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India's Transition Towards Becoming a Carbon Neutral Nation

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Abstract
The escalating impacts of climate change and the imperative to decarbonize global energy systems have spurred a concerted effort towards the exploration and adoption of renewable energy technologies. Out of all these options, wind energy stands out as a top choice. It has a lot of potential to meet the growing need for energy and help the environment at the same time. In this study, we undertake a comprehensive assessment of wind energy potential in five key cities across India: Udupi, Kollam, Surat, Visakhapatnam, and Jamnagar. Leveraging two decades of wind data sourced from reputable repositories such as the Iarc Power Project of NASA, we employ rigorous statistical analysis, including the application of the Weibull distribution, to elucidate the probability distribution of wind speeds and assess the viability of wind energy utilization in each city. We have also focused on other ways for decarbonizing India using new and advanced technologies as Carbon Capture, Utilization and Storage (CCUS) and green hydrogen.
Our analysis extends beyond theoretical considerations to encompass practical dimensions such as infrastructure requirements, cost implications, and technological advancements. Through meticulous evaluation, we aim to provide actionable insights that can inform policy formulation, infrastructure development, and investment strategies aimed at accelerating the adoption of wind energy technologies in India. Our research suggests solution for implementing and policy framework for CCUS to make it more effective in achieving India's carbon neutral goals. We have also discussed about green hydrogen its types, cost of implementation and its current application. By fostering dialogue and collaboration, our research seeks to contribute to the ongoing discourse surrounding renewable energy transitions, facilitating informed decision-making towards a more sustainable energy future.

1. Introduction

The exploration and exploitation of renewable energy technologies have become major imperatives on the world scale due to the acceleration of climate change and the pressing need to shift towards sustainable energy sources. Among these technologies, wind energy stands out as a promising solution, offering abundant potential to meet growing energy demands while mitigating environmental impact.
The year 2018 marked a significant milestone in the trajectory of wind energy, with global capacity surpassing 600 gigawatts (GW), underscoring its status as one of the fastest-growing renewable energy sources worldwide. Notably, China emerged as a frontrunner in wind energy deployment, boasting a maximum capacity of 221 GW, exemplifying the substantial strides made in harnessing wind power on a global scale.
Against this backdrop, our research endeavours to assess the wind energy potential in select cities across India, a country poised at the nexus of economic growth and environmental stewardship. Through

meticulous analysis and evaluation, we aim to ascertain the viability of leveraging wind energy to bolster India's energy portfolio and foster sustainable development.

The quest for sustainable energy solutions necessitates a comprehensive understanding of renewable energy resources, with wind energy occupying a pivotal role in this discourse. By accurately assessing wind energy resources, communities can effectively integrate wind power technologies into their energy mix, paving the way for a cleaner, greener energy future. Motivated by the imperative to address burgeoning energy demands and combat climate change, our research embarks on an exploration of wind energy potential in five key cities across India.

India is also the 3rd biggest emitter of CO2 in the world after China and the US, with evaluated yearly emission of around 2.6 gigatonne per annum (gtpa). The Government of India has committed to decreasing CO2 outflows by 50% by 2050 and coming to net zero by 2070. While India stages down the utilization of coal over time, India will be subordinate on fossil energy sources like coal for a long time to back the industry and meet the prerequisites for reasonable and dependable baseload control. Subsequently, India's decarbonization pathway has to moreover grasp innovations which will decrease emanations from the difficult to decrease mechanical divisions as well as for remaining baseload control generation. Carbon Capture, Utilization and Storage (CCUS) is an effective technology in this regard.

In navigating the complex terrain of renewable energy transitions, collaboration and knowledge exchange emerge as linchpins for success. As such, our research endeavours to contribute to the growing body of knowledge surrounding wind energy and CCUS assessment, fostering dialogue, and collaboration towards a more sustainable energy future.

