Green Hydrogen for a Sustainable Future: Prospects and Challenges for Energy-Based Applications in Major Indian States by 2030

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Abstract. India is a country with a rapidly growing demand for energy. Currently, most of the country's energy demand is met by fossil fuels which are hindering our environment by contributing to greenhouse gas emissions and climate change. Green hydrogen produced from renewable energy sources is clean and free from the pollution which can reduce our country's dependency on fossil fuels. Building a green hydrogen community in India can help the country to transit into sustainable development and achieve net zero emissions. Our review shows that green hydrogen can be produced in India according to the geography of the different regions rich in renewable energy resources such as solar and wind power. Many states in India have high solar energy prospectus, high wind speeds and existing infrastructure and supply chain logistics that can be used for the production and distribution of green hydrogen. States such as Gujarat, Andhra Pradesh and Tamil Nadu have been identified by the Indian government as "renewable energy clusters" and aim to support the development of green hydrogen projects. Additionally, the Indian coastal area's seawater can be used as a water source for electrolysis. These coasts are windy and suitable for wind power generation and have access to excellent ports and transport infrastructure to transport green hydrogen. Overall, India has unlimited potential for green hydrogen production due to its abundant renewable energy sources and favourable geographical conditions. India can use this potential to become a major player in the green hydrogen market with the right political and regulatory framework.

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1 Introduction

Diversification of energy carriers and mediums is vital for the dynamically growing India, both in population and economy. In this regard, ensuring energy security to its ever-growing masses that by insignificantly harming the environment is very critical. To achieve that, along with the diversification of energy sources- diversifying its energy carriers and mediums is also necessary. One such energy carrier is “HYDROGEN” [1, 2].

Though Hydrogen is one of the cleanest forms of fuel, its production of it is not always the cleanest [3]. Based on how it is produced, hydrogen can be classified as green hydrogen, blue hydrogen, brown hydrogen, yellow hydrogen, turquoise hydrogen, and even pink hydrogen. However, relying on unsustainable methods of hydrogen production, like those outlined above, is detrimental to our cause [4, 5]. Hence the "GREEN HYDROGEN" is the only way to clean energy.

India's transportation and industrial sectors are among the biggest in the world, adding to the list of largest emitters of CO_2. Crude oil, which is burnt to provide energy, is the main reason for the emission of greenhouse gases [1]. The increased greenhouse gases are posing a threat to mankind with the effects of climate change. To bring down the effects of climate change, consumer preferences are being shifted to a more eco-friendly way, and this is where green hydrogen comes into the picture [4, 6]. Also, the implementation of the carbon tax in India is currently Rs.400 per ton which links fuel prices to emissions. As a result, fuel prices will escalate, leaving people to switch to cleaner forms of energy [7]. Hydrogen, the non-toxic gas, is the lightest and the most abundant element in the world. It can exist in both solid and liquid form [8]. Its high energy content makes hydrogen a suitable fuel for the transportation and industrial sectors. The end products of the electrolysis process are hydrogen and oxygen gases, therefore it is a clean process as it does not emit any greenhouse gases into the environment [9]. Hence green hydrogen is the best alternative to crude oil as a fuel. However, the cost of producing green hydrogen is slightly higher, which is Rs.350-400/kg [1] and 39kWh of electricity is required to produce 1 kg of hydrogen.

Even though green hydrogen is the cleanest, its generation is undoubtedly complicated. With the complexity and difficulty associated with the storage and transportation of hydrogen, the challenges with production are more complex [10, 11]. The main drawback of green hydrogen at present is its cost and efficiency [12]. Conversion efficiency is also on the lesser side. Advancements in production technologies will resolve the problem and it is happening at a swift pace. At present, the only process to produce green hydrogen is electrolysis, where water gets split into hydrogen and water molecules [5]. Alkaline electrolysis cells (AEC), proton exchange membrane electrolysis cells (PEMEC), and solid oxide electrolysis cells are the three different forms of electrolysis technology or electrolysis cells (SOEC) [13]. Fig. 1 and 2 show the working of the alkaline electrolysis method and PEM method.

