Economic viability and production capacity of wind generated renewable hydrogen

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Abstract

Generally, wind to power conversion is calculated by assuming the quality of wind as measured with a Weibull probability distribution at wind speed during power generation. We build on this method by modifying the Weibull distributions to reflect the actual range of wind speeds and wind energy density. This was combined with log law that modifies wind speed based on the height from the ground, to derive the wind power potential at windy sites. The study also provides the levelized cost of renewable energy and hydrogen conversion capacity at the proposed sites. The calculated cost ($/kWh) suggests that the commercial viability is not feasible. We have also electrolyzed the wind-generated electricity to measure the production capacity of renewable hydrogen. We found that all the sites considered are commercially viable for hydrogen production from wind-generated electricity. Wind generated electricity cost varies from $0.0844 to $0.0864 kW/h, and the supply cost of renewable hydrogen is $5.30 to $ 5.80/kg-H_2. Based on the findings, we propose a policy on renewable hydrogen fueled vehicles so that the consumption of fossil fuels could be reduced. This paper shall serve as a complete feasibility study on renewable hydrogen production and utilization.

Keywords: New model, Renewable energy, Hydrogen energy, Weibull distribution, Hydrogen production capacity, Levelized cost.

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1. Introduction

Growing energy demands and climate regulations encourage the utilization of renewable energy resources including hydrogen energy. Continuous usage of fossil fuels will result in irrevocable damage of environment. Several nations around the globe are striving to provide access to clean and sustainable energy by 2030 [1]. Carbon based power systems should be exchanged with new renewable energy technologies that are able to balance energy demand-supply, ensure energy security, have less impact on climate change and economically viability. According to Renewable Global Status Report, renewable energy contributed 19.2% of the total world's energy consumption in 2014. Among the several renewable energy resources, renewable hydrogen could be a major contributor to sustainable clean energy production and successful Millennium Development Goals (MDGs) [2]. Intergovernmental Panel on Climate Change (IPCC) [3] considers renewable hydrogen energy (RHE) to be the best substitute for fossil fuels. Moreover, RHE would help to ensure 100% integration of renewable energy. RHE can be generated through various resources such as wind, solar, geo-thermal and hybrid sources. RHE systems can improve energy security of developing nations including China and Japan, and help them in reducing China's CO_2 emissions via scientific diversification, and minimizing dependence on imported fossil fuels.

Energy generation using solar systems typically costs 6 to 18 times higher than wind energy and wind turbine systems [4]. At present, hydrogen production through water electrolysis using wind energy is considered as a lowest life cycle greenhouse gases (GHG) emissions of all hydrogen production resources. Most works related to hydrogen production have ignored the regional characteristics of wind power potential to produce renewable hydrogen at country level [5]. Mostly traditional methodologies are adapted to select optimal wind sites and lack exploitation of latest technologies [6]. They have only used present value (PV) cost methods to measure the price of renewable energy. PV cost method combines discount rate and future cash flows, and it is hard to estimate the 100% accuracy of future value and discount rate. In addition, the PV cost method do not incorporate the increasing unit of energy production. Existing literature [7] partially enumerates the wind power potential, the cost of renewable energy and hydrogen production along with its capacity. Based on our knowledge, this is the first of its kind study that takes into account all the above-mentioned issues.

This study uses modified Weibull distribution function to characterize and select optimal wind sites and turbine configurations at a rich windy site to produce wind electricity for hydrogen production. We used a new modified model of the Weibull distribution function and log law, and electrolyze the wind-generated electricity to produce renewable hydrogen energy. Our paper additionally measures the Levelized cost of wind electricity generation via average incremental credit cost to measure the cost of renewable hydrogen production. The advantage of average incremental credit cost is associated with every increasing unit because, few costs are variable and some are fixed cost so the average incremental cost will be decrease with increasing every unit of energy production. We also introduced a new mathematical model to measure the hydrogen production capacity at any windy sites by introducing the wind topography of Pakistan as a practical case study, which shows the total wind power potential. Based on our findings, we suggest a policy to the government to reduce the energy shortfall by shifting vehicles from fossil fuel to hydrogen energy. Our study also provides an empirical estimation, economic viability of the hydrogen production and guidelines for 100% integration of renewable energy. In summary, our objective is focused towards the potential generation of renewable hydrogen from the wind-generated electricity at windy sites and its economic integration is the main objective of the study.