1.1 Wind Energy Potential

Wind energy is one of the fastest growing renewable sources of energy in both developed and developing countries with total available wind power surrounding the earth being in the order of 10^{11}GW, which is several times more than the current global energy consumption [2]. The ability to accurately assess renewable energy resources is an essential prerequisite to integrating renewable energy technologies into the energy supply portfolio of any community [3].

As we know wind has energy which can be extracted to meet our energy demand. But before setting up a wind plant we need to know answer of such questions as how much energy the wind contains, where the plant would be established, will it be economical to set-up the plant there. In order to find out the answer of these questions we will be doing an estimation of wind energy potential in this section.

The assessment of wind energy potential necessitates a multifaceted approach, encompassing factors such as wind speed variability, geographical location, and topographical features. By leveraging comprehensive wind data spanning two decades, sourced from reputable repositories such as the Iarc Power Project of NASA, our research endeavors to elucidate the intricate nuances of wind energy dynamics in the selected cities.

Five cities namely Udupi, Kollam, Surat, Jamnagar, Visakhapatnam from 4 different states were selected and their wind energy potential is determined in the further section. These cities are located at sea shores or near to them. There were several factors for considering these cities such as all the selected cities are among the major cities of their respective states. All these cities are major growing economies in their region:

Udupi is among the fastest growing cities from Karnataka. It is a major tourist attraction spot of the state. Small scale industries, food industries and milk cooperatives play a significant contribution to city's economy. Agriculture and fishing too contribute in the economy. The city is home to Temba Shipyard Ltd.

which is involved in the procurement and construction of multipurpose platform supply vessels (MPSVs), geotechnical research vessel, tugs, platform supply vessel and dredgers for Indian as well as export market. **Jamnagar** has one of the biggest refineries of the world. It contributes approximately 95% of general bauxite produced in Gujarat. Government is developing SEZ (special economic zone) right here a good way to diversify Jamnagar's industrial sector, beef up its financial system and provide large raise to city's GDP.

In terms of economic overall performance, **Kollam** town is on 5th position in India. Called the Cashew capital of global with greater than six hundred processing units. The beach sands of the district have concentrations of such heavy minerals as Ilmenite, Rutile, Monosite and Zircon, which give scope for exploitation for business purposes.

Visakhapatnam with a GDP of $43.9 billion is the 9th richest metropolis in India. The town is known for constructing and repairing of ship. In FY 2015, it crowned seafood exports in terms of price amongst other ports.

Surat is a major hub of diamond cutting and polishing. Around the world, 8 out of 10 diamonds in the marketplace had been cut and polished in Surat. This enterprise earns India approximately US$10 billion in annual exports. Surat's financial system drives from a number of production and enterprise fields along with diamonds, textiles, petrochemicals, shipbuilding, vehicle, port and so forth.

All the selected cities have ample industries that has made them major economies in their states as well as in India. Due to further development, energy demand in these reasons is bound to sky-rocket. One more point to focus is that these cities are located at sea shore so the generated wind energy can also be used in the production of green hydrogen. With adequate supply of water from the sea and the reduced transportation cost of water since the hydrogen generation plant can be established near the sea shore, the production of hydrogen would become further economically feasible. The energy produced will not only full fill the void of electricity demand but also boost the socio-economic growth of these cities and the surrounding region.

1.2 Wind Data for Site

Twenty-three years of wind data in between 2000 to 2022, at an altitude of fifty meters above the surface was gathered from the Iarc power project of NASA so as to examine the energy potential of these locations. But in most part of the globe, the usual altitude above the nearby vegetation for measuring wind velocity is 10 m [6].

City	UDUPI	SURAT	KOLLAM	VISAKHAPATNAM	JAMNAGAR
Altitude(m)	27	13	38	45	17
Density(kG/m^3)	1.173	1.175	1.171	1.170	1.174
Longitude (E)	74.7451	72.8311	76.6141	83.2977	70.07
Latitude (N)	13.3389	21.017	8.8931	17.7042	22.47

The above table presents elevation and geographical location of cities.

