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RESEARCH ARTICLE

Managerial policy and economic analysis of wind-generated renewable hydrogen for light-duty vehicles: Green solution of energy crises

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Abstract

The unconventional energy sources like hydrogen energy have tremendous potential of filling the gap between economic growth and clean energy consumption. A little intention has been made in this regard in the developing economies like Pakistan. This study develops a fusibility analysis to highlight the potential of hydrogen energy source in Pakistan. For this purpose, this study used a hybrid mathematical model that combines the range of wind speed with the log law to push wind power's potential to generate wind hydrogen in Pakistan. The study results indicate that Pakistan has an excellent source to generate hydrogen energy through wind power stations. According to the outcomes, Nooriabad can produce 303.66 million RE/kWh per year through wind energy sources. According to the results, the rest of the seven wind generation sites also can generate enough hydrogen energy. This study also concluded that hydrogen energy has enough sources to meet the demand for light-duty vehicles in Pakistan.

Keywords Energy security · Energy crises · Energy policy · Economic viability · Renewable hydrogen

Introduction

Energy demand for economic growth and carbon emission as a by-product is the leading issue faced by developing economies. Although the developed world is spending money and time replacing dirty fossil fuel–based energy sources, the developing economies face problems maintaining the balance between economic growth and clean energy sources to protect environmental conditions.

The term "climate change" is the topic of concern for political and scientific discussions worldwide. Since the beginning of creation, the climate has changed, but the speed of change is alarming, and it could be a threat that is currently faced by the world. In the last three decades, the carbon dioxide growth rate grew by about 1.4 ppm annually before 1995 and by about 2.0 ppm annually. The Framework Convention of the United Nations Climate Change explains that climate change indirectly or directly ascribed to human activities that

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change the global environment composition which, in turn, show natural variability over time (Shami et al. 2016). Over a decade of increase in global fossil fuel use to dominate the energy supplies lead to rapid growth in carbon dioxide emissions (Sun et al. 2020c) (Sun et al. 2020d) and (Sun et al. 2019) and (Sun et al. 2020a). The aim of reducing global warming to less than 2 °C was a significant focus of international climate discussion. Data from the end of 2016 confirmed that most of the global emission of anthropogenic greenhouse gas (GHG) accounts for the fossil fuel consumption, and levels are above 390 ppm (39) above pre-industrial levels.

Renewable technologies are thus clean sources of energy; the optimal usage of these resources reduces the environment's impact, produces secondary waste minimal, and, based on future and current social and economic needs, is sustainable. Therefore, an opportunity offered by renewable energy technology innovation leads to the reduction in greenhouse gas emissions and global warming through the substitution of conventional (fossil fuel) energy sources. The sustainable development goals (cost-efficient and clean energy) have been designed to ensure that energy is clean, accessible to everyone, and cost-effective and can attain globally distributed renewable energy sources (Higuita Cano et al. 2017; Sun et al. 2020b; Mohsin et al. 2018b, 2019a).

Environmental issues have become important factors that hamper society and the economy's sustainable development. In November 2013, several issues, including the Durban Platform, the Green Gas Reduction Mechanism, the Green Climate Fund, and the Warsaw International Damage Control Mechanism, were reached after lengthy negotiations and discussions between the relevant government departments of different countries in Warsaw, Poland. These agreements have been designed to reduce environmental losses. Each country's citizens also take a more remarkable account of environmental issues and have a growing impact on environmental management decision-making. International scholars consensus on the need for an environmental performance assessment in the sustainability measurement process (Le and Chang 2015). Various studies emphasize on the combination of energy and economic and environmental concerns, such as Anser et al. (2020) and Mohsin et al. (2019c), Mohsin et al. (2020a), Iram et al. (2019), and Baloch et al. (2020).

This study analyzes renewable hydrogen generation's technological assessment by wind power at various wind farms in Sindh, Pakistan. In contrast to other studies, the modified mathematical modeling tools, such as the combination of Weibull and log law, analyze the generation of renewable hydrogen energy through wind power. Also, the costs of leveled wind energy are calculated for measuring the production cost of hydrogen. This study can be generalized for the possible way out to produce hydrogen energy for light-duty vehicles via wind energy resources due to this extensive feasibility analysis.

The rest of the study distribute as follows. The next section explains the importance of renewable hydrogen energy for Pakistan. The literature review presents in the third section, while the data and methodology are explained in fourth section. The fifth section discusses the results, and the last section provides the conclusion and policy recommendations.

The importance of renewable hydrogen energy for Pakistan

Developing and developed countries are adopting many mitigating strategies to reduce the global warming effects, significantly reducing the carbon dioxide emissions as the environmental degradation is mainly due to primary anthropogenic substances (Pulido-Fernández et al. 2019). For Pakistan, this is even more important as it is the 12th most vulnerable country in the world (Adnan et al. 2018). In addition to that, Pakistan has been added in the country-by-country climatic risk list also. Only a single earthquake of 2005 caused more than six million USD, which accounted for 1.1% of the total GDP (Shafique et al. 2016; Mohsin et al. 2020b, and Mohsin et al. 2019b).