2. Literature Review

Numerous studies have investigated the integration and design of the renewable hydrogen energy system. Measuring the availability of renewable energy resources for production of hydrogen with different statistical and mathematical calculations has also been a common trend [8,9]. Olateju et al., [10] explored the production of wind generated hydrogen and determination of potential sites using the measurement of capacity factor by Weibull distribution function over wind. Østergaard et al., [11] stated that wind turbine and heated pump hydrogen storage system provides a continuous supply of energy when energy activity is slow. Katsigiannis et al., [12] examined the multi-criteria assessment for the potential of hydrogen production systems through wind energy, gas turbine and photovoltaic system. Sacramento et al., [13] conducted a study on electrolytic hydrogen production for the Ceara state in Brazil. They observed that the energy consumption and the gross internal product per capita of the region would increase by using the renewable resources to produce hydrogen. Ball et al., [14] stated that hydrogen production through renewable wind energy by electrolyzing the water without carbon dioxide emission or other dangerous gases leads to an optimal energy mix, resulting in reduced dependency on fossil fuels. Dagdougui et al. [15] assessed the potential of the hydrogen generation using wind energy in the province of Cordoba in Argentina. They found that the potential supply of wind energy to produce hydrogen energy in that region is ten times higher than the required level of hydrogen energy for the entire vehicular transportation. Bekele et al. [16] conducted a study to determine the feasibility of hydrogen production using wind energy. Guo et al. [17] examined a wind-energy storage-system model for huge wind energy of China. Akpinar et al. [18] investigated the wind characteristics of (Elazig-Keban, Elazig-Agin, Elazig and Elazig-Maden) by using probabilistic distributions, Maximum Entropy Principle, and traditional normal Weibull distribution through singly truncated application. Mohammadi et al., [19] used six statistical techniques including graphical method shows a weak efficiency while, Lysen empirical method, Justus empirical methods, maximum likelihood method, energy pattern factor method and modified maximum likelihood method shows a strong efficiency to determine the scale (c) parameters and shape (k) parameters of Weibull distribution function to measure wind power density. Ozay et al., [20] analyzed wind characteristics including wind direction, frequency distribution of wind speed, mean speed, scale and shape parameter of Izmir region in Turkey by using two parameter Weibull distribution function. Shu et al., [21] measured the characteristics of renewable energy sources of Hong Kong through traditional Weibull distribution function.

Hill et al., [22] measured the parameters of Weibull probability and Weibull density distribution function for three different sites and found that statistical values of scale and shape parameters for these stations are wide-ranging. Tsekouras et al., [23] proposed probability distribution function by time series data. They estimated the distributional parameters of probability distribution function. Wais et al., [24] concluded that the accurate evaluation of Weibull shape and scale parameters is necessary for the wind energy potential estimation. Wind speed alone does not provide the clear understanding of wind speed distribution and wind potential of any sites in the region, because it is also possible that the same average wind speed have different parameters of Weibull distribution function. Khahro et al., [25] analyzed the numerical characteristics of wind speed to obtain an exact measurement and estimation of wind potential. They focused on wind parameters of Weibull distribution function by using two component mixture Weibull distributions with five parameters and winds power potential. Shin et al., [26] demonstrated that the two-component mixture of Weibull distribution function could be considered as a useful estimation because it provides a heterogeneous wind regime. Boudries et al., [27] predicted the renewable hydrogen energy system for households using a storage medium of renewable hydrogen. Dincer et al., [28] proposed an optimization model of a renewable energy system for zero/low energy structure. Oh et al, [29] measured a techno-economic viability analysis of an integrated renewable energy in order to meet the demand of households in Greece.

Kalinci et al., [30] analyzed a hybrid system consisting of wind turbine and electrolyzer units. Kalinci et al. [31] studied hydrogen energy system in an Island in Turkey and done techno-economic analysis of hybrid renewable energy by hydrogen generation and its storage. . Onovwiona et al., [32] suggested a hydrogen turbine energy system for the domestic households and residential application in which micro-cogeneration has ability to produce electricity and thermal energy from a single source of fuel. Many studies have been done in different regions of the world with outstanding wind conditions, such as Ireland, Norway and the Faroe Islands and they concluded that wind potential pattern to produce renewable energy is similar to Denmark. Mohammed et al., [33] considered the incorporation of a hybrid wind and a renewable hydrogen system to ensure the delivery of a stable 100% renewable energy contribution. The result revealed that although the storage mechanism of renewable hydrogen is costly and inefficient due to higher capital cost, it has numerous advantages towards 100% integration of renewable energy and environment friendly [34]. Lund et al, [35] concluded that the high capital cost of fuel cells makes costly renewable storage systems but by using electrolyzer procedure to produce and sell the renewable hydrogen to responsive load.

Jebaraj et al., [36] investigated the role of renewable energy technology to climate change adaptation via long-range energy options planning and estimated the possible potential reductions of emissions by using different renewable technologies. The industrial application of renewable hydrogen covers from fertilizer production, refineries, fueling of vehicles and metal extracting [37]. Sarrias-Mena et al., [38] studied the electrochemical performance internal parameters of the electrolyzer process including different elements namely the membrane, cathode, anode and voltage accessory. They also explored the fractional pressure required to operate the electrolyzer process. Valverde-Isorna et al., [39] proposed EZ model in order to make a complete comparison with other models and methodologies to perform the electrolyzer process in order to produce renewable hydrogen energy. They also suggest that the cathode and anode accessory perform the similar function, which is to provision of oxygen concentration and hydrogen concentration separately. Currently the hybrid renewable power structure for the hydrogen production mainly concentrating on the wind, and geothermal energy options to produce renewable hydrogen energy [40]. In existing literature, different researchers have used different conventional methods to estimate the wind power potential and suggested various mechanisms to convert this wind-generated electricity into hydrogen and they used traditional cost measurement techniques, which has influenced us to come up with new methodologies to ensure the robustness of the results.