Month\City	Mean Wind Speed(m/s)				
	UDUPI	SURAT	KOLLAM	VISHAKHAPATNAM	JAMNAGAR
JAN	2.98	4.78	3.42	4.09	5.63
FEB	2.86	4.44	3.02	3.88	5.57
MAR	2.69	4.48	2.76	4.55	5.68

APR	2.60	4.75	2.99	5.80	6.29
MAY	3.63	6.20	4.67	6.09	7.85
JUN	5.46	7.12	5.83	6.68	7.90
JUL	5.93	7.87	6.02	7.05	8.22
AUG	5.38	7.14	5.74	6.57	7.43
SEP	4.05	4.98	4.91	4.97	5.66
OCT	2.92	3.86	3.62	4.61	4.14
NOV	2.85	4.62	2.95	5.48	4.57
DEC	3.19	4.80	3.54	5.11	5.47

Table 2 presents the average data of monthly wind speed for the five selected cities throughout the twenty-three years duration. Maximum mean wind speed generally occurs between May and August the reason being it is the monsoon season in India.

1.3 Weibull Distribution

Frequency distribution of wind pace is determined through exclusive statistical distributions which includes Gamma, Rayleigh, and Weibull. Among those techniques, Weibull distribution is the maximum favoured method. This technique is properly suitable to wind distribution. [3,4]

The wind energy practitioners and engineers commonly use Weibull distribution as it's miles extra accurate, specific and dependable than compared to different wind evaluation strategies. [5] **Weibull distribution** is a continuous probability distribution. It models a broad range of random variables, largely in the nature of a time to failure or time between events.

In this, we have two functions probability density function f(v) and cumulative density function or Weibull function F(v) presented by following relation:

$$f(v) = \frac{\beta}{\alpha}\left(\frac{v}{\alpha}\right)^{(\beta-1)} e^{-\left(\frac{v}{\alpha}\right)^{\beta}} \qquad (1)$$

$$F(v) = 1 - e^{-\left(\frac{v}{\alpha}\right)^{\beta}} \qquad (2)$$

where 'v' is the wind speed, β(dimensionless) is the parameter that controls the shape of the distribution and is called the shape factor, while α(m/sec) is known as the scale factor.

For the selected sites, the average (v_m) wind speed was determined from equation (3) while the variances (σ^2) of wind speed data was determined from equation (4) :

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \qquad (3)$$

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(v_i - v_m)^2 \qquad (4)$$

Where, the symbol 'i' refers to the monthly average wind data, while n denotes the total number of months for which wind data was used.

By using average wind speed (v_m) and standard deviation (σ), the two Weibull parameters namely shape factor and scale factor are calculated using following relations:

Shape Factor, $\beta = \left(\frac{\sigma}{v_m}\right)^{-1.086}$ (5)

Scale Factor, $\alpha = \frac{v_m}{\Gamma\left(1+\frac{1}{\beta}\right)}$ (6)

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Through the estimation of Weibull parameters, including the shape factor (β) and scale factor (α), we aim to delineate the probability distribution of wind speeds and elucidate the potential for harnessing wind energy in each city.

1.4 Wind Power Density (WPD)

Wind power expresses the amount of wind passing through an area in per unit time. It is the flux of wind energy through an area of interest. Wind power is given by the following equation:

$$P = \frac{1}{2}\rho A v^3 \qquad (7)$$

Where A = area through which wind is flowing (m^2)

v = velocity of wind (m/sec)

When we divide the ambient wind power by the area of wind-flow we get specific power flow known as Wind Power Density (WPD). The wind power density is more effective in determining the potential of kinetic energy available from wind for generation of electric current in a particular region. Therefore, it has been used to compare wind resources independent of wind turbine size.