The negative impact of climate change could be severe for emerging economies like Pakistan, the world's 6th populated economy. The areas such as Jamshoro, Hyderabad, Sukkur Karachi, and the coastal parts of the country (e.g., Badin) are already suffering climate change issues such as hotter summers, coastal storms, rising sea levels, unpredictable floods, livestock, human displacement, and unprecedented rainfall (Iqbal et al. 2020; Asbahi et al. 2019).

The growing population, industrial revolution, and demand for improved living standards required a higher per capita energy consumption level. However, there are limited natural resource sources, scarcity of high technology for renewable innovations in energy, and inadequate energy policies, especially in the developing world, causing hurdles to find sustainable economic and energy growth. Due to high energy prices, the production cost also suppresses developing economies in their export and forces them to rely heavily on import-based consumption. For example, approximately 140 million Pakistanis suffer from 6–9 h of daily power shortage, without access to the country's power grid, resulting in 2.3 billion dollars annual expenditure on candle and kerosene, purchased from the international market (Mohsin et al. 2020b). There are little understanding and attention that has been paid to renewable energy production, potential greenhouse gases (GHGs) emission, and the ability to produce wind energy in developing economies like Pakistan. More significantly, by 2060, renewable hydrogen energy will gradually fall to zero carbon dioxide, nitrogen dioxide, and other hazardous emissions from fossil energy in Brazil. However, Catapano et al. (2016) used the life cycle analytical method to announce

Table 1 Light-duty vehicle hydrogen demand and potential production

Province	Punjab	Sindh	KPK	Baluchistan	Total
Light-duty vehicles (in number)	1,932,280	4,682,392	35,148	193,393	6843213
Light-duty vehicle H_2 demand (kg/annually)	187,431,160	454,192,024	3,409,356	18,759,121	663,791,661

lead-acid batteries' superiority over hydrogen storage systems regarding energy costs and GHG emissions minimization. Therefore, it is worthwhile to quantify and assess the potential environmental and economic benefits of producing renewable hydrogen from wind energy. The issue of climate change is closely related to vehicle production and consumption. The light-duty vehicle is one of the leading sources of CO_2 due to fossil fuel energy consumption and low maintenance in the developing economies like Pakistan.

According to Table 1, nearly 6.84 million light-duty vehicles are running across Pakistan, out of which 4.68 million vehicles in Sindh province, followed by Punjab (1.93 million). The demand for H_2 is 663.79 million kg annually, out of which 454.19 million in Sindh province and 187.43 million kg in Punjab) (Table 2).

The gasoline consumption in Pakistan is nearly 14.6 billion gallons per year, out of which 6.92 billion used in Punjab while 4.89 billion in Sindh province. The demand for H_2 is more than 4.88 billion kg annually. The most significant share comes from Punjab, followed by Sindh province.

Literature review

Hydrogen is described as a potent energy carrier, so it is a perfect element of meeting global energy demands and, more importantly, for reducing GHG emissions as an international trend has been made towards the carbon-free environment as laid down in the Paris Agreement (Sun et al. 2018). Hydrogen gas is not available as a natural source, like other sources of oil and natural gas. Therefore, hydrogen can be extracted from natural resources, in particular from biomass, coal (Dufour et al. 2009), water, (Acar and Dincer 2014), and biological and methane sources (Uusitalo et al. 2017). The energy spent must be available at a continuous rate so that the hydrogen can be extracted from those existing sources. However, applications of fuel cell power developed are expensive. Therefore, further research and development will help to produce a cost-effective range of hydrogen fuel cell appliances. Thus, it expects that it would take over the existing petroleum vehicles as fossil fuels will deplete. A work by Rodionova et al. (2017) focused on molecular hydrogen production by the culture of the photosynthetic microorganism, a promising approach to producing renewable hydrogen energy. Researchers claimed that renewable hydrogen production through photosynthesis would lead to no emission of dangerous GHGs and pollutants.

Different sources, such as solar, wind, biomass, palm oil, and geothermal, can produce hydrogen (Shuit et al. 2009). However, the cleanest and most straightforward approach is to produce hydrogen via wind. The production of hydrogen is currently used for low GHG emissions by using wind power in the electrolysis process. Furthermore, all wind energy–based renewable energy sources have the lowest cost per kWh (Uyar and Beşikci 2017). A study by (Mohsin et al. 2018a) claimed that the use of wind energy for hydrogen generation at a local level is a primary energy carrier, which has a significant role in shifting transport from fossil fuel to renewable fuels.

A study by Pelaez-Samaniego et al. (2014) is focused on the wind generation's viability, wind hydrogen, and deal price results. The sensitivity analysis showed that the prices of the diesel were less than or equal to US$ 0.73. It favored wind or hydro-producing battery systems, while diesel prices are from US$ 0.74 to $1.08. Moreover, Samsatli and Samsatli (2019) hypothesized that wind-generated renewable hydrogen output results from the reduced reliance on fossil fuels by electrolyzing water without carbon dioxide emission or other hazardous gas indicators of an optimum energy mix. The study focused on meeting the growing demand for energy for long-term transport (He et al. 2020). There is a growing concern about the increase in global energy consumption, rising energy costs, and concerns about energy supply, climate change, energy security, climate change, and air pollution at the local level. Therefore, Brazil's energy requirement was examined, and it reported that renewable hydrogen would contribute reduce energy and carbon emissions (Martín 2016).

