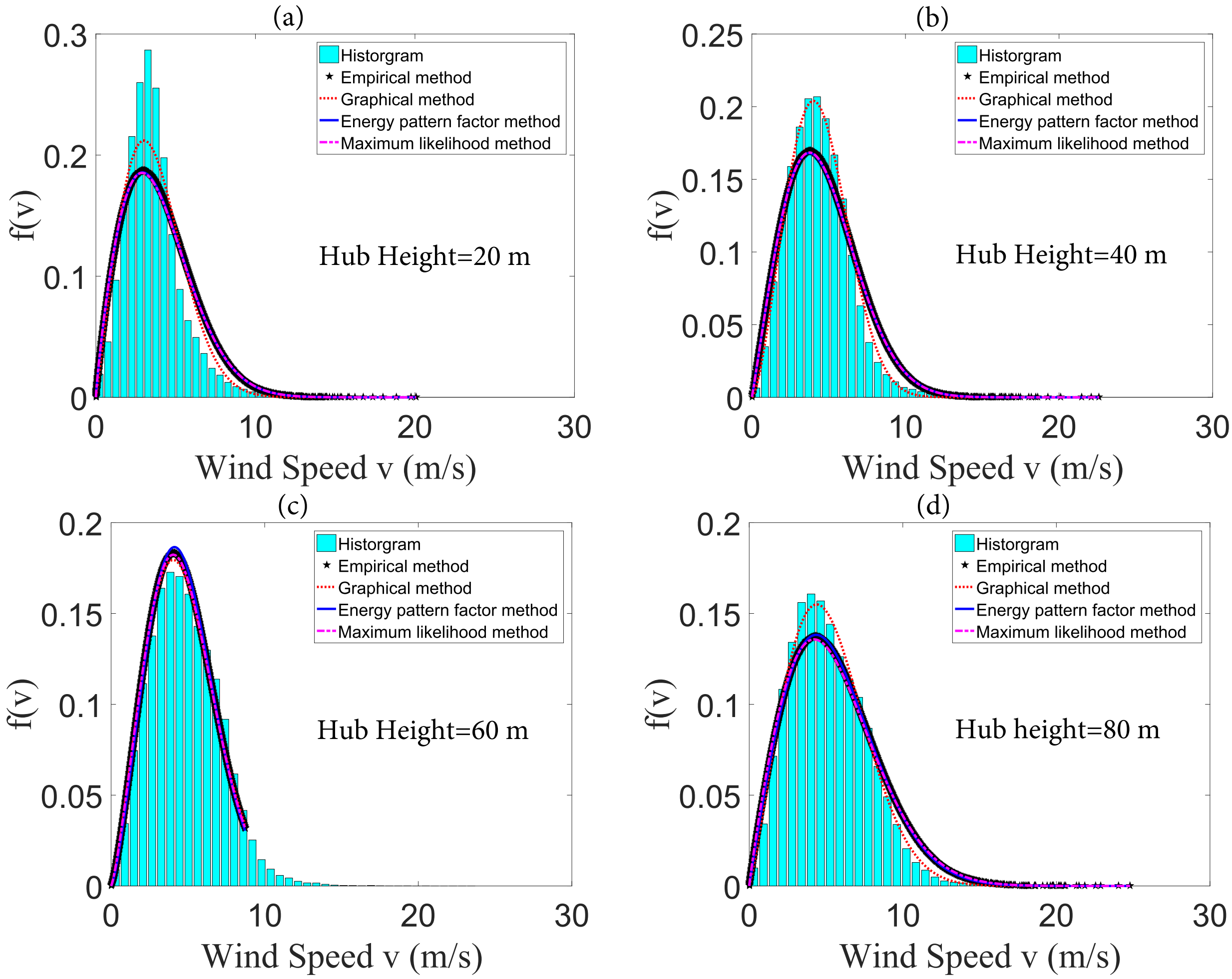


FIGURE 9. Estimated PDF for Bahawalpur (a) 20m (b) 40m (c) 60m and (d) 80m heights.

TABLE 6. Statistical error indicators estimated for selected sites.

Site	Height	RMSE				MAPE				RRMSE				R			
		GM	EM	EPF	MLE	GM	EM	EPF	MLE	GM	EM	EPF	MLE	GM	EM	EPF	MLE
Bahawalpur	$20m$	20.73	1.62	0.68	0.18	27.09	2.120	.89	0.24	7.34×10^{-2}	4.48×10^{-4}	7.94×10^{-5}	5.84×10^{-6}	0.93	0.99	0.99	1
	$40m$	30.51	2.03	0.43	0.97	27.41	1.82	0.38	0.87	7.51×10^{-2}	43.34×10^{-4}	1.51×10^{-5}	7.70×10^{-6}	0.921	0.99	1	0.99
	$60m$	4.86	1.37	0.21	1.81	4.95	1.40	0.21	1.84	2.46×10^{-3}	1.96×10^{-4}	4.6×10^{-6}	3.4×10^{-4}	0.99	0.99	1	0.99
	$80m$	44.40	0.46	1.64	4.20	22.78	0.23	0.84	2.15	5.19×10^{-2}	5.71×10^{-6}	7.141×10^{-5}	4.67×10^{-4}	0.94	1	0.99	0.99
Sanghar	$20m$	31.46	1.61	0.94	0.19	22.16	1.14	0.66	0.13	4.92×10^{-2}	5.80×10^{-3}	1.89×10^{-5}	5.76×10^{-3}	0.95	0.99	1	1
	$40m$	19.17	0.39	1.15	1.17	9.92	0.20	0.59	0.60	9.85×10^{-3}	4.16×10^{-6}	3.58×10^{-5}	3.68×10^{-5}	0.991	1	1	1
	$60m$	5.01	2.52	0.35	3.43	1.99	1	0.13	1.36	3.99×10^{-4}	1.01×10^{-4}	1.95×10^{-6}	1.86×10^{-4}	0.99	0.99	1	0.99
	$80m$	4	5.72	0.34	8.40	1.35	1.93	0.11	2.84	1.84×10^{-4}	3.75×10^{-4}	1.39×10^{-6}	1.86×10^{-4}	0.99	0.99	1	0.99
Gwadar	$20m$	28.48	0.20	0.20	1.39	26.77	0.19	0.19	1.31	7.17×10^{-2}	3.70×10^{-6}	3.70×10^{-6}	1.72×10^{-4}	0.92	1	1	0.99
	$40m$	26.23	0.55	0.55	1.19	20.73	0.43	0.43	0.94	4.30×10^{-2}	1.93×10^{-5}	1.93×10^{-5}	8.88×10^{-5}	0.95	1	1	0.99
	$60m$	23.05	0.10	0.76	0.98	16.69	0.07	0.55	0.71	2.79×10^{-2}	5.30×10^{-7}	3.10×10^{-5}	5.13×10^{-5}	0.97	1	1	0.99
	$80m$	31.11	0.63	0.63	2.47	19.98	0.40	0.40	1.59	3.99×10^{-2}	1.66×10^{-5}	1.66×10^{-5}	2.53×10^{-3}	0.96	1	1	0.99