WPD can be determined by using Weibull parameters as following:

$$\text{WPD} = 0.5\rho\sigma^3(1 + \frac{3}{\beta}) \qquad (8)$$

1.5 Result and Discussion

Figure 1 represents the comparison of wind data for the selected 5 cities. Monthly average wind speed of 23 years has been used in the figure. Among the cities, Udupi has minimum monthly wind speed for most of the time of year while Jamnagar has maximum wind speed for majority of the period of a year. It was found that Jamnagar offers peak monthly wind speed of 4.14 m/s to 8.22 m/s. This was followed by Surat and Vishakhapatnam having almost similar speed range of 3.86 m/s to 7.87 m/s and 3.88 m/s to 7.07 m/s respectively. The variation in wind speed reveals that none of the cities have consistent speed throughout the year. The data reveals that maximum average wind speed occurs during May to August. The average annual wind speed is presented in figure 2.

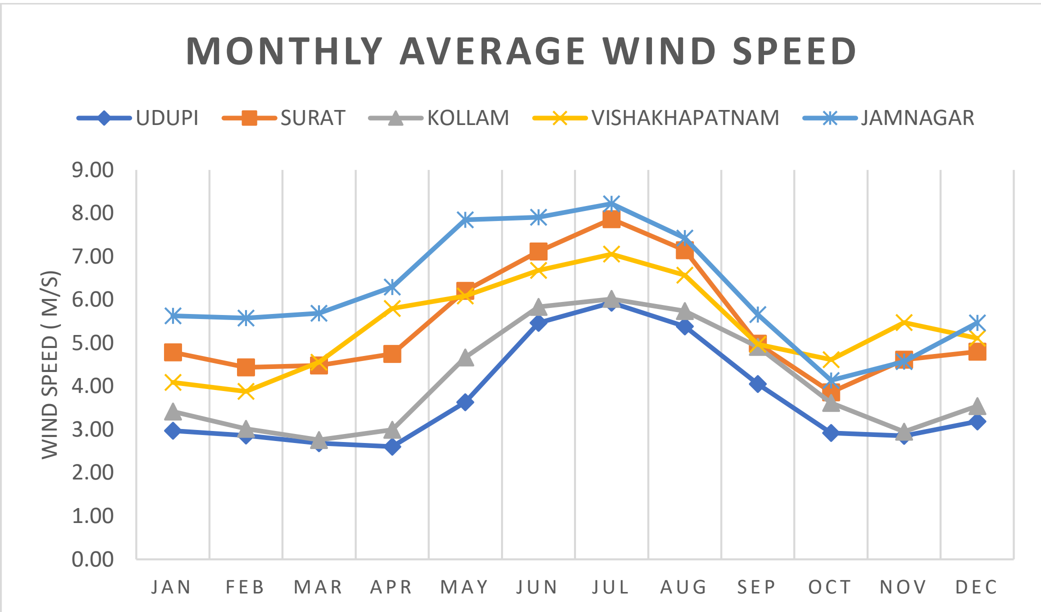

Fig.1 Monthly Average Wind Speed data averaged over a period of 23 years from 2000 to 2022.