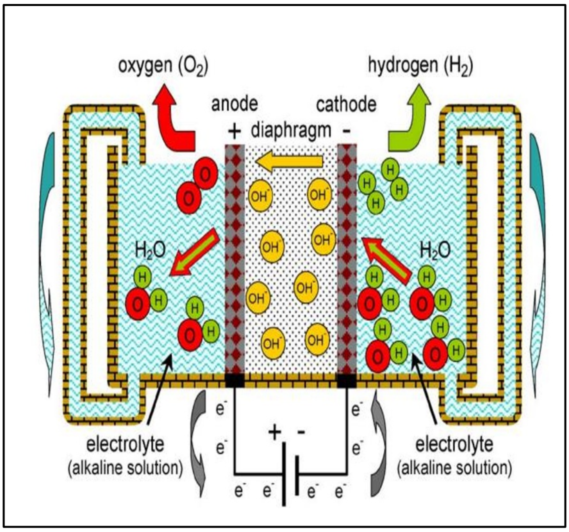

Figure 1: The Alkaline electrolysis method [14]

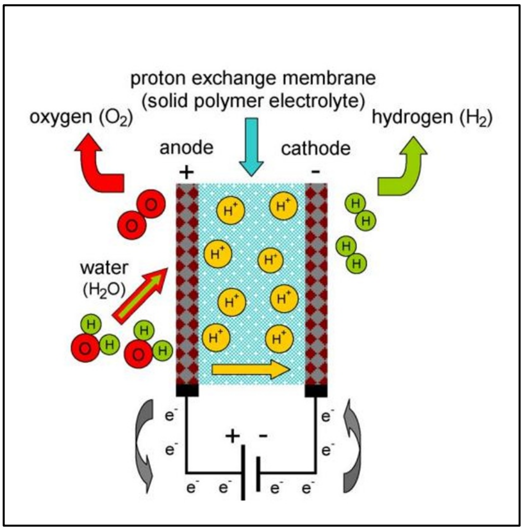

Figure 2: PEM method[14].

The conceptualization and implementation of green hydrogen in various domains and sectors have been already done in various developed and developing countries. It can be used in various fields where using any other technologies is not feasible [2, 12, 15, 16]. For example, in heavy vehicles and aeroplanes where using batteries is inefficient due to low volumetric energy density [17]. Even batteries used in light vehicles include earth metals and materials which are not eco-friendly and disposal of these batteries causes pollution, hence efforts are being put in to curb these issues [18].

The major application of green hydrogen as a fuel is in transportation, as it is one of the leading sectors in India [19]. Hydrogen power trains can be used in road transportation such as passenger cars, motorcycles, buses, and trucks and in off-road transportation such as trains, aircraft, and ships. Currently, available gas boilers and furnaces can be run on hydrogen mixtures. It also finds its use in residential and commercial heating. Industries are responsible for one-fifth of the total greenhouse gases as they mainly rely on fossil fuels. Therefore, to reduce greenhouse gases hydrogen can be substituted to provide heat and energy to industries [20].

India with its huge geographical extent and diversity has humongous potential and capabilities in renewable energy resources of various types [21]. Due to this, the production of green hydrogen is very much beneficial to India and has enormous applications [6]. Currently, India's installed electric capacity is made up of around 40% renewable energy. The right investments and efforts should be made to increase the amount of renewable energy that could be used to produce green hydrogen. India should develop into a multi-source and multi-medium energy ecosystem from its current basic energy ecosystem.

2 Existing energy scenario in India

The Indian economy has soared to a greater height by ranking 5th in the world in the year 2022. It is also expected to achieve rank 3 by the year 2029. This feat was achievable due to the economic performance of states such as Maharashtra, Tamil Nadu, Uttar Pradesh, Gujarat, Karnataka, West Bengal, Rajasthan, Andhra Pradesh, Telangana and Madhya Pradesh [22]. India is the third largest energy consumer in the world, constantly planning to build infrastructures to meet the growing energy requirements [23]. Therefore, let us analyze the energy scenario of our country keeping these economically prosperous states in context.