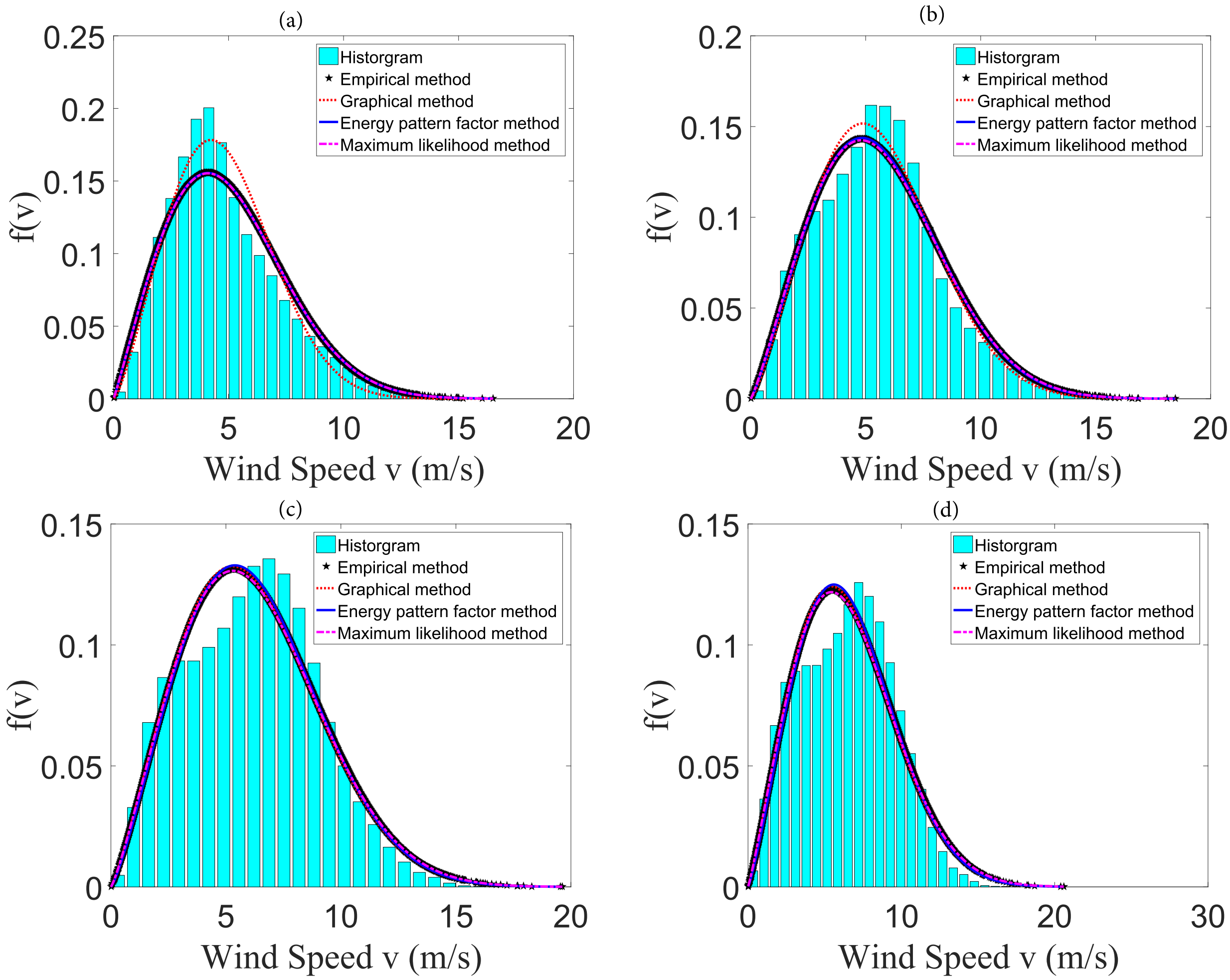


FIGURE 10. Estimated PDF for Sanghar (a) 20m (b) 40m (c) 60m and (d) 80m heights.

TABLE 7. DM test results.

Site	Height	DM for EMP and EPF	DM for EMP and MLE	DM for EPF and MLE	Results at 5% significance level
Bahawalpur	60m	10.62	12.97	17.83	Accept H_1, Reject H_0
Bahawalpur	80m	31.34	30.54	30.82	Accept H_1, Reject H_0
Sanghar	60m	15.86	-9.45	17.31	Accept H_1, Reject H_0
Sanghar	80m	22.76	24.36	23.37	Accept H_1, Reject H_0
Gwadar	60m	4.14	5.56	4.52	Accept H_1, Reject H_0
Gwadar	80m	16.03	17.05	16.85	Accept H_1, Reject H_0

The highest supported capacity factors are 24.50% from DeWind D4/48, 22.30% from DeWind D6, and 25.73% from Nordex N90/2500 for the Sanghar site.