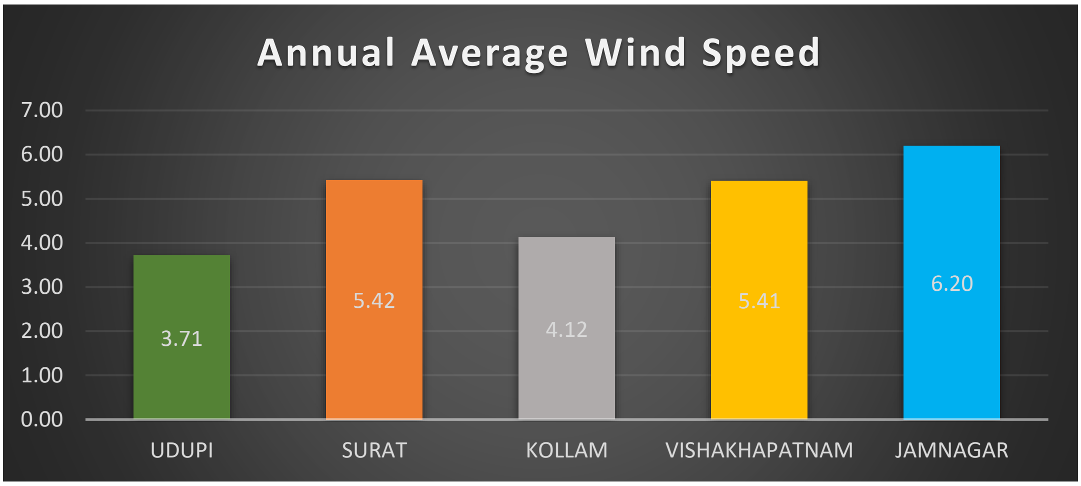

Fig.2 Annual Average Wind Speed

Height above the sea surface along with geographical and climatic conditions of the site is a primary factor upon which the speed of flowing wind and its direction depends [7].

Table 3 presents the findings from data used and from Weibull statistical analysis. In Weibull distribution, the shape parameter (β) was 2.751≤ β ≤5.693, whereas the scale parameter (α) was 4.172≤ α ≤6.861. The calculated Weibull parameters for the selected cities are shown in Figure 3.

Place	UDUPI	SURAT	KOLLAM	VISHAKHAPATNAM	JAMNAGAR
u_m	3.712	5.420	4.122	5.407	6.201
variance	1.462	1.708	1.533	1.090	1.814
shape factor	2.751	3.505	2.928	5.693	3.800
scale factor	4.172	6.024	4.621	5.845	6.861
Density	1.173	1.175	1.171	1.170	1.174
WPD	88.992	238.239	117.015	178.423	339.356

Table 3: Outcome of Weibull Statistical Analysis

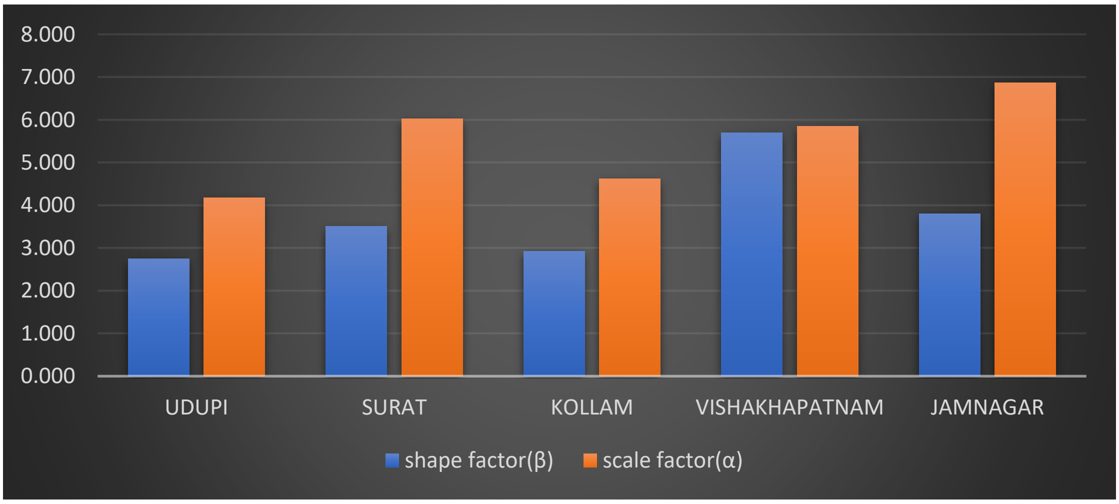

Fig.3 Shape and Scale parameter of Weibull Distribution

The wind power densities WPD of Udupi, Surat, Kollam, Vishakhapatnam and Jamnagar were 88.992 W/m^2, 238.239 W/m^2, 117.015 W/m^2, 178.423 W/m^2, and 339.356 W/m^2, respectively. Jamnagar had the highest wind power density.

A site having wind power density more prominent than 700 W/m^2 is exceptionally great for the generation of energy(electrical) from wind. If WPD measures in between 300 to 700 W/m^2, at that point the location is considered to be great; WPD between 100 to 300 W/m^2 indicates decently great location and that underneath 100 W/m^2 indicates a poor location. Among the 5 sites, Udupi is highly unfit for installation of wind energy farms while Jamnagar is a good site for utilising wind energy resource followed by Surat and Vishakhapatnam.

