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Exploring the Feasibility of Green Hydrogen Production Using Wind Energy in India

Nagababu GARLAPATI[1*], Kunj PATEL[2], Yagna PATEL[3]

[1–3]*School of Technology, Pandit Deendayal Energy University, Gandhinagar, Gujarat, India*

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Abstract **– India heavily relies on coal for about 70 % of its energy demand, leading to a concerning 29 % increase in CO_2 emissions from 2015 to 2022. The need for alternate fuels is evident with rising energy demand and the rapid depletion of fossil fuels. Green hydrogen emerges as a solution, leveraging renewable energy sources to mitigate environmental impact. This study assesses five high-speed wind locations in India for green hydrogen production, analysing wind resource potential using six different wind turbine (WT) models. A comprehensive techno-economic analysis was conducted to evaluate the feasibility of hydrogen production, considering factors like annual energy production (AEP), hydrogen production, levelized cost of energy (LCOE), and levelized cost of hydrogen (LCOH). Furthermore, the study quantified the carbon emissions mitigated using wind energy for hydrogen production instead of conventional methods. Additionally, the study assessed the hydrogen storage capacity. Results indicated Mandvi (S2) as the most potential location, boasting a capacity factor of 50.51 % and AEP by WT4 of 13.273 GWh, yielding 221.21 tons of hydrogen annually. Cost analysis reveals an LCOE of 0.0225 \$/kWh and an LCOH of 2.3103 \$/kg. Furthermore, utilizing WT4 at the S2 location could mitigate 12.37 Mt/year of carbon emissions.**

Keywords **– CO_2 mitigation; green hydrogen; hydrogen storage; levelized cost of hydrogen; wind energy; wind turbines.**

Nomenclature		
Air density	ρ	kg/m^3
Annual energy production	*AEP*	kWh/year
Annual hydrogen production	*AHP*	kg
Capacity factor	*CF*	%
Cut-in wind speed	v_{ci}	m/s
Cut-out wind speed	v_{co}	m/s
Density of compressed hydrogen	σ_c	kg/m^3
Discount rate	*r*	%
Electrolyzer energy demand	$E_{electrolyzer}$	kWh/kg
Environmental cost	*ENV*	\$/kW
Gamma function	Γ	–
Hydrogen production	M_{H_2}	kg

* Corresponding author.
E-mail address: garlapatinagu@gmail.com

Instantaneous power output of the wind turbine at each hour *i*	P_{wi}	MW
Investment cost	C_i	\$/kw
Levelized cost of electricity	*LCOE*	\$/kwh
Levelized cost of hydrogen	*LCOH*	\$/kwh
Mean wind speed	v_m	m/s
Number of hours in period of time	*N*	–
Number of years	*t*	Years
Operation and maintenance cost	*OM*	\$/kw
Operational lifetime of electrolyser	t_e	Years
Project lifetime	*T*	Years
Rated power output of wind turbine	P_r	MW
Rated wind speed	V_r	m/s
Real interest rate	*f*	%
Reciprocating compressor efficiency	η_{comp}	%
Rectifier efficiency	$\eta_{converter}$	%
Replacement cost	*REP*	\$/kw
Shape factor	*k*	–
Size factor	*c*	m/s
Standard deviation of wind speed	σ	m/s
Technology degradation factor	*d*	%
Unit cost of electrolyser	C_u	\$/kw
Wind power density	*WPD*	W/m^2

1. INTRODUCTION

The 2023 Intergovernmental Panel on Climate Change (IPCC) report warns that ongoing high CO_2 emissions, primarily from fossil fuels, could lead to a 1.5 °C global temperature increase by 2050. India, ranking third in CO_2 emissions from fuel combustion, faces significant challenges due to its heavy reliance on coal for electricity production. Transitioning to non-fossil energy sources like hydrogen (H_2) could offer a promising solution, given its electrochemical conversion ability, high energy density, and lightweight nature, facilitating efficient energy transportation [1]. There are various methods to produce hydrogen gas, including fossil fuel reforming and non-fossil fuel techniques like thermolysis, pyrolysis, electrolysis, thermochemical water splitting and biomass gasification [2]. Among these, fossil fuel reforming is noted for its efficiency and cost-effectiveness, while the photonic process showed the lowest environmental impact in terms of global warming and acidification potentials [3]. India is overcoming the energy shortage, despite efforts being made the problems related to energy arises, there is 6.5 % growth in energy demand and it will increase in near future. As primary sources of energy in India are fossil fuel, natural gas and coal which are relatively less costly than renewable energy sources (RES) but their utilization is followed by CO_2 emissions which undermines the steps taken for climate change and CO_2 emissions [4]. Thus, it is necessary for India for to produce energy from alternative source of energy to meet the increasing demand of energy.