B. ECONOMICS OF HYDROGEN PRODUCTION

1) YEARLY HYDROGEN PRODUCTION

Table 12 lists the values of annual Hydrogen production in (Ton-H2/Yr). The Hydrogen production was estimated from Eq. (28) using the annual energy estimate from Eq. (23). The efficiency of the converter, η, was taken as 90%, and the energy consumed by electrolyzer, E_{el}, was considered to be 5 kWh/Nm^3. From the listed values of H_2, it is clear that the most promising site is Sanghar with a Hydrogen production of 91.14 ton/Yr. Clearly, if the Nordex N90/2500 wind turbine is used, the highest amount of Hydrogen can be generated on an annual basis. The corresponding values of Hydrogen production from Bahawalpur and Gwadar were 68.50 and 58.23 ton/yr, respectively.

2) COST OF HYDROGEN PRODUCTION

The cost of Hydrogen production was calculated for long-term, midterm, and short-term periods. Results in Table 12 reveal that for long-term investment, the minimum cost was achieved at Sanghar site with a corresponding cost of 2.29 k$/ton using Nordex N90/2500 turbine and

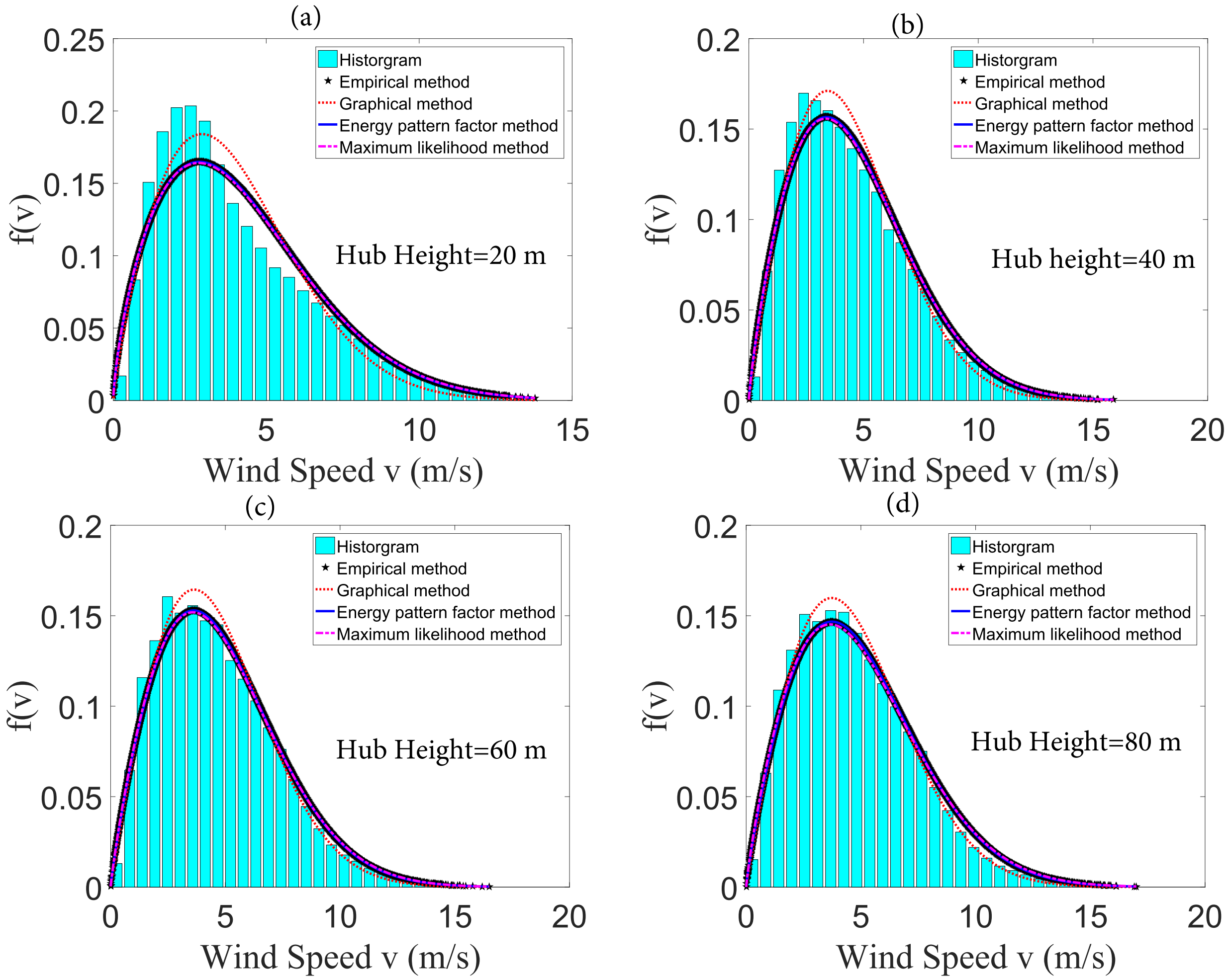


FIGURE 11. **Estimated PDF for Gwadar (a) 20m (b) 40m (c) 60m and (d) 80m heights.**

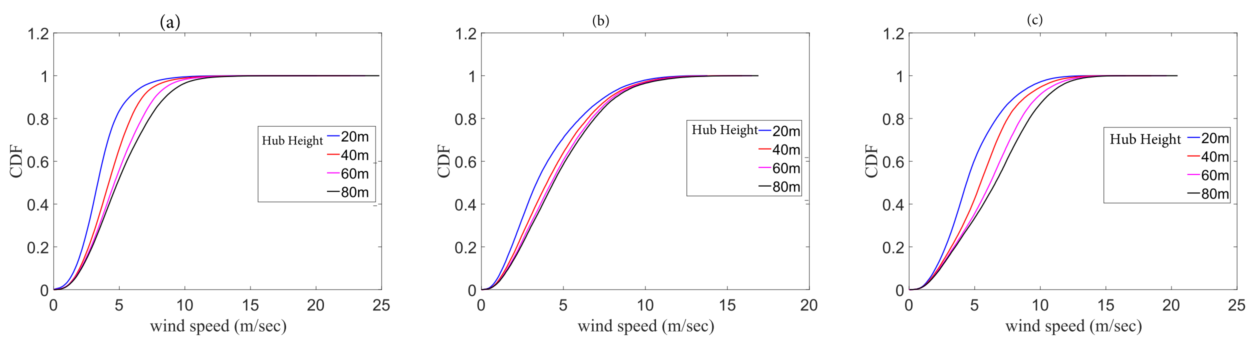


FIGURE 12. **CDF of (a) Bahawalpur (c) Gwadar (c) Sanghar.**

2.41 k$/ton using DeWind D4/48 wind turbine. For midterm investment, the corresponding cost values for this site are 4.01 and 4.22 k$/ton, respectively.