3.Methodology to assess wind electricity for hydrogen production

Data was obtained from the reports of the meteorological department of Pakistan. According to Metrological departments of Pakistan, wind data for this study is measured at heights of 30 meters, 50 meters, 60 meter and 80 meter above from ground level at different locations in northern areas of Pakistan. This section will measure the wind potential to generate electricity for hydrogen production. As in earlier work, the Weibull distribution function is a fundamental building block for the estimation of wind characteristics [41]. Nevertheless, we indicate how we have estimated the average wind speed, wind power density, wind power potential, shape parameter, scale parameter and capacity factors with new hybrid methodology, at different hub height to measure the wind potential of electricity production at proposed sites. For the estimation of wind characteristics we begin with,

$$f(u) = \frac{K}{c}(\frac{u}{c})^{k-1} \times \exp(\frac{-u}{c})^{K} \quad (1)$$

K is a dimensionless shape parameter and it is a measurement of width of distribution, c is called scale parameter, which is very closely near to mean of the wind speed, u is the wind speed and its unit is m/s. The shape parameter K can be calculated with mean and standard deviation of the wind [42] as follows:

To solve the equation (1) we use the following parameters

$$\mathrm{K} = (\frac{\sigma}{\bar{u}})^{-10.86} \quad (2)$$

$Where \quad 1 \leq K \leq 10$

The scale parameter (c) can be expressed as:

$$\mathrm{c} = \frac{\bar{u}}{r(1+\frac{1}{K})} \quad (3)$$

$u$is the mean and σ is called standard deviation of the wind speed and it can be calculated as

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{n} u_i \quad (4)$$

$$\sigma = \left[\sum_{i=1}^{N} \frac{(u-\bar{u})^2}{N-1}\right]^{0.5} \quad (5)$$

Where r of gamma function can be determined by following function.

$$r(m) = \int_0^{\infty} \in^{m-1} exp(-\in)\, d \in \quad (6)$$

$\in$ is the constant real irrational number and its value is $\in$ =2.7182818284590

The Gamma function can be computed as,

$$r(m) = \sqrt{2\pi m}(m^{m-1})\left[1 + \frac{1}{12m} + \frac{1}{288m^2} - \frac{139}{51840m^3} \ldots..\right] \quad (7)$$

Only investigation of wind speed doesn't represent a true picture of wind potential because wind speed's frequency distribution and kinetic energy suppressed in the wind power density. It normally depends upon the wind speed cube, frequency distribution of wind speed, velocity v, area A of turbine blade with air density ρ. The unit of velocity is (m/s), (m^2) is the unit of Area and (Kg/m^3) is the unit of density. Parcel of wind energy having kinetic energy is as follows [43],

$$E = \frac{1}{2} mv^2 \text{ but we substitute v as a u so v = u so } E = \frac{1}{2} mu^2 \quad (8)$$

From this equation power density can be generated as

$$P = \bar{e}/\bar{t} = \frac{1}{2}\frac{dm}{dt} u2 \quad (9)$$

$\frac{dm}{dt}$ is air following mass w.r.t to time t.

By fluid dynamics it is proved that

$$\frac{dm}{dt} = \phi Au \quad (10)$$

Volume of the cylindrical cross section can be expressed as

$$u = \pi l r^2 \quad (11)$$

l Is length and r is the radius of cylinder, Velocity of wind is u, it travel the distance L in time t, so it is

l= ut substituting values in equation (11)

$$u = \pi utr^2 \quad (12)$$

Mass of wind is as follows

$$m = \phi Aut \quad (13)$$

By differentiating

$$\frac{dm}{dt} = \phi\, Au \frac{d}{dt(t)} = \phi\, Av \quad (14)$$

ϕ is called the density of wind;

$$\text{Power is } P = \frac{1}{2}\frac{dm}{dt}u^2 \quad (15)$$

Substitute the value of $\frac{dm}{dt}$

$$P = \frac{1}{2}\phi\, A\, u\, T/t\, u^2;\ P = \frac{1}{2}\phi\, Au^3$$

Power density can be written as

$$P/A = \frac{1}{2}\phi\, u^3 \quad (16)$$

Wind density at the mean sea level is 1.225 kg/m^3 and it mainly depends on the wind velocity. Wind speed increases with increasing height. It shows the direct relationship between hub height and wind speed but generally wind speeds are observed at different heights on a wind turbine. In such cases, although Weibull distribution technique is a popular technique to estimate the relative parameters, we use the log law which modifies wind speed based on the height from the [44] ground, to derive the wind power potential because it provides a best fit of wind speed at increasing height ,

$$\frac{u}{u_R} = log \frac{l_n\left(\frac{H}{H_\circ}\right)}{l_n(H_R/H_\circ)} \quad (17)$$

u is wind speed at height H and u_R is the wind speed height H_R. Roughness length H_o is related to displacement height and displacement height is the height over roughness elements where there is a free flow. Moreover, accumulated annual energy output of a wind energy project is called the capacity factor of wind energy turbines. It varies from site to site and turbine to the turbine. It depends upon the capacity of the machine to produce electricity and mainly the wind speed of proposed sites. Economic viability of a wind turbine is expressed by capacity factor (CF), it is the ratio of average power yield (P_o) to the stated power (Pt) of the turbine. It is the best criteria for selecting any turbine.

$$C_f = \frac{P_o}{Pt} \tag{18}$$

P_o Can be determined from Weibull probability density function as:

$$P_o = \int_{uci}^{uco} \rho u f(u)\, du \tag{19}$$

Power generated through a pitch-controlled turbine is calculated from the power curve. The variable $f(u)$is (operational wind speed) is the function of the duration of the wind speed.$uco$is the cut- out wind speed and uci is the cut-in wind speed,ρu is wind turbines power curve,Pt is rated wind speed capacity of the turbine. Wind turbine power generation (P) is approximated by the power curve,

$$P_t = \frac{1}{2}\rho A C_P u^3 \tag{20}$$

Putting values of P_t and P_o in equation (11)

$$C_f = \frac{P_o}{P_t} = \frac{\int_{uci}^{uco} \rho u f(u) du}{\frac{1}{2}\rho A C_P u^3} \tag{21}$$

Power generated through a pitch-controlled turbine is calculated from the power curve. Capacity factor can be shown with C_f.