Numerous studies have been conducted worldwide to assess green hydrogen production. Table 1 provides an overview of literature reviews investigating hydrogen potential assessments across world.

TABLE 1. SUMMARY OF LITERATURE REVIEW

References	Location	Technical Assessment	Economical Assessment	Social Assessment	Environmental Assessment	GIS and MCDM	Hydrogen Production	Hydrogen storage	Carbon mitigation
[14]	Algeria	✓	✓		✓	✓	✓		
[6]	South Africa	✓	✓				✓	✓	
[7]	Morocco	✓	✓				✓		
[15]	Afghanistan	✓	✓			✓			
[16]	Iran	✓			✓	✓	✓		
[17]	Egypt	✓	✓		✓		✓		✓
[18]	Egypt	✓	✓	✓	✓				

The assessments encompass technical, economic, social, and environmental factors, as well as considerations such as geographical Information system (GIS), multi-criteria decision making (MCDM), hydrogen production, storage, and carbon mitigation strategies. In Rezaei *et al.* [5], the feasibility of producing green hydrogen using wind energy in different locations of Afghanistan was examined. Levelized cost of electricity (*LCOE*) and levelized cost of hydrogen (*LCOH*) were calculated under three study scenarios, considering the degradation parameter ranging from 0 to 0.04. Results showed that the Fayzabad region could generate most electricity using WES 100 general wind turbine, with electricity production costs ranging from 0.063 to 0.112 \$/kWh and *LCOH* ranging from 2.11 to 2.26 \$/kg. In another study Ayodele and Munda [6], the viability of hydrogen production from wind energy sources was investigated for 15 locations in South Africa. Economic viability and cost of hydrogen production were analysed for commercially available wind turbines at selected locations. The study revealed that the Napier region produced the most amount of hydrogen (226.82 tons) using a 4.5 MW turbine, with electricity generation costs ranging from 0.23 to 0.42 \$/kWh. Hydrogen production costs ranged from 1.4 to 6.16 \$/kg for large turbines and 5.93 to 157.22 \$/kg for small and medium turbines. Technical and economic assessment was conducted in [7] to produce green hydrogen in five Moroccan locations utilizing photovoltaic (PV) panels and wind turbines (WT). Dakhla and Laayoune were identified as the most suitable locations for hydrogen production, with the lowest *LCOH* of \$ 2.54/kg and Net Present Value (NPC) of about \$ 593.16 million. The study also emphasized the importance of selecting hydrogen buffer storage over batteries in renewable energy systems to achieve cost-effective operations [7]. Furthermore, in Djibouti, [8] conducted a techno-economic assessment, predicting substantial yearly hydrogen production potential alongside varying *LCOH* (\$1.79–\$3.38/kg H_2) and *LCOE* (6.94 to 13.30 US cents/kWh) values. Positive returns on investment were shown by the net present value (NPV) analysis, with an average payback duration of roughly 6.5 years and an annual return on investment (ROI) of at least 2 %. Nasser and Hassan [9] investigated green hydrogen production feasibility in Middle East and North Africa (MENA) region using renewable energy, employing solar and wind energies for water electrolysis. The study revealed Egypt and Saudi Arabia have the highest power density for both PV/H_2 and WT/H_2 systems. And also suggested that the WT/H_2 system is more efficient than the PV/H_2 system. Furthermore, Akdağ [10] conducted a comparative analysis of offshore and onshore wind energy for green hydrogen production, emphasizing regional preferences, particularly in the Edirne-Enez location. The study introduced a comprehensive 7-step model for hydrogen production, storage and transportation. Notably, the findings suggested a prospective decrease in the costs associated with hydrogen vehicles, thereby potentially fostering greater adoption of hydrogen as an energy source. Moreover, the study underscored existing challenges in leveraging RES for green hydrogen production, emphasizing the imperative to enhance cost-effectiveness through the reduction of expenses associated with technical components. Additionally, Karayel and Dincer [11] conducted a comparative aspects of green hydrogen production using offshore and onshore wind energy systems. Their study shed light on the prevalence of onshore wind energy in regions like Canada, attributed to constraints such as limited coastal access and political considerations. Specifically, Quebec, British Columbia, and Ontario were identified as favourable regions for onshore hydrogen production, while Quebec, British Columbia, and Nunavut emerged as prime locations for offshore hydrogen production. Safronova and Barisa [12] explored critical factors influencing the development of a hydrogen economy. Their findings emphasized the importance of political commitment, technological and economic feasibility, stakeholder collaboration, research and development (R&D) investment, social acceptance and robust policy frameworks in fostering hydrogen adoption. Mendrela [13] compared the hydrogen production using renewable and non-renewable energy sources based on their environmental efficiency. They introduced a new measure called thermos-ecological cost (TEC) for a more through comparison. Results showed that renewable energy systems with electrolysis had lower TEC values compared to fossil fuel systems.