3) HYDROGEN DELIVERY OPTIONS FROM PRODUCTION SITES

Hydrogen produced can be utilized on-site or can be transported to demand sites for domestic usage or to meet industrial energy needs through a distribution network. The lack of existence and widespread of the fuel cell technology, electric cars, and Hydrogen fuel require extensive distribution infrastructure which needs to be developed. Generally, Hydrogen is distributed through three major modes of delivery:

1) Pipeline: This is most efficient and convenient method of large volume of Hydrogen delivery; however,

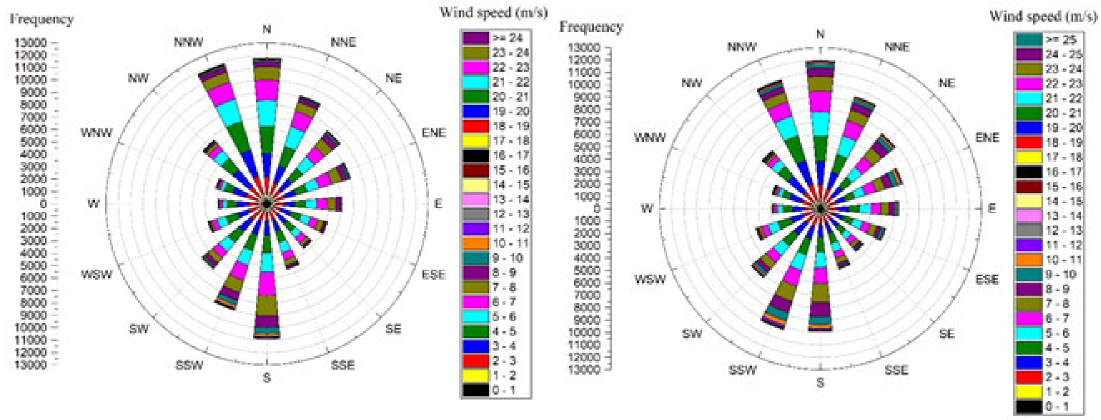


FIGURE 13. Wind Rose of Bahawalpur (a) Speed rose at 80 m hub height and direction sensor at 78.5 m height (b)Energy Rose at 80m and direction sensor at 78.5m height.

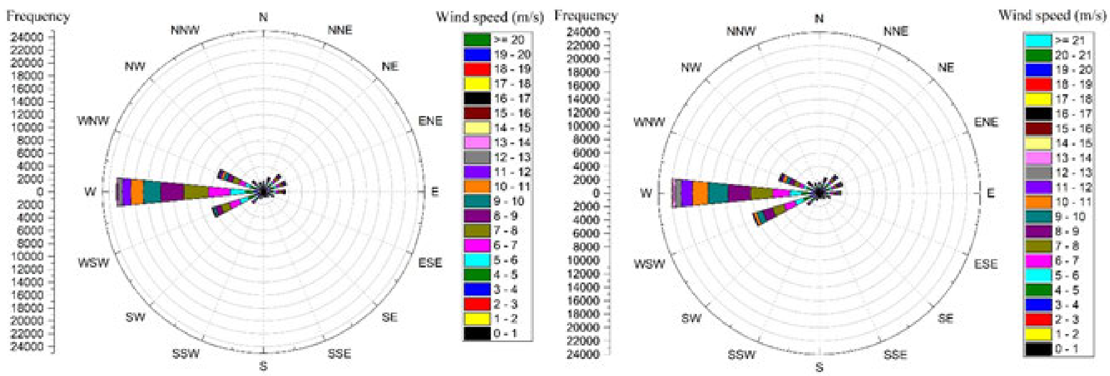


FIGURE 14. Wind Rose of Sanghar (a) Speed Rose at 80m hub height and direction sensor at 78.5m height (b) Energy Rose at 80m and direction sensor at 78.5m height.

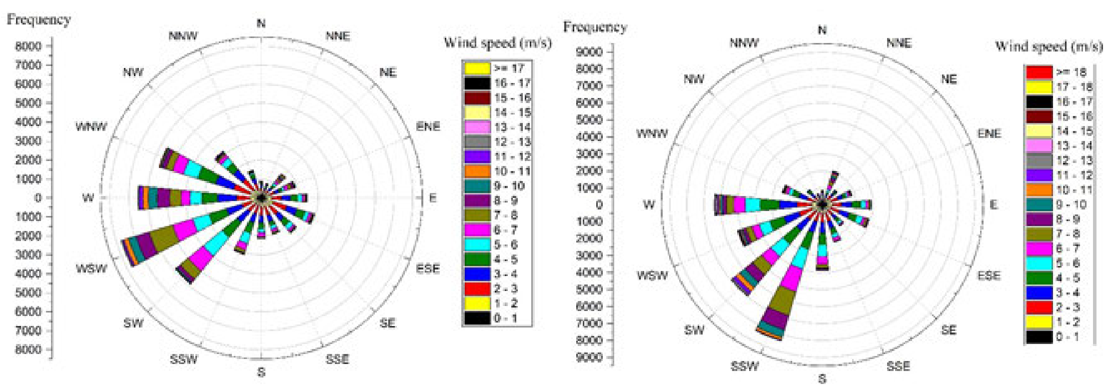


FIGURE 15. Wind Rose of Gwadar(a) Speed Rose at 80m hub height and direction sensor at 78.5m height (b) Energy Rose with at 80m and direction sensor at 78.5m height.

it requires huge capital investment and the length of the pipe impose restriction to the capacity of the Hydrogen being delivered.