3.1Cost of Production

The Levelized cost of electricity is a valuable economic indicator to compare the cost of different production types of electricity calculated in terms of the cost per unit of electricity output ($/MWh). It includes carbon, fuel, capital and other sources of cost. The Levelized cost of electricity can be measured by the annual cost of energy production divided by annual energy production [45].Annual energy production (AEP) is inversely proportional to the annual energy production. By increasing of wind resources, the total cost remains constant but the cost per unit energy will decrease. The annual fixed charge rate transfer the lump-sum investment into annual payment. Kanchana et al, [46] measured the average incremental energy credit of the wind park over the study period ($/MW h) as levelised cost as,

$$AICEn = \frac{\frac{\sum_{n=1}^{N}\left(FC_{Rn} - FC_{Wn}\right) + \left(VO\&M_{Rn} - VO\&M_{Wn}\right) + \left(ENS_{Rn} + ENS_{Wn}\right)}{\left(1+i\right)^{n}}}{\sum_{n=1}^{N}\left(1+i\right)^{n}} \tag{22}$$

AICEn is the average incremental energy credit of wind sites (available for hydrogen production) over the study period ($/MW h). N is Study period (Years), i is discount rate, FC_{Rn} is the fuel cost of the year (n) under reference case, FC_{Wn} is fuel cost of year n under wind power case, $VO\&M_{Rn}$ is variable O&M in year n under reference case. $VO\&M_{Wn}$ is variable O&M in the year n under wind power case, ENS_{RN} is electricity costs in year n under reference case, ENS_{WN} is electricity costs of year n under wind power case, WG_n is the wind electricity generation in year n. Although this model measured the cost of electricity in the term of ($/MW h) but it ignored the fundamental pillars of capital expenditure and operational expenditure of levied cost of the electricity presented by the national renewable energy laboratory as,

$$LCOE = \frac{(Capex \times CFR) + Opex}{AEP} \tag{23}$$

LCOE is the Levelized cost of energy ($/MWh),FCR is the fixed change rate (%), Capex is capital expenditures ($/MWh), AEP_{net} is the net average annual energy production (MWh/year), Opex is the operational expenditure ($/MWh). To measure the per unit cost of wind energy in ($/kWh) we can measure as,

$$\text{Ccu= Total cost/Annual average yield} \tag{24}$$

C_{cu} is per unit cost in($/kWh).Three basic pillars into the Levelized cost of electricity are operational expenditures (OPEX), capital expenditures (CAPEX) and annual energy production (AEP). The fourth basic pillar is the fixed charge rate (FCR) which symbolize the amount of revenue required to pay the capital including return on debt, return on equity taxes and depreciation associated to the CAPEX investment during the expected project life of the wind park on an annual basis. All analysis and LCOE results are in constant 2015 dollars throughout the report unless otherwise noted. National Renewable Energy Laboratory (NREL) has breakdown the structures of Levelized cost in order to organize and provide a general terminology across varying technology. Study provides a description about each component of the Levelized cost of electricity such as CAPEX , OPEX, AEP and FCR. Fix charge rate (FCR) can be calculated as,

$$r = \frac{\mathrm{r} \times (1+\mathrm{r})\mathrm{t}}{(1+\mathrm{r})\mathrm{t}-1} \tag{25}$$

where r is the current interest rate.

3.2 Electrolysis modeling

Renewable Hydrogen energy can be generated through water electrolysis by using the wind renewable electricity generated through electricity generation systems $\mathrm{E}_{\mathrm{t}}^{\mathrm{RES}}$. To operate electrolysis systems polymer alkaline electrolyze system has been considered in the study which is a scientifically proven process and it is measured due to its simple use and comparatively cheaper price. For production of 1 kg of renewable hydrogen the 53.4 kWh of electricity and 10.6 kg of water is needed. The amount of renewable hydrogen from the process of electrolyzer $\mathrm{H}_{\mathrm{kt}}^{\mathrm{el}}$ is determined using the following model [47,48] ,

$$H_{kt}^{el} = \vartheta_{jt}^{el} E_t^{RES} \qquad \forall_j \in J^{el}, \ t=1,.............n \qquad (26)$$

where ϑ_{jt}^{el}j is the electrolyzer operation efficiency and it includes the extra energy consumption for additional apparatus operations. And simultaneously the amount of oxygen produced by the process of this electrolysis system is $O_{kt}^{el}$and it is calculated with following model,

$$O_{kt}^{el} = \mu_j^{o/h} H_{jt}^{el} \qquad \forall_j \in J^{el}, \ t=1,.............n \qquad (27)$$

where$\mu_j^{o/h}$j is the ratios of produced hydrogen and produced oxygenic the system of electrolyzer j $\in J_{el}$. To meet the demand and supply of renewable hydrogen the number of parallel units of electrolyzer are required. The quantity of renewable hydrogen produced through an electrolysis system H_{jt} in the time period (kg/period) is calculated by the following equation,

$$H_{jt} = M_t N_{jt}^{el} H_{jt}^{el} \forall_j \in J^{el}, \ t=1,.............n \qquad (27)$$

where$N_{jt}^{el}$is the number electrolyzer in the system and M_t is the number of hours counted in the electrolyzer system.