Despite the increasing global interest in green hydrogen production, there is a notable research gap concerning its exploration in India. To address this gap, this study aims to assess the potential of five high-speed wind locations in India for green hydrogen production. The objectives include analysing the wind resource potential using six different wind turbine models, conducting a comprehensive techno-economic analysis, and evaluating factors such as annual energy production (AEP), hydrogen production, *LCOE*, *LCOH*, and carbon emissions mitigation. This research seeks to provide valuable insights into the feasibility and viability of harnessing wind energy for hydrogen production in India, thus contributing to the advancement of sustainable energy initiatives in the country.

2. Data and Methods

2.1. Study Area and Data

The study area encompasses India, occupying 3.278 million km^2 land area situated in the southern region of Asia. India's geographical coordinates span from 8°4' to 37°6' north latitude and 68°7' to 97°25' east longitude. Within study area, five different plausible locations for wind turbine installation for green hydrogen – Una, Mandvi, Hosur, Shrinadgi and Rampura – were identified based on their rankings obtained from GIS-MCDM method [19]. To assess the feasibility of these locations, wind speed was collected from ERA5 reanalysis data. The data includes both the u and v components of wind speed and encompassed hourly data from 2020 to 2023, measured at a height of 100 meters. Subsequently, the resultant wind speed was estimated from the collected data, which was further utilized on the further analysis and decision-making process, see Table 2.

TABLE 2. WIND CHARACTERISTICS AT 100 M HEIGHT IN THE FIVE LOCATIONS OF INDIA

Index	Location	Longitude, °E	Latitude, °N	v_m, m/s	k	c, m/s	WPD, W/m^2
S1	Una (Gujarat)	71.039	20.827	6.4339	2.5122	7.2353	254.77
S2	Mandvi (Gujarat)	69.355	22.833	6.7752	2.3595	7.6150	323.02
S3	Hosur (Tamil Nadu)	77.825	12.740	5.3214	2.5751	5.9830	142.14
S4	Shirnadgi (Maharashtra)	75.429	17.297	5.1155	2.7022	5.7391	121.19
S5	Rampura (Karnataka)	76.782	14.882	5.6274	2.6298	6.3176	164.64

2.2. Methodology

2.2.1. Weibull distribution function

The Weibull probability density function is most commonly used to model wind speed distributions and estimate wind resource potential accurately. The general equation for Weibull distribution is given in Eq. (1):

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

where k and c represent the shape factor and size factor of the Weibull function. A higher k implies greater consistency in wind speeds, thus making wind conditions more predictable. Conversely, a lower k value suggests more variability in wind speeds. The size factor (c) reflects the average wind speed at the site. Higher c values suggest greater wind availability and higher average wind speeds, while lower values indicate lower average wind speeds. The values of k and c are estimated using Eq. (2) and Eq. (3):

$$k=\left(\frac{\sigma}{v_{\mathrm{m}}}\right)^{-1.086}, \tag{2}$$

$$c=\frac{v_{\mathrm{m}}}{\Gamma\left(1+\frac{1}{k}\right)}, \tag{3}$$

where σ and v_{m} are the standard deviation of wind speed and mean wind speed respectively.

2.2.2. Power generation and capacity factor generation

The wind power density (WPD) has been calculated using the Eq. (4):

$$WPD=\frac{1}{2}\rho\frac{\sum v^{3}}{n}, \tag{4}$$

where ρ is the air density; in this study it is taken as 1.225 kg/m^3; n is total numbers of wind speed data.

In order to estimate power generation, a power curve is initially obtained from the manufacturer and subjected to segmented curve fitting model. This power curve is divided into three segments, for the first segment power output is set to zero when the wind speed is lower than the cut-in speed and higher than the cut-out speed. For the second segment, a polynomial curve fitting approach is used for wind speeds between the cut-in speed and the rated speed. In the last segment, when the wind speed falls in range of rated speed to the cut-out speed, the power output is considered same as the rated power of the WT [20]. In the present study, six different WT models with various capacities are considered to assess the power output and hydrogen production at each location. The specification details of WT are given in Table 3. The power curve equation for Gamesa G128 is presented in Eq. (5) and the power curve equations for the remaining WTs are provided in Table 4.

$$p_{\mathrm{w}} = \begin{cases} 0,\ v < v_{\mathrm{ci}} \\ -7.773v^3 + 189v^2 - 862.5v + 1034,\ v_{\mathrm{ci}} \le v \le v_{\mathrm{r}} \\ p_{\mathrm{r}},\ v_{\mathrm{r}} \le v \le v_{\mathrm{co}} \\ 0,\ v \ge v_{\mathrm{co}} \end{cases}, \quad (5)$$

where v is the instantaneous wind is speed (m/s), v_{ci} is cut-in speed (m/s), v_{co} is cut-out speed and v_{r} is rated wind speed.