2) High-Pressure Trailers: For short distance and larger volume, Hydrogen in compressed gaseous state is considered ideal choice. However, it is relatively more expensive due to large cost associated with Hydrogen compression.

3) Liquid Hydrogen Tanks: Lowering the temperature of the liquid Hydrogen to cryogenic condition converts the gaseous Hydrogen to liquid. Although, this process is more expensive than others, and only recommend for large distances transportation of Hydrogen.

For the above three modes of transportation, it is essential to ensure that the consumption of Hydrogen and delivery of Hydrogen are matched with reasonable accuracy. For liquid

TABLE 8. Measured and estimated power density (PD) (W/m^2) and annual energy density (AED) (kWh/m^2) from the four selected methods.

Site	Height	Measured		Estimated							
				GM		EM		EPF		MLE	
		PD	AED	PD	AED	PD	AED	PD	AED	PD	AED
Bahawalpur	$20m$	76.51	670.23	55.78	488.63	74.89	656.04	75.83	664.27	76.33	668.65
	$40m$	111.31	975.08	80.80	707.81	109.27	957.21	110.88	971.31	110.33	966.49
	$60m$	98.12	859.53	102.98	902.10	99.49	957.21	97.90	857.60	99.93	875.39
	$80m$	194.85	1706.89	150.44	1317.85	195.31	1710.92	193.20	1692.43	199.05	1743.68
Sanghar	$20m$	141.91	1243.13	110.45	967.54	140.29	1228.94	140.97	1234.90	141.72	1241.47
	$40m$	193.26	1692.96	174.08	1524.94	192.86	1689.45	192.10	1682.80	194.43	1703.21
	$60m$	251.41	2202.35	246.39	2158.38	253.93	2224.43	251.06	2199.29	254.84	2232.40
	$80m$	295.46	2588.23	291.45	2553.10	301.18	2638.34	295.11	2585.16	305.86	2665.81
Gwadar	$20m$	106.39	931.98	77.90	682.40	106.18	930.14	106.18	930.14	107.78	944.15
	$40m$	126.55	1108.58	100.31	878.72	125.99	1103.67	125.99	1103.67	127.74	1119.00
	$60m$	138.10	1209.76	115.05	1007.84	138.20	1210.63	137.33	1203.01	139.09	1218.43
	$80m$	155.73	1364.19	124.61	1091.58	155.10	1358.68	155.10	1358.68	158.21	1385.92

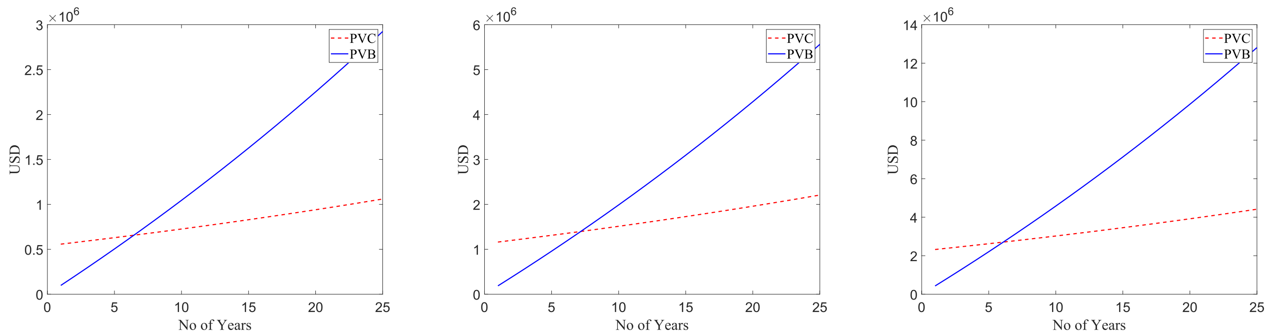


FIGURE 16. Payback period using (a) Dewind D4 (b) Dewind D6 (c) Nordex N90/2500.

TABLE 9. Payback period of wind turbines.

Turbine	Payback Period (years)
DeWind D4/48	6
DeWind D6	7
Nordex N90/2500	6

Hydrogen, it is critically important to use it at high rate of release at the utilization site else it evaporates from the storage vessel. Therefore, the Liquid Organic Hydrogen Carriers (LOHC) are commonly used in the liquid Hydrogen transportation, LOHC absorbs and release the Hydrogen through chemical reaction. LOHC can be transported over long distances [92].

The Hydrogen distribution and delivery infrastructure to link the distribution sites with the fueling stations or point of utilization is complex and complicated task which presents a number of challenges. Due to lower energy density of the Hydrogen, it is very expensive to store, transport and deliver Hydrogen compared with other fuels. Due to unique properties of Hydrogen, the storage and delivery equipment is relatively costly, and thus results in significant increase in Hydrogen delivery cost. Considering the fact that there are number of various resources and technologies to produce Hydrogen, the centralized and distributed Hydrogen production can counteract the cost of transportation and delivery.

Considering the huge investment cost of pipeline, the economically viable option of Hydrogen transportation is either as liquid Hydrogen through trucks, or as gaseous Hydrogen in trailers. For transportation and utilization of the Hydrogen, the closest cities from the Hydrogen production sites have been selected, as presented in Table 13. In order to simplify the transportation route, a transportation radius based on longest distance has been chosen. Therefore, the Hydrogen produce at Sanghar will be transported within a radius of 250km, at Bahawalpur within a radius of 450 km, and at Gwadar within a radius of 650 km. The costing model for Hydrogen transportation is based on [93], under similar transportation settings and assumption. The Hydrogen transportation cost include the capital cost (vehicle, compressor etc.), labor, and vehicle fuel cost. The Hydrogen transportation cost for each site to their transportation radius is presented in Table 14. Supply-chain model for Hydrogen production, storage and transport network can be visualized through Fig. 17.