4. Mechanism of PEM electrolysis

Electrolysis became a cheap and popular hydrogen production method worldwide. Three types of electrolyze rare identified in the hydrogen production literature. They are polymer electrolyte membrane (PEM), alkaline and high temperature solid oxide electrolyzer (SOE). Among all these, alkaline water electrolyzer is considered as a mature technology. These are safe, reliable and globally counted as a most extended electrolysis technology at the commercial level. It can be seen from Figure (1) that, water (H_2O) decomposition of oxygen (O_2) and hydrogen gas (H_2) due to passing through an electric current from water is called electrolysis of water. As a result of water decomposition breathing oxygen can be produced and hydrogen gas can be produced for fuel purpose. Inert metal (stainless steel, platinum, or iridium) is used to make two electrodes which are connected with electric power. Both electrodes and plates are placed in the water. Hydrogen will appear at the negatively charged electrode, which is also called the cathode, while oxygen will appear at the positive charge side, which is also called the anode. The hydrogen amount produced in this process is double that of oxygen production. At the global level production of hydrogen, more than 85% is derived from the steam reforming processes which use fossil fuels at large and small size.

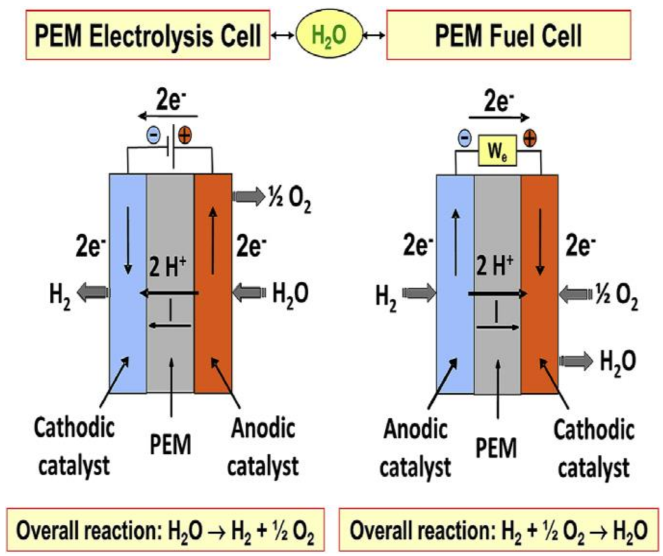

Figure.1 Electrolysis process

In the polymer electrolyte membrane electrolyzer, there is a solid plastic, which is also called the electrolyte. Water reaction with the anode yields the results of a configuration of positively charged hydrogen ions and oxygen ions. Then hydrogen ions move towards the cathode. Finally, the hydrogen gas will form at the cathode plate [49]. Currently hydrogen is identified as an environmentally friendly fuel worldwide. In addition, hydrogen is a recyclable element. After burning it converts into water. Hydrogen can be a viable substitute for diesel and gasoline. Hydrogen can be produced with an environmentally friendly source of wind energy with minimum cost. Wind power costs have continually descended compared too many other methods and technologies over the last five years. It is now approaching the lowest level cost where it can compete with other conservative technologies.

4.1 Application: the case of Pakistan

Pakistan is facing a major energy crisis over the past few years. The electricity industry has numerous problems including insufficient collection rates, line losses, high natural gas subsidies, power generation theft, expensive furnace oil and the older transmission network. Also the month of May, June, July and August are extremely hot in Pakistan. At, 28 June 2015, a great heat stroke and the heat wave killed 1200 people in the city of Karachi. Nearly 67,000 heatstroke patients were treated in different hospitals of Karachi (www.aljazeera.com) during heat wave in that summer. In the summer season, there is a huge energy shortfall in Pakistan so there is an emergency need to bridge up the energy crises in summer in Karachi city to arrest this problem. Pakistan is a rich country in geographic aspects and the wind blows 24 hour in many areas of the country. Pakistan wind energy production capacity is 5 MW/km^2in windy areas [50]. Wind measurement data of southern areas of Pakistan has been analyzed form 47 towers at a height of 30 m and 50m because southern areas of Pakistan consist of mountains.

Table1: Wind energy capacity as per guideline of National Renewable Energy Laboratory (NREL)

Class	Wind power (w/m^2)	Speed (m/s)	Area (Km^2)	Windy area	Electricity capacity (MW)
7	>800	>8.6	796	0.1%	3980
6	600-800	7.8-8.6	2388	0.3%	11940
5	500-600	7.4-7.8	3980	0.5%	19900
4	400-500	6.9-7.6	16718	2.1%	83590

USAID Wind Resource Assessment and mapping for Afghanistan and Paksitan (2006)

According to area wise capacity of wind electricity production, Pakistan has been classified as a different wind characteristics and the availability of wind in the country. Table 1 shows that, Pakistan land is 803,950 km^2 and 3% of the total land is 24hour wind availability of excess wind speed and other wind characteristics so the total capacity of wind electricity generation is 1,19,410 MW and total demand is 21,153MW.

5.Results and discussions

5.1Wind characteristics for hydrogen production

From table 2 the annual average wind speed is 6.4 m/s at 50-meter height. The highest wind speed 8.6 m/s is observed in June and the average wind speed is more than 5 m/s. According to wind frequency distribution records (WFDR), during 76% of the time the average wind speed is 5.1 m/s or above. Baghan's annual power density is 276.3 W/m^2. Annual power production with a 600-kW wind turbine is1.2 million kWh. It shows that the capacity factor of Baghan is 23% which is internationally considered suitable for wind power project installation. The annual average wind speed (table.2) DHA Karachi is 5.9 m/s at 50-meter height. During March and September average wind speed is more than 5 m/s and the highest wind speed is 9.1 m/s in July. Annually wind variation records shows that the maximum wind speed is available in the evening times.