TABLE 3. WIND TURBINE SPECIFICATION

Wind turbine model	**Wind turbines**	**Rated power, kW**	**Lifetime, years**	**Cut-in speed, m/s**	**Rated speed, m/s**	**Cut-out speed, m/s**	**Rotor diameter, m**	**Swept area, m^2**
WT1	EWT DW 54	900	20	2.5	13	25	54	2290
WT2	Vestas V90	2000	20	4	13	25	90	6362
WT3	Suzlon S128	2800	20	3	9.5	20	128	
WT4	Suzlon S144	3000	20	3	9.2	18	144	16 618
WT5	Gamesa G128	4500	20	1	12	27	128	12 868
WT6	Gamesa G128	5000	20	1.5	13	27	132	13 685

TABLE 4. WIND TURBINE POLYNOMIAL CURVE FITTING EQUATION FOR POWER

S. No	**Equations**	***R*^{2}**
WT1	$-1.239v^3 + 34.22v^2 - 189.7v + 312.4$	0.998
WT2	$-4.136v^3 + 110.9v^2 - 691.5v + 1393$	0.998
WT3	$-3.162v^3 + 112.7v^2 - 545.7v + 745.3$	0.998
WT4	$-19.203v^3 + 398.55v^2 - 2069.8v + 3276.1$	0.997
WT5	$-7.773v^3 + 189v^2 - 862.5v + 1034$	0.992
WT6	$-0.9239v^4 + 19.397v^3 - 76.73v^2 + 122.05v + 1034$	0.999

The capacity factor (*CF*) of a wind turbine provides valuable information on the financial feasibility of wind turbines at particular locations. The *CF* can be defined as the ratio of the average power output of wind turbine for period of time to the rated power of the turbine operated for same period of time [21]:

$$CF = \frac{AEP}{p_r \times N} , \tag{6}$$

where *AEP* is the annual energy production of the wind turbine and p_r is the rated mechanical power of the wind turbine, and *N* is the number of hours in period of time under consideration. The *AEP* can be determined using the following equation:

$$AEP = \sum_{i=1}^{N} p_{wi} , \tag{7}$$

where p_{wi} is the instantaneous power output of the wind turbine at each hour *i*.

2.2.3. Hydrogen production from wind turbine

Electrolyzer works on water electrolysis which is electrochemical process where heat and electrical energy at room temperature is supplied to pure water which disassociates in hydrogen and oxygen upon reaction. Electrolysis is a clean and efficient process which make its suitable for green hydrogen production. Various water electrolysis processes are described in [22] where pros and cons of different electrolysis process and challenges associate with them is stated. Among these, proton exchange membrane (PEM) electrolysis is highlighted in this study due to its lesser footprint compared to other processes. Though, there are some areas where there is need of doing research in improvement of catalyst materials and membrane thickness for better operation and performance. Technologies like anion exchange membrane and solid oxide water electrolysis are in development phase which can impose future challenges for H_2 production. PEM electrolysis offers higher efficiency and a longer lifetime as compare to alkaline water electrolysis process. Therefore, the electrolyzer used in this study is a PEM with an energy consumption ($E_{\text{electrolyzer}}$) of 54 kWh/kg and a converter with an efficiency of 90 % [6]. The amount of green hydrogen, that can be produced, is given by Eq. (8).

$$M_{H_2} = \frac{AEP}{E_{\text{electrolyzer}}} \times \eta_{\text{converter}} \tag{8}$$

2.2.4. Economic assessment

For the present study, *LCOE* and *LCOH* are considered crucial parameters to evaluate economic performance. According to [23] there are several different *LCOE* models used to determine the cost of energy. Thus, the following expression (9) is used to determine *LCOE* in the current study.

$$LCOE(\$/\text{kWh}) = \frac{c_i + \sum_{t=1}^{T} \frac{OM + REP - ENV}{\left(\frac{1+f}{1+r}\right)^t}}{\sum_{t=1}^{T} \frac{AEP}{(1+d)^t}} , \tag{9}$$

where T represents the project lifetime (in years), t is the number of years, r is the discount rate or cost of capital (in %), f is the real interest rate (in %), d is the technology degradation factor (in %), c_i is the initial capital cost (in \$/kW), REP is replacement cost (in \$/kW), and ENV is the environmental cost (in \$).