Since all relevant costs have been considered, therefore the results of the Hydrogen transportation cost are presented in USD/kg for specific radius of each side as shown in Table 14. If the transportation radius is changed, the cost of the Hydrogen transportation will also increase due to additional cost of the vehicle fuel. The results also have reasonable agreement with the Hydrogen transportation cost estimated in number

TABLE 10. Capacity factor, annual energy production (MWh/Yr), and cost of Energy($/MWh).

Turbine	Site	CF	E(MWh/Yr)	CoE($/MWh) (n=20 Yr)
DeWind D4/48	Bahawalpur	0.168	16998	56.03
	Sanghar	0.245	25722	37.03
	Gwadar	0.189	19930	47.79
DeWind D6	Bahawalpur	0.100	21900	90.60
	Sanghar	0.223	48925	40.56
	Gwadar	0.148	32324	61.38
Nordex N90/2500	Bahawalpur	0.193	84709	46.85
	Sanghar	0.257	112697	35.21
	Gwadar	0.164	72007	55.11

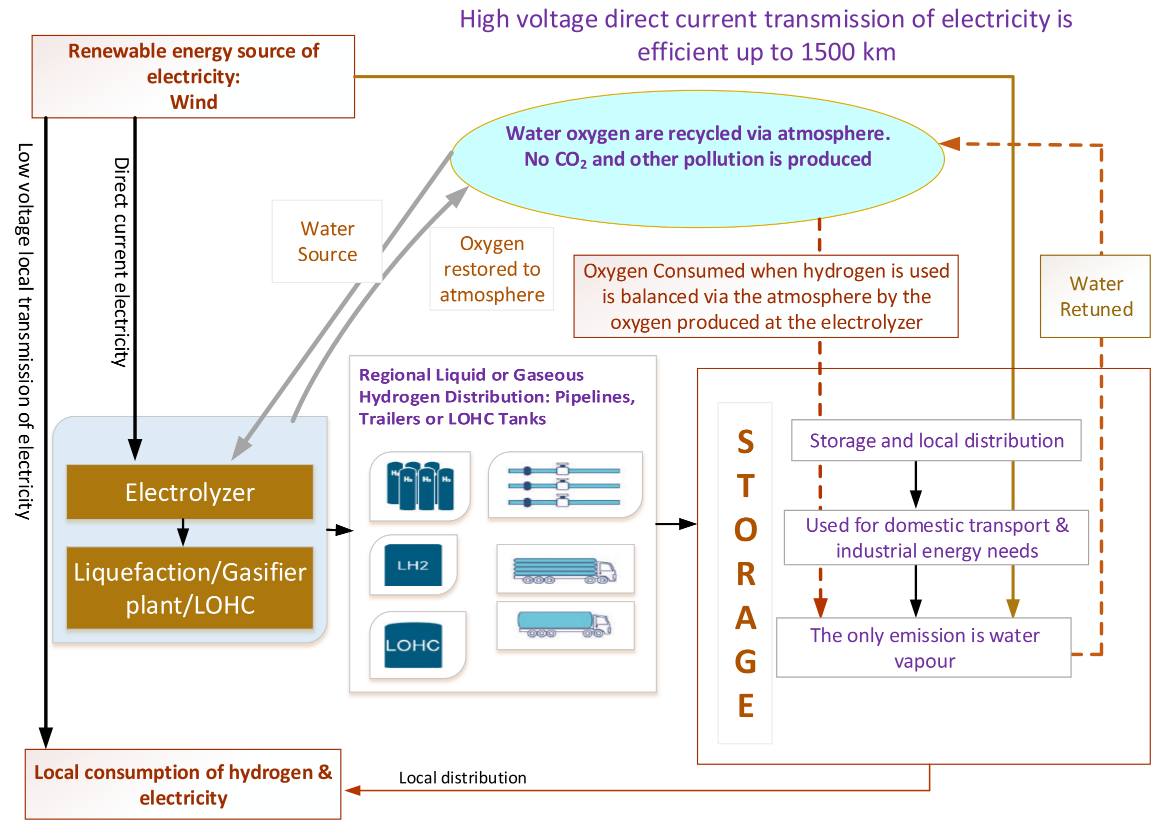


FIGURE 17. Supply-chain model for Hydrogen production, storage and transport network.

of other studies [94], [95]. It can be seen that the liquid Hydrogen is more feasible for larger distances, generally, for transportation distances of more than 500km [96]. For distances under 500km, the gaseous Hydrogen transportation is economically feasible than liquid Hydrogen. The compressor energy usage, and equipment cost for the liquid transportation is expensive than gaseous Hydrogen. Sanghar site has the lowest transportation cost with the gaseous liquid as economically viable mode of transportation. The transportation of the Hydrogen from Gwadar is economically not feasible, as the cost of transportation either as liquid or gas phase is above 17 USD/kg, almost three times the production cost of the Hydrogen.

The sites are usually geographically displaced and efficient transportation of this fuel is a major concern. In this regards many approaches are possible for example consume Hydrogen where it is produced thus meeting the local demand of the locality. If Hydrogen supply is surplus then it can be dispatched to other distribution centers. With the development of smart cities in near future and increased penetration of renewable energy, the flux of electric vehicles (EVs) with batteries are steadily increasing. Hydrogen fuel is an alternative solution to EV which if utilized can

TABLE 11. Wind power classification for sites.

Site	Wind Power Class	Class Designator
Bahawalpur	Marginal to Fair	2-3
Sanghar	Fair to Good	3-4
Gwadar	Marginal	2

TABLE 12. Cost of hydrogen for long-term($n = 7$ Yr), mid-term($n = 4$ Yr) and short-term($n = 1$ Yr) investment.