Hydrogen gas is not a natural energy source, like other energy sources, such as natural gas and oil. Thus, hydrogen extraction is not done from a natural resource, particularly biological sources, methane, biomass, coal, and water. Consequently, a new methodological evaluation initiative to

Table 2 Gasoline consumption and hydrogen demand

Province	Punjab	Sindh	KPK	Baluchistan	Total
Gasoline consumption (in billion gallons)	6.92	4.89	1.90	0.89	14.6
H_2 demand (in billion kg)	2.31	1.63	0.64	0.30	4.88

improve energy security lowers carbon emission levels in the area, including off-grid and remote wind-powered renewable hydrogen.

Data and methodology

Data

Pakistan has an area of 796,096 km^2, out of which 770,875 km^2 without water. Pakistan has sufficient areas having a constant speed of the wind. The conventional estimates suggest that the total installed capacity in the country to per kilometer square of wind power is 5 MW to evaluate the wind power potential (Aized et al. 2018).

Table 3 shows the overall resources of wind potential in numerical terms. It clarified that about 3.5% of the total area has a class 4 or higher wind power production with cost-effectiveness wind energy production. Findings indicate that over nine percent of Pakistan's land is ideal for utility-scale wind turbines. Consequently, wind energy's total output capacity is around 349 GW (Valasai et al. 2017).

In addition to the wind energy potential available on-shore, Pakistan has good wind resources potential on coastal sides. It can help achieve a significant share in the generation of electricity. Furthermore, in Pakistan, air pollution can be minimized by harnessing offshore resources. Around the globe, hydrogen chemical is present in a significant amount and constitutes about 75% of the mass among the earth elements (Nabgan et al. 2017).

The hydrogen used to produce a cleaner energy source provides several benefits, such as the carrier of clean energy. At the stage of final use, hydrogen is emission-free. Resultantly, hydrogen evades the production of air pollution and CO2 emission by transport.

The wind power system to generate hydrogen

For the simulation of wind speed, different density functions are applied. However, a Weibull distribution is a standard method accepted and used in a probability distribution, mainly due to its capability to fit extensive data input (Dabbaghiyan et al. 2016). The Weibull $f(v)$ probability distribution for the evaluation of wind characteristics defines the frequency of wind speed expressed as follows:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where v is the wind speed at m/s and k and c are the sizzling outline and size dimensions. k is the form factor causing wind capacity and optimum transmission, whereas c is the level factor explaining the site's windy situation (Fazelpour et al. 2017).

The standard deviation (σ) and mean wind speed v are determined with the following relations:

$$\sigma_v = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(v-\overline{v}\right)^2} \tag{2}$$

$$\overline{v} = \frac{1}{N}\sum_{\mathrm{i}=1}^{N} v_{\mathrm{i}} \tag{3}$$

The n is the hourly wind velocity quantities during the time of review, the wind velocity value (v_{i}) is the wind velocity value, and σ_v is the density of wind speed according to the month it ensues (v_{i}). This experiment used the moment method (Justus et al. 1978). The regression coefficient of wind speed is v, and the standard deviation is σ to determine Weibull c and k distribution factors. It is understood that the wind flow is at velocity V, and then it swings through blades A and increases with the velocity cube. The following equation is used for expressing the power density (St. Pé et al. 2018):

$$\mathrm{P_w(v)} = \frac{1}{2}\mathrm{A}\ \rho\overline{\mathrm{v}}^3 \tag{4}$$

A probability density function of Weibull is used for average air density of sites and explained as:

$$\overline{\mathrm{P}}_{\mathrm{w}} = \frac{1}{2}\rho\overline{\mathrm{v}}^3 \frac{(1+3/\mathrm{k})}{[(1+3/\mathrm{k})]^3} \tag{5}$$

The air density size is determined at sea level of 1225 kg/m^3 at 15 °C and 1 atm (Wiser 2012).

Table 3 Assessment of wind resources for Pakistan at a height of 50 m (Ali et al. 2018)

Wind class	Resource potential	Area of wind (km^2)	% of total area	Installable capacity (MW)
3	Moderate	43,266	5.62	216,326
4	Good	18,220	2.37	91,096
5	Excellent	5,321	0.70	26,601
6	Excellent	2,514	0.34	12,571
7	Excellent	546	0.08	2,724
Total		69,864	9.07	349,316

With the increase in hub height, the wind speed also increases, which defines a relationship between the hub's wind speed and height. In the wind turbine, the wind speed determines at different hub heights since this provides the best wind speed when the altitude is increased (Sempreviva et al. 2008).

$$\frac{v}{v_R} = log \frac{l_n\left(\frac{H}{H_\circ}\right)}{l_n(H_R/H_\circ)} \tag{6}$$

The H defines the height, v is the velocity of wind, and v_R is the speed of wind indication regarding height (H_R). Ho explains the length roughness and is related to the displacement height.