The techno-economic inputs parameters considered for computing $LCOE$ include capital cost for wind turbines of 715 \$/kW, operation and maintenance cost (OM) at 2 % of the capital cost, and an annual increment in OM cost of 5 % [24]. The project lifetime is assumed to be 20 years, with real interest rate (f) of 2 %, as per the Reserve bank of India, a degradation rate (d) of 1.6 % and a discount rate (r) of 10 % [25]. To perform economic viability of wind to hydrogen production the key parameter is the $LCOH$ and this can be calculated using Eqs. (10), (11) and (12):

$$LCOH = \frac{C_{\text{electrolyzer}} + C_{\text{electricity}}}{\sum_{t=1}^{T} M_{\text{H}_2}}, \tag{10}$$

where $\sum_{t=1}^{T} M_{\text{hydrogen}}$ mean total hydrogen produced during the operational lifetime of the electrolyzer t_e.

$$C_{\text{electricity}} = LCOE \times \frac{\sum_{t=1}^{T} AEP_t}{T}, \tag{11}$$

$$C_{\text{electrolyzer}} = C_u \times \frac{M_{\text{H}_2} \times E_{\text{electrolyzer}}}{t_e \times 8760 \times CF \times \eta_{\text{electrolyzer}}}, \tag{12}$$

where
C_u is the unit cost of the electrolyzer; $\eta_{\text{electrolyzer}}$ is electrolyzer efficiency and t_e is the operational life of the electrolyzer, where the values for C_u and $\eta_{\text{electrolyzer}}$ are taken as 969 (\$/kW) and 65 %, respectively. The operational life of the electrolyzer is taken as 15 years.

2.2.5. Evaluation of CO_2 emission reduction from wind energy

Wind power is recognized as a key solution in mitigating global warming and achieving sustainable development goals. Among greenhouse gases, CO_2 is considered as primary contributor to climate change, primarily due to the combustion of fossil fuels. According to [26] and the Clean Development Mechanism (CDM) methodology, the emission factor of CO_2 in the Indian power sector is 0.95 (kCO_2/kWh). In this study, the emission reduction associated with the use of wind turbines in green hydrogen production were considered. Hydrogen is produced via electrolysis, powered entirely by wind energy, making the process carbon-neutral with no significant CO_2 emissions. In order to calculate the CO_2 emission reduction, the following equation is used [5]:

$$\text{CO}_2\text{emission reduction} = AEP(\text{kWh/year}) \times 0.95(\text{kCO}_2/\text{KWh}). \tag{13}$$

2.2.6. Hydrogen storage

Hydrogen is now considered an important energy source which can help replace the conventional fossil fuels because of the advantages of its wide source of preparation, high utilization rate and no pollution during its utilizations. However, a major challenge lies in its storage, as hydrogen has an extremely low volumetric density of 0.089886 kg/m^3. This creates opportunity for the research to develop on-board hydrogen system and hydrogen refuelling station. The most commonly used method is to store compressed hydrogen in cylinder tanks. In this study, 70 MPa high presser tank is selected for hydrogen storage consists of thin liner made of high-density polyethylene (HDPE) [27]. Therefore, the amount of compressed hydrogen can be stored (Q_{H_2}) is determined using following equation (14):

$$Q_{H_2} = \frac{M_{H_2}\eta_{comp}}{\sigma_c}, \quad (14)$$

where M_{H_2} is amount of hydrogen produced in kg, σ_c is the density of compressed hydrogen at 70 MPa, 20 °C taken as 39.6 kg/m^3, η_{comp} is the reciprocating compressor efficiency taken as 95 %.

3. Results and Discussions

This section discusses the results obtained from the assessment of the wind power in the chosen areas of the India. The results of the calculations for power generation, AEP by various WTs and for different locations are been discussed. The corresponding amount of H_2 production at different sites, using different WTs, has been compared. The cost of generation of energy and cost of H_2 production has been determined and the results are discussed. Additionally, the CO_2 mitigated using wind energy compared to fossil fuels and the cost reduction due to CO_2 mitigation, have been calculated and discussed.