Turbine	Site	$H_2(ton/Yr)$	$CoH_2(k\$/ton)$ (n=7 Yr)	$CoH_2(k\$/ton)$ (n=4 Yr)	$CoH_2(k\$/ton)$ (n=1 Yr)
DeWind D4/48	Bahawalpur	17.34	3.65	6.39	25.55
DeWind D4/48	Sanghar	20.80	2.41	4.22	16.88
DeWind D4/48	Gwadar	16.11	3.11	5.45	21.79
DeWind D6	Bahawalpur	17.42	5.90	10.33	41.32
DeWind D6	Sanghar	41.15	2.64	4.62	18.48
DeWind D6	Gwadar	27.19	4.00	7.00	27.98
Nordex N9/2500	Bahawalpur	68.50	3.05	5.34	21.35
Nordex N9/2500	Sanghar	91.14	2.29	4.01	16.04
Nordex N9/2500	Gwadar	58.23	3.59	6.28	25.11

TABLE 13. H_2 production sites and distance of closest cities.

	Distance of closest cities		
H_2 production sites	1	2	3
Sanghar	Nawabshah - 65 km	Hyderabad - 120 km	Karachi - 260 km
Bahawalpur	Multan - 105 km	Faisalabad - 335 km	Lahore - 430 km
Gwadar	Pasni - 126 km	Turbat - 160 km	Karachi - 631 km

TABLE 14. H_2 transportation cost for a given transport radius from production site.

	Transportation radius	Transportation cost	
H_2 production sites		Gaseous H_2	Liquid H_2
Sanghar	250 km	7.52 USD/kg	17.2 USD/kg
Bahawalpur	450 km	14.2 USD/kg	19.3 USD/kg
Gwadar	650 km	17.6 USD/kg	21.1 USD/kg

further reduce pollution in the environment and create new job market. There are still many hurdles in totally moving towards Hydrogen economy the major factors being low profit, less societal adaption and higher logistics, operational and maintenance costs. In the near future when fossil fuels will deplete or the supply becomes expensive then demand for EVs and Hydrogen based vehicles integrated with fuel cells will increase.

For energy efficiency and optimizing cost of supply-chain network, an efficient Hydrogen dispatch model is required. In this model Hydrogen tank refilling and swapping stations play a key role which will directly affect operational cost of the network. A coordinated effort is required to provide logistics support for multi-regions operation and management. Costs for storage and compression of Hydrogen are also important considerations in overall cost optimization process. It has been reported in [97] that demand for Hydrogen fuel will increase and by year 2050 many countries of the world will be enjoying Hydrogen as a fuel. The source of this Hydrogen production will be mostly from renewable energy sources such as wind and solar. The number of Hydrogen re-filling and swapping stations will be increased because of increased Hydrogen demand. Even the day-ahead or month-ahead forecast would become inevitable to meet the Hydrogen demand market. Hydrogen re-fill station (HRS) and Hydrogen swapping stations (HSS) are geographically displaced, so a logistic system is required to keep track of Hydrogen tanks needed in a particular location. HRS will be responsible for Hydrogen re-filling and

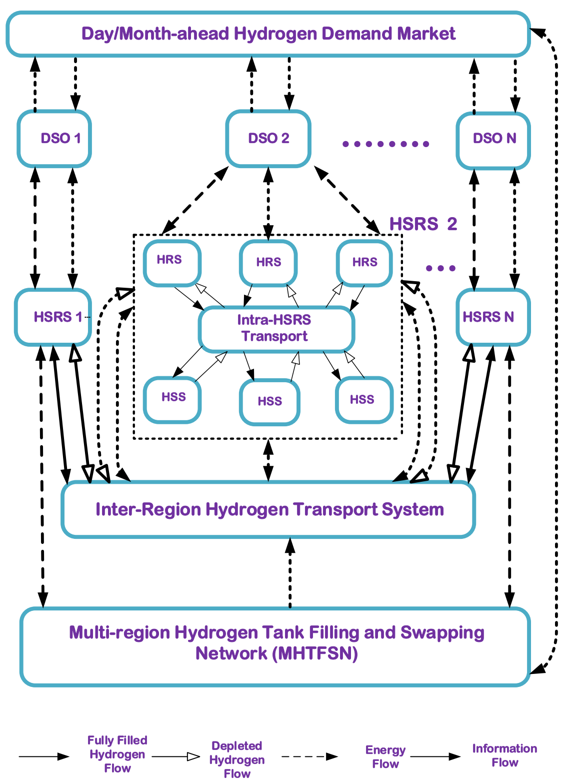


FIGURE 18. Multi-region Hydrogen tank filling and swapping network.

HSS will be responsible for Hydrogen tank swapping at stations. A Multi-region Hydrogen Tank Filling and Swapping