A significant indicator used for determining the wind turbine power output is a nameplate capacity (CF), which is determined by dividing the total energy to the maximum power. The capacity factor relies on the wind turbine to produce electricity, relying on the proposed location (Akdağ and Güler 2018). Here CF is defined as follows:

$$C_f = \frac{P_{out}}{P_r} \tag{7}$$

where P_{out} explains the mean of power output and P_r denoted as wind machine rated power. By using the Weibull density function, the value of the mean power output P_{out} is found by the following method:

$$P_{out} = \int_{v_{ci}}^{v_{co}} \rho v f(v) dv \tag{8}$$

where $f(v)$ explains the wind speed function and $v_{ci}$and $v_{co}$are the cut-in and cutout speed of wind, respectively; wind turbines' power curve is shown by ρv and the power generation (Pr) of the wind turbine shows the power curve by the following formula:

$$P_r = \frac{1}{2}\rho A C_P V^3 \tag{9}$$

The ability factor could be determined using the P_r value and of course P_{out} in Eqs. 6, 7, 8, 9, and 10.

$$C_f = \frac{P_{out}}{P_r} = \frac{\int_{v_{ci}}^{v_{co}} \rho v f(v) dv}{\frac{1}{2}\rho A C_P v^3} \tag{10}$$

The annual electricity production level can be determined by using a nominal turbine power and capacity factor from the given equation.

$$E_{out} = 8760 \times C_f \times P_r \tag{11}$$

The wind level attributed to the specific area depends on wind availability. Table 4 lists the groups of wind power, which are distinguished universally and their percentage of the total area of Pakistan.

Wind data speed explains that about 20% of the area has adequate wind "fair to excellent" for power generation; usually, a wind class level of 3 plus is appropriate. Table 4 explains that a wind class of 4 is very suitable for using technology. Moreover, for power generation at the economic level, wind turbines' response is positive, speeds more than 5.5m/s.

Hydrogen generation through electrolysis

Water electrolysis is explained as the H_2O (water) breakdown into O_2 (oxygen gas) and H_2 (hydrogen gas) because electric current passed via water, which is alternatively operated with PEM for greater efficiency and provides purity of gas (Boudries 2018). Using the electricity generation system through the watercourse, renewable hydrogen generates by using renewable wind electricity. Through the electrolysis of water, hydrogen generation is an excellent option for using renewable energy at an optimal level. Using electricity, the water electrolysis from renewable resources provides 80-90% efficacy by using different hydrogen production technologies. The following equation will explain the hydrogen output from renewable energy sources using wind energy (Gandía et al. 2007):

$$h = \frac{\eta_{el} E_{out}}{ec_{el}} \tag{12}$$

where h is the amount of hydrogen production; E_{out} is the input of wind electricity for hydrogen production through electrolyzer; η_{el} is the electrolysis efficacy process, which varies from 80 to 90% (Alavi et al. 2016); ec_{el} is the intake of the electrolyzer; and its worth remains between 5 and 6 (kWh/Nm^3). The decomposition of water (H_2O) to provide H_2 needs ΔH = 286 kJ mol-1(Dixon et al. 2016). An overall

Table 4 Electricity capacity and wind class at 50 m height (Gondal et al. 2018)

Wind class	Wind resource	Power of wind (W/m2)	Wind speed (ms-1)
6	Excellent	600–800	< 8.70
5	Good	500–600	7.80–8.70
4	Marginal	400–500	6.90–7.50
3	Moderate	300–400	6.20–6.99

chemical reaction of water electrolysis defines as:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{13}$$

At least 1.48 V (25C, 1 atm) is required for decomposition without heating (thermal-neutral), varying only by pressure and temperature. V_{TH}, TH-V is the thermo-neutral voltage that is clarified by the enthalpy change and the shift of reaction charges:

$$V_{TH} = \frac{\Delta H}{2F} \tag{14}$$

F is fixed for the molar load, and its quality is 69,486 (C mol-1). Electrolyzer voltage (V_{el}) can determine the electrolyzer process efficiency (η_{el}) in contrast to V_{TH} of n number of cells.

$$\eta_{el} \approx \frac{1.48n}{V_{el}} \tag{15}$$

Different loss mechanisms are generated by overvoltage, e.g., transmission-related electrochemical increase with the existing compactness. The electrolyzer process will be conducted at standard value and energy densities while linking wind turbines.

It also observed that the cell's complete reaction contains two half reactions. Typically, the EMF cell is a mixture of two quarter-cell potentials, oxidation voltage (E^o_{ox}), and reduction (E^o_{red}):

$$E^0_{cell} = E^0_{(ox)} + E^0_{(red)} \tag{16}$$

It is difficult to determine the capacity of two half cells, first to pick a typical hydrogen half-reaction as a reference and then to give a typical reduction potential of just 0,000 V.

$$2H^+_{(1M)} + 2e^- \ = H_{2(1atm)} \quad \left(E^o_{red} = 0.00V\right) \tag{17}$$

Let us focus again on the above-explained Daniell unit. The standard half-cell potential is:

$$\begin{aligned} &(\text{Anode}) \ Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^- \quad (oxidation) \ E^o_{Zn/Zn^{2+}} = 0.76V \\ &(\text{Cathode}) \ Cu^{2+} + 2e^- \rightarrow Cu_{(s)} (reduction) \ E_{Cu^{2+}/Cu} = 0.34V \end{aligned} \tag{18}$$