Table.2: Wind characteristics

Month	u(m/s)				C (m/s)				K				ρ (w/m^2)				C_f (%)				Re ~ MWh			
	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4
May	7.9	7.4	7.7	9.3	8.9	8.4	8.7	10.4	2.7	3.3	2.7	2.5	458.3	346.4	428.4	772.8	0.36	0.31	0.34	0.47	160	139	152	209
June	8.6	7.7	9.1	10.6	9.7	8.7	10	11.2	2.6	3.0	2.8	2.3	616.8	404.5	683.5	1028	0.42	0.34	0.46	0.50	180	147	199	218
July	8.3	9.0	8.5	10.4	9.4	10.	9.4	11.3	2.6	3.4	2.5	2.5	549.6	620.3	560.3	981.3	0.40	0.47	0.39	0.53	180	209	176	235
Aug	8.4	8.1	7.5	9.7	9.4	9.1	8.7	10.5	2.9	3.2	2.9	2.5	515.9	447.6	404.5	784.3	0.40	0.38	0.34	0.47	180	168	151	212

While S_1 stand for Baghan site, S_2 for DHA Karachi, S_3 for Golarchi and S_4 stands for Nooriabad site. R_e is renewable electricity production at any site. $C_f$is capacity factor and its measured in percentage. $\rho$is density of the wind. R_e is measured in (W/m^2). According to WFDR, during 73% of the time the average wind speed is 5 m/s or above. DHA Karachi annual power density is 241 W/m^2. It shows that the capacity factor of DHA Karachi is 21% which is internationally accepted for the wind power project installation. Golarchi annual average (Table2) wind speed is 6.4 m/s at 50-meter height. Except March and October, the average wind speed is more than 5 m/s and the highest wind speed is 9.2 m/s in June. According to WFDR, during 78% of the time the average wind speed is 5.1 m/s or above. Golarchi annual power density is 283.4 W/m^2 and the capacity factor of Golarchi is 23% which is internationally accepted for wind power project installation. The annual average (table2) wind speed is 7.0 m/s at 50-meter height at Nooriabad. From March to September the highest wind speed 10.6 m/s is observed in June and the average wind speed is more than 5 m/s. According to WFDR, during 79% of the time the average wind speed is 5.1 m/s or above. Nooriabad annual power density is 455.3 W/m^2. Annual power production with a 600 KW wind turbine produces 1.5 million kWh. It shows that the capacity factor of Nooriabad is 29% which is internationally accepted for wind power project installation.

Excess flow of wind is necessary to produce electricity which is further required to produce hydrogen. Hydrogen via wind energy in four proposed sites of Pakistan can fuel 10545 cars annually by using the wind turbines of high quality models. Further, the atomic weight of hydrogen is 1as it is a light element but in liquid form, having a density of 0.04 g/cm^3. Comparing the two energy sources gasoline and hydrogen, a 25 kg of gasoline is equal to 9.5 kg of hydrogen. A 25 kg of gasoline can be stored in a 14 kg tank but 25 kg hydrogen storage requires the tank of 145 kg mass. The reason is that volume of gasoline fuel is 4 times smaller than hydrogen fuels. As a result, we conclude that hydrogen fuel efficiency is 1.33 better than gasoline fuel for automobiles.

Table 3: The summary of average Wind speed, C, K, C_f, H2 production and power density

Sites	u (m/s)	c (m/s)	K	ρ (w/m^2)	C_f	H_2 (kg/day)
Baghan	8.30	09.35	2.70	535.12	0.40	2519
DHA K	8.60	09.10	3.23	454.70	0.39	2404
Golarchi	8.20	09.28	2.73	520.00	0.40	2460
Nooriabad	10.0	10.80	2.45	891.60	0.50	3162

Different size wind turbines of the larger diameter rotors could be used to produce the maximum hydrogen energy in Pakistan. Nooriabad has (table.3) 3162 kg/day potential of hydrogen production because the average capacity factor at Nooriabad is 0.50 in the summer season. As per NREL guideline a 0.25 capacity in factor is enough to install a wind project. This suggests that DHA Karachi would have a minimal potential of hydrogen production since its capacity factor is 0.39 in the summer season. But still this site meets the requirements of capacity factor given by NERL guidelines for wind power project installation.

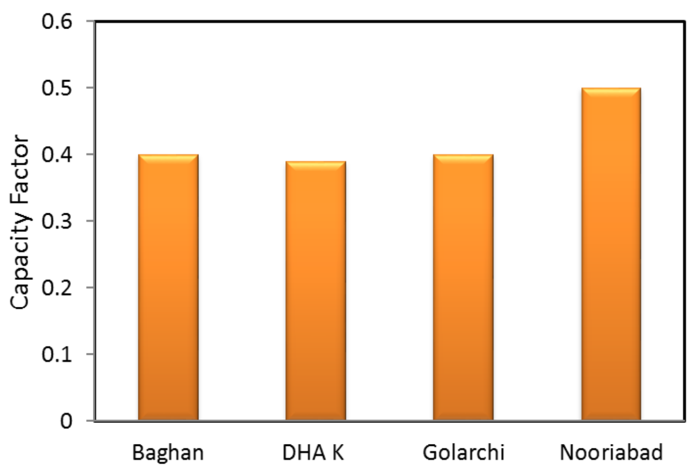

Figure 2. Capacity factor of the sites

Fig.2 shows that capacity factor of each site is greater than 0.25 which are suitable for the wind power project.