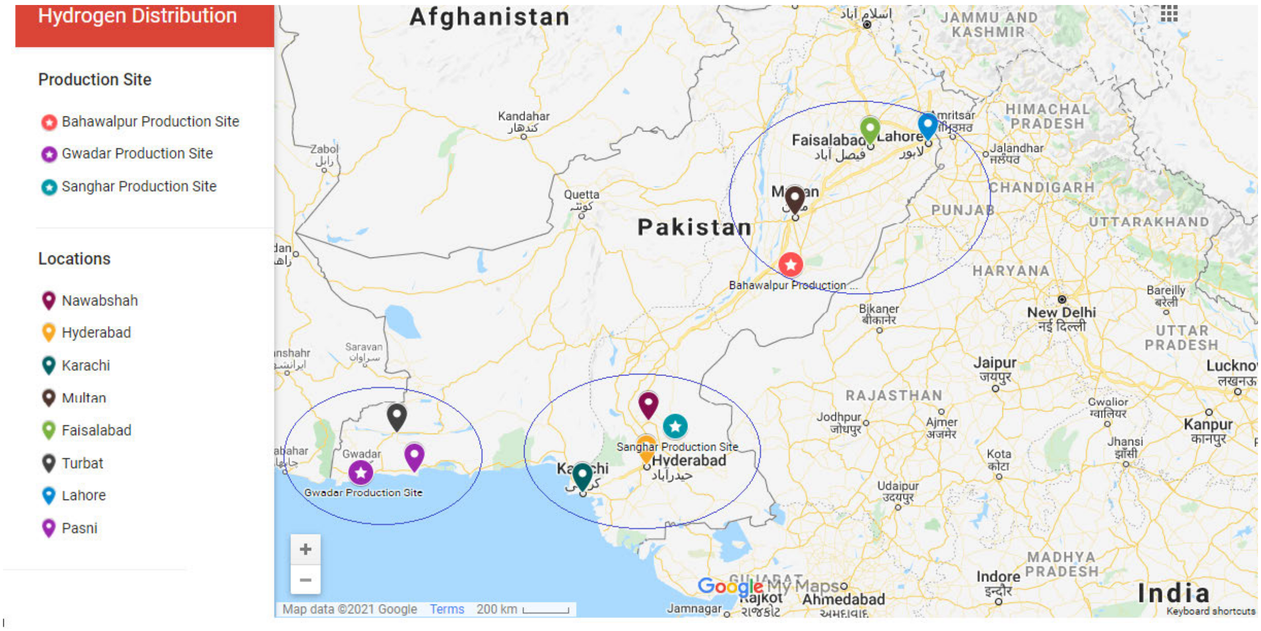


FIGURE 19. Production and possible distribution sites for Hydrogen.

Network (MHTFSN) will coordinate all supply-chains and will provide the required coordination among various regions.

Due to increased penetration of information and communication technology (ICT), MHFTSN will interact with regional supply-chains of Hydrogen swapping and refilling stations (HSRS) which will provide services within their communities. The need for efficient and cost effective distribution network will arise. Therefore these HSRS will work under the control of distribution system operators (DSO). In our current work we have proposed such a supply-chain model for Hydrogen demand and transport network as shown in Fig. 18. However due to different consumer's Hydrogen consumption patterns, the prices for Hydrogen transport may vary. The market clearing prices (MCP) may change dramatically in open energy market and the stations can participate in Hydrogen fuel trading [98]. DSOs will help in this energy trading. Based on the wind power forecast using artificial neural networks (ANN) or machine learning approaches for a region and MCP forecast using statistical models, a multi-objective optimization algorithm can be developed for Hydrogen production schedule for a day-ahead or month-ahead energy market and optimize production cost of a particular station. The algorithm can also optimize the transportation cost, storage and compression cost subject to certain constraints by transporting either compressed Hydrogen [99] or liquid organic Hydrogen [100].

Based on our finding for feasible sites for Hydrogen production with lowest cost values, production sites as well as distribution nodes can be identified. These sites are identified in distribution network for Hydrogen as shown in Fig. 19. From the map it is clear that Gwadar site can serve Pasni and Turbat, whereas Sanghar site can meet the Hydrogen demand of Hyderabad and Nawabshah. However, Karachi is at a distance of 260km and therefore transport of Hydrogen is not much feasible. Wind sites close to Karachi such as Gharo (at a distance of 86km), Jhimpir (at a distance of 127.3km via Hyderabad Motorway), Keti Bandar (at a distance of 154.1 km via Gharo Rd/Gharo-Keti Bunder Hwy/N-110), Babaurband village (about 67 km in Northeast of Karachi, Sindh) are better suited for production of Hydrogen. Province Sindh, identified with its rich wind corridors for energy production can benefit from this study and move towards Hydrogen economy by the end of 2035 if Hydrogen production plants are installed. Surplus Hydrogen can be transported to other major cities such as Bahawalpur, Multan, Faisalabad, Lahore. This will move Pakistan towards a real Hydrogen economy with socio-economic benefits for the society and drastically reducing oil and gas imports.

VII. CONCLUSION

In this work, the wind resource potential was probed for three sites located in Punjab, Sindh, and Baluchistan provinces of Pakistan. The actual data of wind speeds at the selected sites between November 2016 to October 2017 were analyzed to determine the mean wind speeds on monthly and daily basis for the selected sites suggesting that these sites belong to a class performance of two or higher wind potential. The parameters of the Weibull distribution were estimated by GM, EM, EPF, and MLE methods. The wind turbine models with the highest capacity factors were proposed to install wind farms at mentioned sites. The actual wind profile data recorded from selected sites tightly fit the Weibull distribution function. The scale parameters k and c for 80m installations were 2.12 and 7.34, respectively, for Sanghar. The obtained values were validated using statistical error indicators. Further, the wind-power density and annual energy yield were estimated using Weibull parameters. DeWind D4/48 and Nordex N 90/2500 wind turbines were recommended for wind-to-Hydrogen production. The highest capacity factor values were 24.47% from DeWind D4/48, 22.34% from DeWind D6, and 25.73% from Nordex N90/2500 for Sanghar. Concerning cost of energy, Sanghar can be regarded as a suitable site for wind energy projects followed by Bahawalpur and Gwadar.

The amount of Hydrogen production, using coupled wind energy conversion system with water electrolyzer was estimated for Bahawalpur, Sanghar and Gwadar sites. The cost of Hydrogen production was also estimated. An implementation scheme was provided for practical realization of wind-to-Hydrogen production. In terms of Hydrogen production using electrolysis, Sanghar is the best site. The cost of Hydrogen was calculated for three different periods—long-term (7 years), midterm (4 years), and short-term periods (1 year). For long-term investment, the minimum cost was achieved at Sanghar with the corresponding cost of Hydrogen being 2.29 USD/kg using Nordex N90/2500. Transportation cost of Hydrogen was also determined based on a given transport radius. Hydrogen is considered as one of the major energy carriers for future energy systems and transition to renewable and zero-carbon energy technologies is inevitable. This paper particularly aimed to analyze the techno-economic aspect of Hydrogen production from available wind resources in Pakistan. Transportation cost is relatively higher compared to the Hydrogen production cost. It is found that the cost of Hydrogen transportation is 1.2 to 4 times higher than the cost of Hydrogen production. Including the detailed costing and economics of modes and ways of Hydrogen transportation is multi-variable, complex, complicated and challenging optimization task and therefore will be considered in our future work.

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