Therefore,

$$\begin{aligned} E^o_{cell} &= E^o_{(ox)} + E^o_{(red)} \\ E^o_{cell} &= 0.76 + 0.34V \\ E^o_{cell} &= 1.10V \end{aligned} \tag{19}$$

Wind power plant's investment cost

For different technologies, the tool used for unit cost over economic life is the levelized cost of electricity (LCOE). Moreover, for different technologies, the cost of generating electricity as benchmarking tool is a method of LCOE (Lai and McCulloch 2017). The calculation of LCOE is done by dividing the annual cost of energy generation by the annual energy generation (Al-Sharafi et al. 2017). The wind power economy is based on factors like cost of total investment, cost of operation and maintenance, production of electricity, selected site, and characteristics of the wind turbine. Site selection for a wind turbine between all the defined factors is to achieve economic viability. Various techniques are usually used for evaluating the per unit cost of operation for produced wind energy by conversion system of wind energy. This study measures the per unit cost (C_W), which is the ratio of the present value of total costs (PVC) to the total energy (E_{tot}) generated by the system.

$$C_W = \frac{PVC}{E_{tot}} \tag{20}$$

Cost of electrolysis for the wind power plant

Several studies proposed electrolyzer economic modeling, which has three main costs: maintenance, operating, and replacement costs. The electrolysis investment cost is dependent on the generation capacity of hydrogen. The electrolysis cell's investment depends on the capability of generating hydrogen. The electrolyzer's capital cost depends on the hydrogen production rate. At nominal production, an estimated per kWh cost of capital and the electrolyzer measures significant efficiency measurement:

$$C_{ele,\ u} = \frac{M_{H_2} K_{el,th}}{8760.f\eta_u} \tag{21}$$

$$C_{ele,\ u} = \frac{M_{H_2} K_{el,th}}{8760.f\eta_u} \tag{22}$$

where $C_{ele,\ u}$ is the unit cost of the electrolyzer, f is a factor of capacity, and $K_{el,\ th}$ is the electrolyzer's required energy. The electrolyzer's unit cost considers for reference, which is $368/kWh, which is following the target value.

To investigate the economic impact of chosen sites, it requires determining the operating costs. Different researchers in the previous studies used various techniques for calculating the per unit operating cost ($/kWh) (Enevoldsen et al. 2018). There is a need to calculate per unit of wind power generation cost. The vector must quantify unique specified power costs (C1) for a wind turbine, miscellaneous (C2), installation (C3), maintenance and service (C4), inverter (C5), and battery bank (C6) (Voormolen et al. 2016).

Here, variables from C1 to C4 could be combined to present value cost (PVC); on the other hand, for interest rate (r), cost of wind turbine maintenance and operation (Dolter and Rivers 2018), inflation rate (i), cost of turbine investment (I), scrap value (S), and a lifetime of the turbine (L), their value is measured as:

$$PVC = I + C_2\left(\frac{1+i}{r-1}\right)\left[1-\left(\frac{1+i}{1+r}\right)^L\right]-S\left(\frac{1+i}{1+r}\right)^L \quad (23)$$

Total wind energy (CT) costs can be determined by:

$$C_T = \mathrm{PVC} + C_5 + C_6 \quad (24)$$

Wind turbine maintenance and operational costs are typically 25% of the overall annual wind turbine investment cost, and the damp cost is considered at 10% of the overall annual investment cost (US Energy Information Administration 2015). Pakistan's interest and inflation levels are 6.9% and 12.63%, respectively. Refurbishment and contract administration expenditures measure at 4% of infrastructure costs. Investment cost (IC) could be measured by:

$$\mathrm{I_c} = \mathrm{C}_{\mathbf{ASPEC}} + \mathrm{P_r} \quad (25)$$

where $\mathrm{C}_{\mathbf{ASPEC}}$ is an average per unit cost kW, while $\mathrm{P_r}$ is the rated power cost of a wind turbine (Bangalore and Patriksson 2018). The wind turbine's rated cost and real cost are specific and described in Table 5. Per unit cost of (C_{cu}) the wind energy can be measured by (Table 6):

$$C_{\mathrm{cu}} == \mathrm{Total\ cost/Annual\ average\ yield} \quad (26)$$

Hydrogen development costs, CH_2, remains a significant metric to assess hydrogen output size and measure as:

$$\boldsymbol{C_{H_2}}\frac{\mathrm{C_W}+\mathrm{C_{ele}}}{\mathrm{M_{H_2}}.\mathrm{T}} \quad (27)$$

where $\mathrm{M_{H_2}}$ and $\mathrm{C_W}$ are the annual production of hydrogen and the cost of energy, respectively. $\mathrm{C_{ele}}$ is the capital. T is the project's lifetime and considered 20 years.