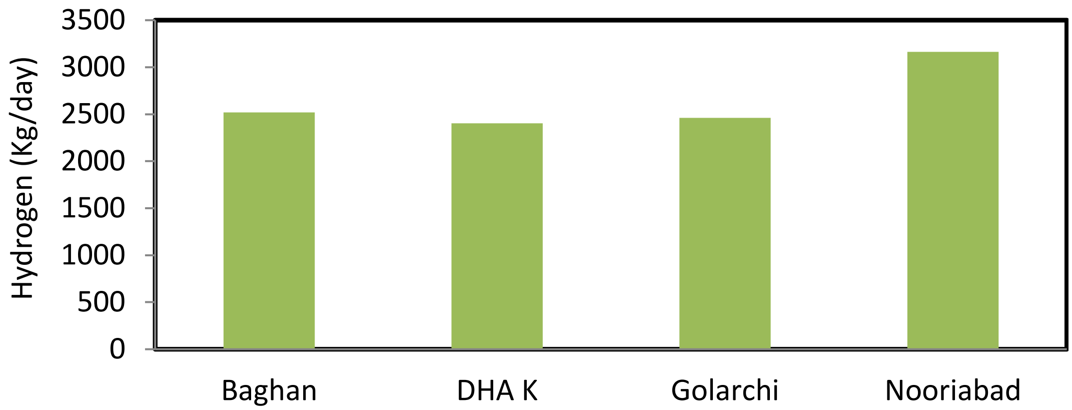

Figure.3 Hydrogen production of proposed sites

If the Pakistani Government makes the decision to install wind hydrogen projects, there is a better opportunity to overcome the electricity shortage especially in the summer season. Using the wind-generated electricity at 4 sites 10,545 kg/day hydrogen can be produced. Further, the total capacity of Wind generated electricity in Pakistan is 1,19,410 MW which can produce 51917.39×10^3 kg/day of hydrogen annually, which is a cheap, clean and safe way to flee the cars and other vehicles in Pakistan. The transportation oil consumption can be used to produce electricity to reduce power shortage.

Hydrogen energy can be used to reduce the use of gasoline fuel and CO_2 emission of road transportation. The stored form of hydrogen can be used as renewable fuel and carbon free electricity production at specific areas. Hydrogen energy can be used in chemical industrial process for manufacturing and other purpose, for instance in mixtures of methane (CH_4) used in auto gasoline. It can also be used for heating and cooking purposes. In addition, it may be used as a hydrocarbon fuel or other synthetic fuel protection, but these options are not discussed because our focus was to provide wind generated hydrogen fuel to decrease the burden of oil so that oil should be consumed to produce electricity in time of emergency. The ultimate objective is to reduce the power shortage during the summer season especially during heat waves. The road transport sector is another concerning issue addressed here.

5.2 Calculation of Renewable Generation cost

Economic analysis is carried out by assuming the operating and maintenance cost as 25% of the annual investment cost of wind turbine (lifetime/machine price). The interest rate and inflation rates are 12.63 and 6.9 respectively while wind turbine machine life has been considered as 20 years. The installation and civil work cost is 4% of investment cost and miscellaneous cost is 10% of investment cost while the battery cost is taken as 9% of investment cost. Inverter cost is taken as 4% of the investment cost of the wind turbine project. We measure the unit cost of electricity generation with the help of the equation (24) by each site and wind turbine cu C ($/kWh). The economic and technical consideration used for renewable hydrogen production consists of the capital expenses intended for the system is about $402 and annualized the capital expenditure of $36.8 yr. To maintain a renewable hydrogen conversion system the total raw material and operating cost are $710,000/yr and $283,000/yr respectively, and the credits reaches about $20 M/yr. Evaluation of technical characteristics of wind and electricity generation vary from sites to sites. It is assumed that in our study the average wind speed is 8.20 m/s to 10.0 m/s and the capacity factor of electricity generation is 0.40 at three sites while at Nooriabad sites the capacity factor is 0.50. From the table 6 it is clear that the Nooriabad site has maximum capacity factor 0.50 and cost is $0.0868 ($/kWh). Rest of the sites have the average capacity factor of 0.40 (DHA K capacity factor is 0.39) and average cost is $0.0864 ($/kWh). In Pakistan, electricity price per unit and tariffs vary from states to states with respect to consuming purpose, so overall price changes at the final supply stage is with the given proposed sites.