3.1. Wind Characteristics

Wind characteristics influence the power generated and the AEP of a turbine. Table 2 illustrates the calculated wind speed, shape and size factors, and WPD for each site. The mean wind speed ranged from 5.11 m/s at Shirnadgi (S4) to 6.77 m/s at Mandvi (S2), highlighting Mandvi's superiority in wind speed. This translated to Mandvi having the highest WPD among all sites, measuring 323.02 W/m^2, while Shirnadgi exhibited the lowest WPD at 121.19 W/m^2. Due to the unpredictable nature of winds, Weibull distribution was utilized to analyze the data, focusing on the shape factor (k) and size factor (c). Mandvi's lower shape factor of 2.36 indicated smoother wind speed variations, making it more suitable for consistent energy production, whereas Shirnadgi's higher shape factor of 2.7 suggested more fluctuating winds. Furthermore, the size factor ranged from 5.73 at Shirnadgi to 7.61 at Mandvi, underscoring Mandvi's potential for consistent hydrogen production compared to the inconsistency observed at Shirnadgi. Additionally, the area of Una (S1) emerged as the second-highest potential site for hydrogen production, boasting a mean wind speed of 6.4 m/s and shape and size factors of 2.51 and 7.24, respectively.

3.2. Energy Production and Hydrogen Production Considering Various Turbine

In this study, wind turbines with varying rated power capacities were analysed to evaluate their energy production potential and corresponding green hydrogen generation. The hourly power output of each wind turbine was calculated using the power curve equation presented in Table 4. Based on these hourly outputs, the amount of green hydrogen produced per hour was estimated. This detailed approach enables for accurate *AEP* and *AHP* estimations, accounting for the variability in wind speed and its impact on system performance.

By incorporating hourly data, the dynamic relationship between wind power generation and electrolyser operation was effectively modelled, providing a realistic assessment of the feasibility of green hydrogen production from wind energy. The performance of various WTs across the five locations is summarized in Table 6, highlighting key metrics such as *CF*, *AEP*, *AHP* and hydrogen storage and CO_2 reduction potential. The analysis reveals site-specific variations in turbine efficiency and hydrogen production potential, driven by differences in wind speeds and turbine rated power capacities.

TABLE 6. ENERGY PRODUCTION AND CORRESPONDING HYDROGEN PRODUCTION CONSIDERING VARIOUS TURBINES ACROSS DIFFERENT LOCATIONS

Location	Wind turbine	*CF*, %	*AEP*, GWh	*AHP*, tons	Q_{H_2}, m³	CO_2 reduces, Mt/year
S1	WT1	26.01	2.05	34.17	901.74	1.91
	WT2	28.52	5.00	83.27	2197.40	4.66
	WT3	43.49	10.67	177.80	4691.90	9.94
	WT4	46.97	12.35	205.74	5429.30	11.51
	WT5	32.52	12.82	213.63	5637.40	11.95
	WT6	30.33	13.29	221.42	5843.10	12.38
S2	WT1	28.42	2.24	37.34	985.44	2.09
	WT2	31.11	5.45	90.84	2397.20	5.08
	WT3	46.81	11.48	191.35	5049.60	10.70
	WT4	50.51	13.27	221.21	5429.30	12.37
	WT5	35.33	13.93	232.14	6125.80	12.98
	WT6	32.86	14.39	239.86	6329.60	13.41
S3	WT1	15.06	1.19	19.79	522.34	1.11
	WT2	17.12	3.00	49.99	1319.20	2.80
	WT3	27.70	6.79	113.23	2988.10	6.33
	WT4	30.46	8.01	133.43	3521.10	7.46
	WT5	19.82	7.81	130.25	3437.10	7.28
	WT6	18.89	8.27	137.88	3638.60	7.71
S4	WT1	13.41	1.06	17.62	464.92	0.99
	WT2	15.22	2.67	44.43	1172.40	2.48
	WT3	25.75	6.32	105.28	2778.10	5.89
	WT4	28.85	7.58	126.35	3334.20	7.07
	WT5	18.07	7.12	118.74	3133.30	6.64
	WT6	17.06	7.47	124.50	3285.50	6.96
S5	WT1	17.86	1.41	23.47	619.27	1.31
	WT2	20.04	3.51	58.52	1544.30	3.27
	WT3	32.16	7.89	131.46	3469.10	7.35
	WT4	35.41	9.31	155.10	4093.00	8.67
	WT5	23.35	9.20	153.40	4048.10	8.58
	WT6	21.86	9.57	159.58	4211.10	8.92

Across all sites, the Suzlon S144 3.0 MW (WT4) turbine achieved the highest *CF*, ranging from 28.85 % to 50.51 %. This consistently high *CF* makes WT4 an efficient and cost-effective choice for hydrogen production. For example, at Mandvi (S2), WT4 delivers a *CF* of 46.97 %, and at Una (S1), it reached 50.51 %. Despite its high *CF*, WT4's energy and hydrogen production were not as high as those of larger turbines in locations with optimal wind speeds. On the other hand, larger turbines like WT6, with higher rated power, produced more energy and hydrogen, especially at sites with favourable wind conditions. For instance, at Mandvi (S2) and Una (S1), WT6 generated the highest *AEP* (13.29 GWh and 14.39 GWh, respectively) and AHP (221.42 tons and 239.86 tons, respectively), producing a larger volume of hydrogen (5843.1 m^3 and 6329.6 m^3) and contributing significantly to CO_2 reduction (12.38 Mt/year and 13.41 Mt/year). However, while WT6 offers increased hydrogen production, it also had a lower *CF* compared to WT4, indicating that higher-rated turbines could result in increased production costs despite their larger energy output.