The emission emission is due to CO_2, SO_2, and NO_2 in recent publications, such as climate change, air pollution, human health, and energy efficiency. The US Environmental Protection Agency measures the carbon emission cost in US$ per ton:

Table 5 Nominal power-specific costs (per kW of a wind turbine)

Average (CASPEC) ($/kW)	Pt (kW)	CASPEC ($/kW)
2200–3000	< 20	2600
1775	20–200	1250–2300
700–1600	> 200	1150

$$\begin{aligned} &Emission\ Reduction = \frac{1}{N}\sum\nolimits_{n=1}^{N}\left(\frac{EPI_{RN}+EPI_{Wn}}{(1+i)_n}\right) \\ &PVEmission\ Reduction = \frac{1}{N}\sum\nolimits_{n=1}^{N}\left(\frac{EPI_{RN}+EPI_{Wn}}{(1+i)_n}\right) \end{aligned} \quad (28)$$

where pollution reduction is the average pollution reduction per year (ton/year), the number of the year is denoted as N, while i represents the discount rate. EPI_{Wn} is retention pollution 1 in 1 year under wind energy (tons), while EPI_{Rn} is the overall pollution matter 1 in 1 year under comparison (tons). Levelized costs are expected, including carbon costs, because carbon costs are not used to calculate the evaluated costs (Jayaraman et al. 2017).

Results and discussion

Analysis of renewable hydrogen generated from wind

The mean values of the shape parameter, wind speed, capacity factor, scale parameter, and power densities were studied for generating electricity. The amount of hydrogen is determined by the power produced for wind generators and its economic evaluation of hydrogen output.

Figure 1 presents the average monthly wind speed for the selected location. The highest mean wind speed for the station of Katti Bandar is found to be 10.20 m/s in July, while the lowest (4.90 m/s) in January. At Talhar station, the highest and lowest monthly wind speed observed were 2.70 m/s to 10.2 m/s in November and June, respectively. The lowest wind speed (3.8 m/s) is observed in Gharo wind station in November while the highest (9.4 m/s) was in May. The monthly mean value of wind speed in Jamshoro recorded 5 m/s in January and the highest (13.9 m/s) in July. The lowest monthly mean value (4.40 m/s) is recorded in December for Baghan, while the highest (8.6 m/s) was in June. The monthly wind range speed ranges between 9.5 and 4.5 m/s from December to January for the Golarchi location. Finally, at Nooriabad wind station, wind speed is recorded lowest at 4.2 m/s in October while the highest wind speed recorded is at 10.6 m/s in June.

According to the wind speed data observation, the wind speed's highest mean value remained between May and August. During this period, the summer season is observed at all places under study. From January to April and September to December, the mean of the speed is at the lowest. As the daytime length increases, the climate is hotter, and there is an increase in electricity demand during the summer. Thus, the peak electricity demand corresponds with the maximum wind speed for all stations included in the analysis

Figure 2 explains the annual mean value of wind speed in the selected cities. According to the results, Nooriabad holds the highest (9.8 m/s) annual mean value of wind

Table 6 Selected wind turbine specifications (Ashrafi et al. 2018)

Wind turbine model	Swept area (m2)	Rated power (kW)	Rotor diameter (m)	Hub height (m)	Cutout speed (m/s)	Cut-in speed (m/s)
GW-109/2500	9516	2500	109	50	25	3

speed, followed by Jamshoro (8.5 m/s) and Katti Bandar (7 m/s). The lowest annual mean station in this dataset is DHA Karachi (5.9 m/s). The rest of the stations hold approximately the same annual mean of wind speed ranging from 6.3 to 6.6 m/s.

Table 7 presents the results of annual Weibull shape parameters (k) and scale parameter (c) for the wind locations under study. Nooriabad has the highest annual average density (745.10 w/m^2) with a multiplier of 0.51 among the locations, widely agreed to integrate wind power plants. Baghan, Katti Bandar, and Talhar wind power stations have adequate wind energy in May, June, and August. From May to August, Gharo and DHA Karachi's power density is more than 400 W/m2, suitable for wind energy generation. Consequently, it presumes that specific locations selected for the experiment are appropriate for wind power generation.

Hydrogen production

The GW-109/2500 energy production is estimated through renewable source basis of Weibull data. Table 8 offers findings from the annual hydrogen output review for eight selected cities as below.

The annual hydrogen production ranges from 570,522 to 306890 kg/year and renewables from 16,380,040 to 303,660,120 kWh/year. The capacity factor range ranges from 0.25 to 0.50 in Table 8. Wind produces hydrogen from Nooriabad and Jamshoro at 569,522.8 kg/year and 420,090.1 kg/year. Sites like Gharo, Golarchi, Talhar, Karachi, and Baghan have the smallest hydrogen production.

Economic analysis

Equations 13, 14, and 27 are used for calculating the unit cost of electricity, total energy output, and the capacity factor based on the assumption given in Eq. 24, the infrastructure investment for power generation is $410, and the annual expenditure is $36.8. The average expense for hydrogen conversion treatment is $720,000 and $275,000, respectively. The highest capacity factor in Nooriabad is 51 and the other three locations, Gharo, Talhar, and Katti Bandar, are 0.27 on average. Power generation per unit costs range from $0.080/kWh to $0.083/kWh. Thus, the average price movements in the consumption purpose at the ultimate financial support rely on the proposed site.

Here 1kg generation of 1kg renewable hydrogen, the water, and electricity requirements are 10.5kg and 53.4 kWh. Moreover, it also assumed that generating renewable hydrogen includes operating, a direct and indirect cost, which is 0.27/kg. The leveled water supply cost believed at 4.1/ton of water (Chi and Yu 2018). Pakistan's interest rate stood at 10% to repay the capital cost, and the estimated life of the project is 25 years.