2. Carbon Capture, Utilization and Storage (CCUS)

CCUS stands for Carbon Capture, Utilization, and Storage. It's a set of advances and methods planned to diminish the discharge of carbon dioxide (CO_2) into the climate, a major nursery gas contributing to climate alter. CCUS includes the capture of CO_2, for the most part from huge point sources like control era or mechanical offices that utilize either fossil fills or biomass as fuel. If not being utilized on-site, the captured CO_2 is compressed and transported by pipeline, transport, rail or truck to be utilized in a run of applications, or infused into profound geographical arrangements such as drained oil and gas stores or saline aquifers.

Components of CCUS

Carbon Capture: This includes capturing CO_2 outflows from different sources, such as control plants, mechanical forms, or indeed straightforwardly from the air. There are diverse strategies for capturing CO_2, counting post-combustion capture, pre-combustion capture, and oxy-fuel combustion.

Utilization: Instep of basically putting away the captured CO_2, CCUS innovations point to discover useful employments for it. This can incorporate carbon utilization in forms such as upgraded oil recuperation, the generation of engineered powers, or the creation of building materials.

Storage: Carbon capacity includes the secure and changeless capacity of captured CO_2 in topographical arrangements, regularly profound underground. This can offer assistance avoid the discharged CO_2 from re-entering the atmosphere.

CCUS plays a significant part in mitigating climate alter by decreasing the sum of CO_2 in the environment. It is considered one of the devices in the toolbox of techniques to address worldwide warming, nearby renewable sources of energy, energy proficiency, and other emission reducing techniques. CCUS can be retrofitted to existing power and mechanical plants, permitting for their proceeded operation. It can handle outflows in hard-to-abate segments, especially overwhelming businesses like cement, steel or chemicals. CCUS is an enabler of least-cost low-carbon hydrogen generation, which can back the de-carbonization of other parts of the energy framework, such as industry, trucks and ships. At long last, CCUS can evacuate excess CO_2 from the atmosphere to adjust emissions that are unavoidable or in fact troublesome to abate.

Problem. The decarbonization challenge for India is to recognize versatile and sustainable economic arrangements for the decarbonization of segments that contribute to 70% of emissions. CCUS has an imperative and critical part to play, particularly for India to finish net-zero by 2070.It is hence critical to actualize the framework and policy instrument for CCUS to gotten to be a reality in India and make an important commitment to decarbonization in India.