At Shirnadgi (S3), the performance of WT6 aligns with the trend observed at other sites with higher wind speeds. It produced the maximum *AEP* (8.27 GWh) and *AHP* (137.88 tons), but its *CF* (30.46 %) was still lower than that of WT4, highlighting the trade-off between efficiency and total production. For Shirnadgi (S4) and Rampura (S5), similar patterns emerged: WT6 achieved the highest *AEP* and *AHP* but at a lower *CF* compared to WT4, suggesting that WT6 was most effective for maximizing output where wind speeds were optimal, while WT4 remains more cost-efficient in moderate conditions. While smaller turbines like WT1 and WT2 were less effective for large-scale hydrogen production due to their relatively low *CF* and *AEP*, they are more cost-effective in regions with lower wind speeds. For instance, WT1 at Shirnadgi had a *CF* of just 15.06 %, resulting in lower hydrogen production. This reinforces the notion that smaller turbines were more suitable for locations with low to moderate wind speeds but were not ideal for large-scale hydrogen production.

3.3. Cost Analysis

The present study investigated the cost efficiency of hydrogen production from wind energy by analysing the *LCOE* and *LCOH* across different wind turbines (WT1 to WT6) and five locations (S1 to S5). The results highlighted significant variations in both energy production and hydrogen generation costs, which were influenced by turbine capacity and local wind conditions. As shown in Table 7, smaller turbines such as WT1 and WT2 were less cost-efficient for hydrogen production, especially in regions with higher wind speeds. In contrast, larger turbines like WT5 and WT6 incurred higher costs in areas with moderate wind conditions.

TABLE 7. COST ANALYSIS OF HYDROGEN PRODUCTION BY TURBINE TYPE AND LOCATION

Turbines	S1		S2		S3		S4		S5	
	LCOE	*LCOH*	*LCOE*	*LCOH*	*LCOE*	*LCOH*	*LCOE*	*LCOH*	*LCOE*	*LCOH*
WT1	0.0497	2.5247	0.0454	2.3103	0.0858	4.3588	0.0964	4.8972	0.0724	3.6764
WT2	0.0453	4.3196	0.0415	3.9596	0.0755	7.1957	0.085	8.0969	0.0645	6.1470
WT3	0.0297	2.8320	0.0275	2.6314	0.0466	4.4472	0.0501	4.7834	0.0401	3.8305
WT4	0.0274	2.6221	0.0255	2.4387	0.0424	4.0435	0.0448	4.2702	0.0364	3.4785
WT5	0.0397	3.7884	0.0365	3.4862	0.0652	6.2141	0.0715	6.8166	0.0553	5.2760
WT6	0.0426	4.061	0.0393	3.749	0.0684	6.5221	0.0758	7.2231	0.0591	5.6353

At locations with lower wind potential, such as S1 and S2, smaller turbines like WT1 and WT2 demonstrated relatively lower *LCOE* and *LCOH* values, suggesting their suitability for these regions. For example, the *LCOE* for WT1 in S1 is 0.0497 \$/kWh, and the *LCOH* is 2.5247 \$/kg, indicating that despite producing less energy, these turbines could still be cost-effective in regions with lower wind speeds. Similarly, WT2 showed slightly lower costs in these locations (*LCOE* 0.0453 \$/kWh and *LCOH* 4.3196 \$/kg in S1), reinforcing the appropriateness of these turbines for such conditions. However, as the wind potential increases in areas like S3, S4, and S5, these smaller turbines became less competitive due to higher production costs.