Finally, all the calculations show that the production cost of renewable hydrogen for the optimal and efficient system is between \$4.012/kg-H_2 and \$4.320/kg-H_2. The side of Nooriabad has the lowest hydrogen generation price of \$4.012/kg-H_2 due to the highest power factor. In comparison,

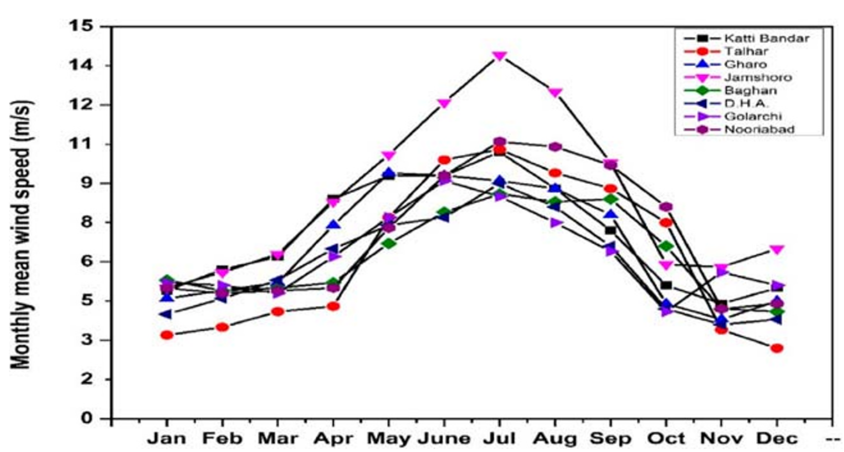
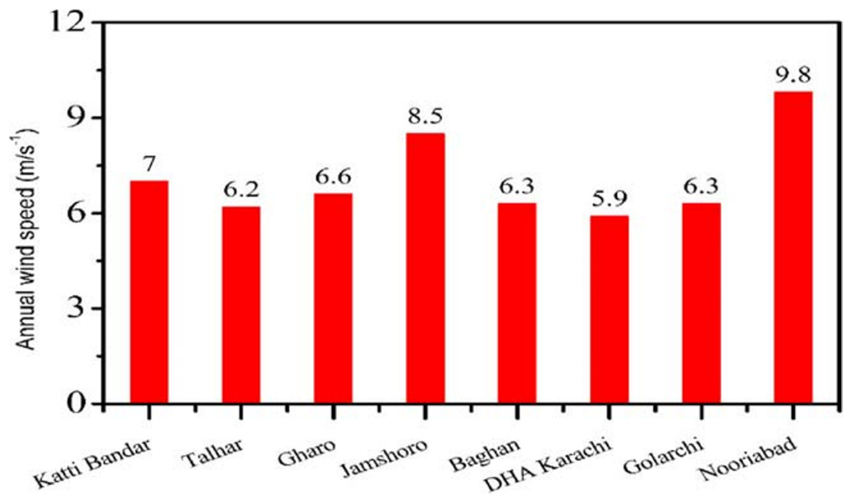


Fig. 1 Monthly mean wind speed (m/s)

Fig. 2 Mean annual wind speed (m/s)



Talhar has the highest hydrogen production price due to the lowest generating capacity shown in Table 8. The primary supply factor for renewable hydrogen is an annualized capital cost against the annual expenses like facility operation and raw material purchase. Prior studies show that enormous capital expenditure in renewable energy production is a significant obstruction to renewable energy. Moreover, for planning the excessive electricity, a realistic strategy is to adjust, plan, sell, and extend the market demand, which improves the development of renewable energy economics.

In this regard, a primary goal is to recognize the cost-efficient method for generating renewable hydrogen from electricity generation through the wind. The integration of hydrogen economic explains that the supply of hydrogen for hydrogen fluctuates from 4.90 to 5.10/kg. The hydrogen supply and hydrogen production cost depend on the wind turbine configuration and the alkaline electrolyzer quality. The electrolysis efficacy fluctuates from 56 to 75%, and the production of electricity per kg of hydrogen ranges from 52.4 to 53.5kWh, for producing 1000 kg/day. Annually, 20 GWh or 2.30 MW electricity is needed. At each point, some of the hydrogen energy production with the electricity is generated from wind (Table 9).

Discussion

According to the study results, Pakistan has sufficient hydrogen production resources by utilizing wind energy sources of a single province (Sindh). In this analysis of eight sites, Nooriabad can produce enough clean hydrogen due to high CF, low per kWh, and being one of the lowest H_2 price/kg-H2. This outcome supports the notion that Pakistan can produce renewable energy sources, especially from unconventional methods. All the under-consideration sites have a sufficient potential to be utilized for commercial purposes. The overall cost of producing hydrogen energy via wind energy sources is one of the cheapest regions, encouraging a large scale. The same results are also generated by He et al. (2020), Rauf et al. (2015), and Safari et al. (2018).