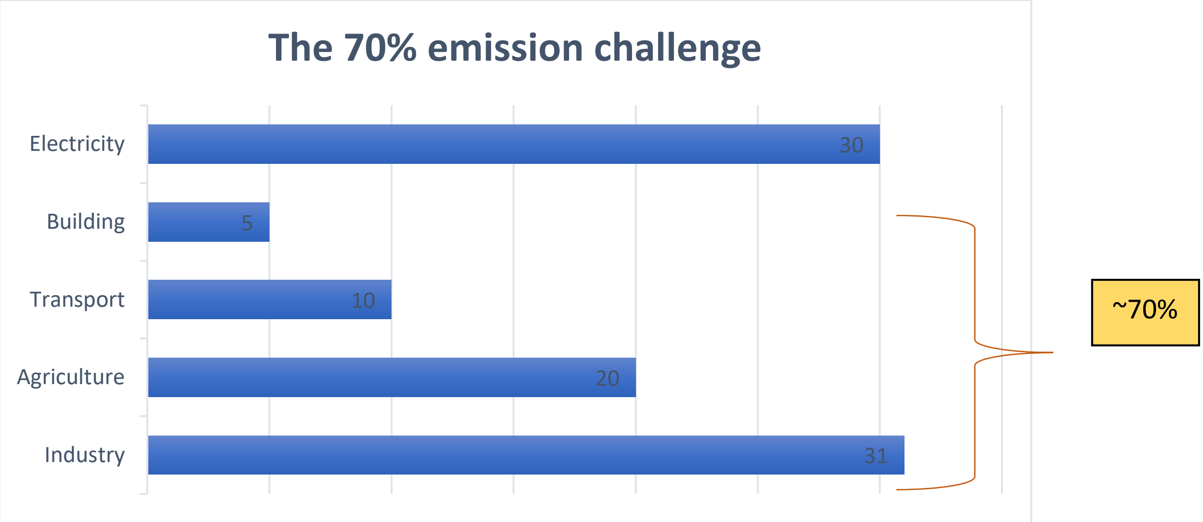

Figure 4. The 70% emission challenge

Solution. A review of carbon capture projects around the world uncovers that a policy framework and Government support for CCUS are key to overseeing project costs & risks. Incentivizing the private segment and setting up the CCUS value chain comprising CO_2 capture, transportation and storage. A carbon credits-based policy is most suited for a fast-pace growing nation like India, to incentivize CCUS acceptance and bring down the cost of carbon capture, setting-up markets for low-carbon products and decarbonize India's huge and moderately new industrial asset base by offsetting carbon capture costs.

2.1 Hydrogen/Hydrogen based Fuel: Hydrogen compound with oxygen in the form of water and water vapour is present in abundance in the environment but pure hydrogen is very less this hydrogen has the potential to create a revolution in tackling the low emission energy source challenges as it doesn't produce greenhouse gases and the main by product while using hydrogen as a fuel or energy source is water vapour. It can be used as **Hydrogen fuel cells**, **Hydrogen blending** and **Hydrogen combustion** for e.g. in industrial processes like metal processing, chemical production etc. to get this pure hydrogen there are many methods of its production based on these methods and their impacts the hydrogen is classified into three category i.e. Grey Hydrogen, Blue Hydrogen and Green Hydrogen.

Types of Hydrogen are as follow:

1. **Grey Hydrogen:** Grey hydrogen is the most common Hydrogen produced worldwide and it is formed by the process of **Steam methane Reforming (SMR)** using Natural gas or methane or **coal gasification**. During production it does not captures carbon dioxide emissions hence it leads to emissions of carbon or greenhouse gases. So this from of hydrogen is not considered as eco-friendly due to its high carbon emissions.
2. **Blue Hydrogen:** Blue hydrogen is low carbon emission hydrogen as during its production the CCS (Carbon capture and storage) technique is used to capture and store CO2 produced by the process of **Steam methane Reforming (SMR)** or **Auto thermal reforming process (ATR)**. It is also produced by Fossil fuels like natural gas. Although it has lesser carbon footprint than grey hydrogen but the problem still lies because of the usage of Fossil fuels and CCS technology which is not that much cost effective yet.
3. **Green Hydrogen:** Hydrogen produced by using renewable sources of energy as the energy source for its production method is called as green hydrogen. It is produced using **electrolysis** method in which water molecule gets splits into hydrogen and oxygen using electricity. Its production emits zero carbon or green house emission which makes it cleanest fuel. Utilising this hydrogen on large scale will be a

life saver to tackle the problem of climate change. Many countries like Germany, Korea, and Australia etc. have already started taking initiative, making strategies in investing in green hydrogen technology. India also has the potential of adopting this as a energy source.

Adopting green hydrogen as an alternative of conventional fossil fuel based energy sources in India has a high scope as it is a diverse country in terms of weather here many types of season weather and climatic conditions are available which makes it rich in availability of renewable energy sources like Rajasthan and Gujrat for solar energy, Maharashtra and Tamil Nadu for wind energy etc. it can be used in the Applications such as in power generation, transportation, industries etc.