Table.4: Price of renewable energy

Sites	**Price in $**
Price of electricity at Baghan site	$0.0864/kWh
Price of electricity at DHA K site	$0.0868/kWh
Price of electricity at Golarchi site	$0.0862/kWh
Price of electricity at Nooriabad site	$0.0868/kWh
Price of hydrogen at all sites	$4.304/kg-$H_2$
Supply price of hydrogen at all sites	$5.30-$5.80/kg

Other sites : DHA Karachi, Baghan and Golarchi

The water and electricity requirements for 1 kg of the renewable hydrogen generation are and 10.6 kg and 53.4 kWh respectively. Further assumptions are that the capital cost of renewable hydrogen production per hour is $2.2 that includes direct and indirect costs and the operating cost is $0.027/kg of renewable hydrogen production. The leveled water supplying cost is assumed (Table 4) about $4.1/tons of water for simplicity of calculations that does not consider the extra cost of storing water due to the low coupled cost. To repay the capital cost, the interest rate is assumed to be 10% in Pakistan and the project life time has been considered as 20 years. Therefore, the capital charge factor is 0.10 and 0.115 for the electrolysis system. Further, the selling price of oxygen is assumed to be $61/ton and $ 0.06/kWh. Capital cost electricity production is 87%, hydrogen production is 8% and hydrogen storage cost is 5% while operating wind turbine, configuration cost is 51%, gasification cost is 7%, electrolysis cost is 1%, storage operation cost is 10%, raw material cost is 10% and water supply cost is 20%. The revenue, the hydrogen supply cost, and the breakdown of capital and operating costs shows that the renewable electricity production coordination is the main capital cost component of the production of renewable hydrogen energy. This cost structure is due to the substantial cost of the wind turbine configuration for renewable hydrogen. The total capital cost can be decreased if the wind turbine configuration cost per unit cost is lower or the lower cost of raw material. It is because in the electrolysis process the purchase of raw material is the second highest contributor cost in this process system. Economic integration of renewable hydrogen shows the production cost of renewable hydrogen is $4.304/kg while its supply cost varies from to $5.30/kg to $5.80/kg while the supply cost of renewable hydrogen increased due to supply cost. Renewable hydrogen production and supply cost of renewable hydrogen depends upon the quality of wind turbine configuration, alkaline electrolyzer. Efficiency of the electrolysis process ranges from 56% to 75%. Electrolysis electricity consumption per kilogram of hydrogen production is 52.5 to 53.4 kWh. For production of 1000 kg/day, a unit of 2.3 MW or 20 GWh electricity is annually required. However, the price of electricity and hydrogen can vary during the other months of year due to different wind speed and different capacity factor.

6. Conclusion and policy implication

Economic viability, wind characteristics of different sites and wind energy utilization has been investigated to assess the wind power potential for renewable hydrogen production. For this objective a scientific and methodological assessment of wind characteristics have been studied. Summary of wind power potentiality of renewable hydrogen production from the wind-generated electricity in the region of Karachi (Pakistan) has been investigated. The sites of Baghan, Nooriabad, Golarchi and DHA Karachi have been studied where the data of the metrological department of Pakistan is available. Results reveals that all of the sites are commercially viable for renewable hydrogen production. Hydrogen production depends upon the wind speed, air density, the size of the wind turbine and efficiency of the electrolyzer system. The results reveal that using the wind generated electricity at 4 sites, 10,545 kg/day hydrogen can be produced while the hydrogen production in summer season can be optimized up to 51917.39×10^3 kg/day of hydrogen annually by using 660 kW wind turbines. Moreover, this production can be improved by increasing the efficiency of electrolyzer system. Further, the economics of cost for renewable hydrogen shows the production cost of renewable hydrogen is \$4.304/kg while its supply cost varies from to \$5.30/kg to \$5.80/kg-H_2. For renewable hydrogen production from the wind-generated electricity, it is necessary to pick optimal wind site by using the most accurate methodology like adopted in this study. Renewable hydrogen can contribute to reduce electricity shortage.

To address energy crises and climate change concerns, Pakistan should align itself with Renewable Portfolio Standard (RPS) similar to developed economies. The policies of developed economies encourage the renewable hydrogen utilization. For example, currently numerous hydrogen stations are operating in the Düsseldorf city of Germany. Japan has also opened five public hydrogen stations at Nagoya, Toyota, Saga, Fukuoka and Kobe. In contrary, the present energy policy of Pakistan does not encourage utilization of hydrogen energy produced using RE technologies. The present energy resources dominated by thermal power stations increase the CO_2 emission and it might reach 55.2 million metric tons by 2030 from 22.2 million metric tons in 2012. Therefore, the policies should be revised to adapt RE technologies while taking measures to deal with less dependency of imported oil, its threats of supply disruption, price fluctuation and fuel storage. . RE development will not only cater to the modern industrial needs but also supply to rural areas (71% population lives in rural areas). The following guidelines could be considered for developing a robust and effective renewable energy policy;

i. Renewable energy technologies (RETs) deployment should increase in Pakistan so that RE can provide larger (minimum 9700 MW by 2030) proportion in total energy mix.

ii. Entice foreign direct investment in RE sector by introducing and facilitating renewable energy markets to promote the competition for lower prices of RE.

iii. Feed-in-tariffs should be made ease for individual and private energy generation.

iv. RE deployment impact should be optimized in rural areas by assimilating power provision with other societal infrastructure, e.g., sanitation and water supply, medical and educational facilities, telecommunications and roads to endorse the productivity, trade, social welfare and economic well-being.

v. Facilitate and help the technical, institutional and operational capacity to establish the domestic RE to improve the technical skills.

vi. The cars and other transportation could be fueled via renewable hydrogen so that the fossil flues demand should be cut down. In addition, the usage of hydrogen should be ensured in light of Paris agreement.

vii. Decentralized RE production can decrease distributional line losses and theft amounting to 22%. Therefore, the policy should encourage the hybrid and multi grid systems.

The study can be extended to add storage features and to measure the cost of storage of renewable hydrogen. This study can also be extend by increasing the fidelity of the analysis. To address the issue of renewable hydrogen production with minimum availability of wind at windy site may attract researcher for future work.

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