The potential of wind-generated hydrogen energy and the demand for energy for the light-duty vehicles are very compatible. Even a single province (Sindh) has enough to supply the light-duty vehicles' energy demand. It will save billions of dollars in the form of an energy import bill and help improve the carbon emission condition in the country as hydrogen energy can be the zero-emission source of energy. The source of wind-generated hydrogen

Table 7 Yearly average Weibull parameters, wind speed, and energy

Sites	V	C	K	P/A (w/m^2)	CF	RE kWh/year
Talhar	6.2	7.1	1.50	545.40	0.22	16,380,040
Katti Bandar	7.0	7.9	1.80	595.90	0.27	21,009,552
Baghan	6.3	7.1	2.10	575.90	0.44	20,705,733
Gharo	6.6	7.5	1.90	359.50	0.25	16,977,724
Nooriabad	9.8	10.9	1.7	745.10	0.51	30,360,119
Jamshoro	8.5	9.6	1.90	647.50	0.47	22,379,630
Golarchi	6.3	7.1	2.10	382.01	0.39	19,199,308
DHA Karachi	5.9	6.7	2.0	540.50	0.41	20,448,179

Table 8 Hydrogen production, renewable energy, and capacity factor

Sites	H_2-kg	RE/kWh	C.F
Talhar	306,892	16,380,040	0.22
Katti Bandar	393,437	21,009,552	0.27
Baghan	387,747	20,705,733	0.44
Gharo	317,934	16,977,724	0.25
Nooriabad	569,522	303,660,119	0.51
Jamshoro	420,090	22,379,630	0.47
Golarchi	359,537	19,199,308	0.25
DHA Karachi	382,924	20,448,179	0.41

Table 9 Electricity and clean hydrogen prices

Sites	C.F	Electricity ($/kWh)	H_2 Price/kg-H_2
Nooriabad	0.51	0.081	4.012
Katti Bandar	0.27	0.082	4.314
Golarchi	0.39	0.080	4.224
Talhar	0.22	0.083	4.320
DHA Karachi	0.41	0.081	4.223
Gharo	0.25	0.082	4.312
Baghan	0.44	0.082	4.219
Jamshoro	0.47	0.083	4.220

energy in the coastal area of Sindh province can enhance electricity production. It has a relatively low cost of producing per unit of electricity. During the hot season in the country, when the electricity demand increases a lot, the wind stations, as mentioned above, can generate electricity from April to August. The results of this study are also in line with Mohsin et al. (2020b) and Anser et al. (2020).

Fossil fuel imports are high in South Asia, making these economies vulnerable to "climate security," as most nations in the area are in constant shortages of energy. The shortage of fossil fuel in these countries is mostly due to heavy reliance on fossil fuel from external sources. Multiple oil shocks have been observed in the South Asian countries, which is considered a wrong signal for a healthy supply of energy in any of those countries. The growing demand for fossil fuel in the South Asian region makes the supply-demand curve unmatched of energy sources. Thus, South Asia's energy instability stems from resource shortages and increases the gap between energy supply and demand. There is a need by the South Asian region to fulfill the increasing demand of energy of the country and secure reasonable prices and sustainable sources. There is a significant imbalance in South Asia between supply and demand from sources of national energy, resulting in the country being heavily dependent on importing energy from external sources. Energy preservation and legacy differ between South Asian countries, but several primary energy sources deny in neighboring countries. It raises energy supply costs between countries and decreases the region's energy stability. Besides that, an energy trading system is deficient in this area, including several barriers to effective energy transmission. The region's energy trading system is a strategy to deal with energy shortages and improve energy protection (IEA PVPS 2015).

Conclusion and policy implication

In this analysis, a hybrid mathematical model established combines the range of wind speed with the log law to push wind power's potential of generating wind hydrogen in Pakistan. Wind energy's quantitative assessment deals with wind speed at a specific location. Thus, eight sites of Pakistan use it as an example for generalizing the results as it is challenging to analyze South Asia. From the study results, all the sites can produce a significant amount of hydrogen through wind energy.

The results include renewable hydrogen and wind, showing that switching from fossil fuel will increase the security of energy and provide the presence of clean energy in remote and rural areas for the long term. The areas included in this study have significant potential for producing renewable energy, which includes renewable hydrogen energy and wind energy. Moreover, renewable energy is of benefit to countries under the umbrella of the Paris agreement and Kyoto protocol to decrease global warming and harmful emissions. The analysis of different renewable energies explains that renewable energy adoption can enhance energy security in the region.

The government needs to adopt policies that help them save oil reserves, such as gasoline and petroleum. Oil supply risk is always there when a country is dependent on oil resources. New technology development, energy system optimization, and higher efficiency of energy can improve the cost of per-unit cost of energy. It can also help promote renewable energy and alternative energy sources, ultimately reducing oil consumption, which will resultantly decrease the dependency on oil and ultimately balance the supply and demand of oil.

This study is based on the dataset of eight sites of a developing country's province, as mentioned above. Therefore, it is not easy to forecast the country's capacity for hydrogen energy via wind source. Therefore, this study cannot forecast the economies of scale impact of the country's hydrogen energy source. This study has also not explained the impact of economies of scale on hydrogen energy per unit cost and overall emission condition of the county. This study can help the researcher and policymaker view the generalized impact of a country's or region's hydrogen energy production and its impact on emission and economy.

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Compliance with ethical standards

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