Conversely, larger turbines like WT4 and WT5, which were designed for higher energy output, showed their efficiency in areas with moderate to high wind speeds. WT4, for instance, had the lowest *LCOE* values across several locations, with the most cost-efficient performance at S1 (*LCOE* = 0.0274 \$/kWh, *LCOH* = 2.6221 \$/kg) and S2 (*LCOE* = 0.0255 \$/kWh, *LCOH* = 2.4387 \$/kg). This indicated that WT4 was optimal for these regions, offering a balance between energy production and hydrogen generation costs. On the other hand, while larger turbines such as WT5 and WT6 produced higher energy and hydrogen quantities, their *LCOE* and *LCOH* values increased at certain sites, particularly at locations like Una (S2) and Mandvi (S1). For example, the *LCOE* for WT5 at Una (S2) was 0.0397 \$/kWh, and the *LCOH* was 3.7884 \$/kg, which was higher than the *LCOE* values observed for WT4, despite the higher energy output of the larger turbines. This suggested that in locations where wind speeds were not optimal for large turbines, the increased capital and operational costs outweigh the benefits of additional energy production.

The study also reveals that turbines WT3 and WT4 strike an optimal balance between energy production and cost efficiency, with WT3 demonstrating particularly favorable results at higher wind speed locations such as S3 and S4. For instance, in S3, WT4 produces a relatively low *LCOE* (0.0424 \$/kWh) and *LCOH* (4.0435 \$/kg), indicating its effectiveness in harnessing the available wind resource efficiently. Additionally, the *LCOE* and *LCOH* values for WT3 at S4 and S5 remain competitive, underlining its suitability for regions with moderate to high wind speeds.

4. CONCLUSION

The present study explored the feasibility of green hydrogen production utilizing wind energy as a renewable source to mitigate GHG emissions from hydrocarbon fuels. A comprehensive techno-economic analysis was performed at different locations in India using hourly wind data from ERA5. The analysis included estimating energy production, hydrogen generation, and the economic viability of the process. Key findings from the study are summarized as follows:

– Mandvi (S2) and Una (S1) emerged as the most promising locations for hydrogen production, with mean wind speeds at 6.77 m/s and 6.43 m/s, respectively, positioning them as optimal sites for wind energy utilization.
– Suzlon S144 (WT4) achieved the highest *CF* of 50.51 % at Mandvi (S2), whereas Shirnadgi (S4) exhibited the lowest *CF* of 28.85 %. On other hand, EWT DW54 (WT1) turbine displayed consistently low *CF* values across all locations due to its limited rated power and inadequate compatibility with local wind conditions.
– Mandvi (S2) recorded the highest *AEP* of 14.391 GWh using WT6 (siemens Gamesa 128) turbine, whereas Shirnadgi (S4) produced the least, at 7.47 GWh with the same WT. Despite WT6 generating substantial power, its lower *CF* relative to WT4 and WT3 rendered it less cost-effective. WT1 consistently produced the least energy, ranging from

1.0571 GWh at S4 to 2.2406 GWh at S2.

- Hydrogen generation was directly linked to energy output, with Mandvi (S2) achieving the highest annual hydrogen production of 239.86 tons using WT6. Shirnadgi (S4) produced the lowest hydrogen output, at 17.618 tons using WT1.
- Mandvi (S2) exhibited the greatest potential for CO_2 emission reduction, mitigating 13.413 Mt/year using WT6. In contrast, Shirnadgi (S4) achieved the lowest reduction of 0.985 Mt/year using WT1.
- Mandvi (S2) and Una (S1) showed the lowest *LCOE* values at $0.0255/kWh and $0.0274/kWh, respectively, using WT4. Shirnadgi (S4) recorded the highest *LCOE* of $0.0964/kWh.
- *LCOH* varied across locations, with the lowest value of $ 2.3103/kg achieved at Mandvi (S2) using WT4. The highest L*COH* was observed at Shirnadgi (S4) using WT2, at $ 8.0969/kg. Notably, WT1, WT3, and WT4 displayed comparable *LCOH* values at Una (S1) and Mandvi (S2), further underscoring their cost-effectiveness in these regions.

Overall, Una (S1) and Mandvi(S2) emerged as the most feasible locations for green hydrogen production using WT3 and WT4 turbines, delivering the lowest *LCOE* and *LCOH* along with the highest hydrogen yields, demonstrating their economic and technical feasibility.

Future research should focus on integrating advanced technologies, such as next-generation electrolyzers, to improve efficiency and reduce costs, while conducting a detailed life cycle assessment (LCA) to evaluate the environmental impact of green hydrogen production, including transportation and storage. Addressing wind power variability through energy storage systems can further enhance production reliability. Additionally, economic and policy analyses are crucial to understand the impact of government incentives, market dynamics and regulatory frameworks on the scalability of hydrogen production. Advancements in wind turbine technologies and hybrid renewable energy systems could optimize energy generation and resource utilization. A comprehensive spatial analysis of wind resources across India is also vital for identifying additional high-potential locations, enabling policymakers to make informed decisions and accelerate the nation’s transition to a sustainable energy future.

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