2.2 Cost of Implementing Green hydrogen technology

a. Operational cost: operational costs depends on factors such as cost of alkaline electrolyser (equipment used for electrolysis process) , cost renewable energy, cost of technological advancements, Production scale. And according to International renewable Energy Agency (IRENA), India has one of the lowest prices of renewable energy worldwide. For example, in India the LCOE (levelized cost of electricity) produced from solar photovoltaic is down by 83% from 2010 to 2020 which means the operational cost associated with the use of renewable energy will be less comparatively. But this sector still needs much technological advancement which may leads to increased cost.

b. Infrastructure cost: this cost depends on the factors such as installation of the electrolysers, hydrogen storage and transportation facilities, infrastructure, location. India is investing in different Storage technologies like liquid or compressed hydrogen storage and solid-state hydrogen storage. Also, pilot projects are implemented to get the idea of technical and economical practicality of transportation of pure hydrogen.

Locations: as renewable energy is the main content for production of green hydrogen the favourable location for establishing its production unit must have easy availability of these energies. so the locations which has this potentials includes Tamil Nadu, Andhra Pradesh and Karnataka for wind energy, Gujrat and Rajasthan for solar energy, for installing electrolyser proper access of water is required hence coastal areas such as Andhra Pradesh coast(Vishakhapatnam, Nellore etc.) will be best suited for it.

2.3 Applications

Many organisations in India is already implementing or taking initiatives for adopting green hydrogen as a fuel.

Some of the underway projects and initiatives are as follow: -

1. National Thermal Power Corporation (NTPC): NTPC is a largest power generation company of India is utilising green hydrogen technology for its projects of renewable energy they also are plans to establish green hydrogen production units.
2. Tata Motors: Tata Motors which is the leading manufacturer of automobile in India is exploring the hydrogen fuel cell technology the research and development for the same has been started. They are aiming to build Fuel cell Vehicles (FCEV) which will use hydrogen and will produce zero carbon.
3. Jindal Steel and Power Limited (JSPL): it is one of the prominent steel producer in India, they are aiming to produce “green steel” by replacing fossil fuels with the green hydrogen for their production and hence low carbon footprint.

3. Conclusion:

In conclusion, our study has focused on how India can transit from being a carbon emitting nation to carbon neutral nation utilizing various advanced technologies. Our study has shed light on the complex

dynamics of wind energy potential in select cities across India, offering valuable insights into the feasibility and implications of harnessing wind power as a sustainable energy solution. Through careful analysis and evaluation, we have uncovered the various factors influencing wind energy generation, ranging from wind speed variations to geographical and climatic factors.
The findings of our research underscore the significant role of wind energy in India's journey towards a cleaner, greener energy future. From Udupi to Jamnagar, our analysis has revealed differing levels of wind energy potential, with some cities showing promise for wind energy deployment. Notably, Jamnagar stands out with the highest wind power density among the cities studied, while Udupi poses challenges due to lower wind speeds. With advancement in wind blade layout and blade substances, we might be able to generate sufficient wind electricity at 10 m peak.
As India grapples with the dual challenges of energy security and environmental sustainability, our findings gain importance. By effectively harnessing wind energy resources, India can reduce its dependence on fossil fuels, cut greenhouse gas emissions, and promote inclusive economic growth. CCUS can play a critical role in achieving carbon neutrality goal. It can help India by helping capturing the emitted CO_2 from industries which depend heavily on fossil fuels and those are not feasible to shift to renewable energy source for the time being. Green hydrogen technology is getting a lot of attention this decade because of its immense availability and the amount of energy it generates. Clearly, more advancement is needed in this technology to make it feasible for a huge country like India to adopt it on a large scale. Though India can slowly introduce green hydrogen technology along with other renewable energy mix to overcome the cost factor.
Looking ahead, concerted efforts will be needed to translate our research findings into tangible actions and policies. Collaboration between policymakers, industry stakeholders, and research institutions will be vital in scaling up clean energy deployment, fostering innovation, and overcoming existing obstacles. By tapping into the abundant renewable resource, India can pave the way towards a more sustainable and resilient future, characterized by clean energy access, economic prosperity, and environmental stewardship.

4. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

5. Data Availability

Data will be made available on request.

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