2.1 Maharashtra

Maharashtra is the second most populated state and the third largest state by area spread over 307,713 km^2 (118,809 sq. mi) in India. The major contributors to the state's economy (89%) are the industrial and service sectors. The state consumes 12% of the country's electricity production and the electricity demand has gone up. The state has a large scope for renewable energy, most of which is left untapped [24]. Table 1 represents the installed capacity of electricity generation in GW from different energy sources in Maharashtra state.

Table 1: Installed capacity of electricity generation of Maharashtra in GW as of 31.12.2022.

HYDRO (GW)	THERMAL (GW)	NUCLEAR (GW)	RES* (GW)	TOTAL (GW)	GREEN SOURCES		
					WIND POWER (GW)	SOLAR POWER (GW)	TOTAL (GW)
3.33	23.37	0.0	11.67	38.37	5.01	3.65	8.66

2.2 Tamil Nadu

Tamil Nadu is the tenth largest state and the sixth most populous state in India and has the highest number of business firms. It ranks 4th in the consumption of electricity in India. The state is blessed with sources of renewable energy, such as solar and wind [25]. It also has a coastal region with great ports that facilitate easy transportation of energy. Table 2 represents the installed capacity of electricity generation in GW from different energy sources in Tamil Nadu state.

Table 2: Installed capacity of electricity generation of Tamil Nadu in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	RES* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
2.18	8.51	0.0	17.51	28.2	9.94	6.41	16.35

2.3 Uttar Pradesh

Uttar Pradesh covers 240,928 km^2 (93,023 sq. mi) of land area and is the most populous state in the country with a population of 200 million. It ranks 10th in the country for total power requirements as it has seen huge demand for power in the last decade. But it lags in renewable energy capacity compared to other larger states [26]. Table 3 represents the installed capacity of electricity generation in GW from different energy sources in the state of Uttar Pradesh.

Table 3: Installed capacity for electricity generation of Uttar Pradesh in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	Res* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
0.72	12.77	0.0	4.73	18.22	-	2.49	2.49

2.4 Gujarat

Gujarat is a state with a coastline of 1600 km which is the longest in the country. It is the fifth largest state by land area 196,024 km^2 (75,685 sq. mi) and the ninth most populated state in India. It stands first on the list of states consuming the most power in a year.

Gujarat is one of the most anticipated states as currently, the renewable energy generation capacity is higher than the other states of India because it is geographically situated in the most favourable location [27]. Table 4 represents the installed capacity of electricity generation in GW from different energy sources in the state of Gujarat.

Table 4: Installed capacity for electricity generation in Gujarat in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	RES* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
0.77	20.23	0.0	18.56	39.6	9.9	8.5	18.4

2.5 Karnataka

Karnataka is located in the West-Central part of the Deccan peninsula of the Indian union with a land area of about 191,791 km^2 (74,051 sq. mi) occupying around 5.84% of the total geographical area of our country. The population of the state accounts for 61,095,297. The main source of energy is hydroelectric plants, as Karnataka has no coal deposits [28]. Karnataka currently ranks 4th amongst the other states in the total installed capacity of renewable energy [29]. Table 5 represents the installed capacity of electricity generation in GW from different energy sources in the state of Karnataka.

Table 5: Installed capacity of electricity generation of Karnataka in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	RES* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
3.59	7.11	0.0	16.34	27.04	5.27	7.89	13.16

2.6 West Bengal

West Bengal is situated to the east of India along the Bay of Bengal [30] with a land area of 88,752 km^2 (34,267 sq. mi) being the thirteenth largest state. It is the fourth most populated state, with a population of 91 million. The development of West Bengal's energy sector since 2000 has been the most extraordinary and periodically encouraging [31]. The state's current renewable energy status is not encouraging, though it is situated in a geographically strong location. The energy generated from solar is minimal and nil from wind sources. Table 6 represents the installed capacity of electricity generation in GW from different energy sources in the state of West Bengal.

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Table 6: Installed capacity for electricity generation in West Bengal in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	Res* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
0.99	7.43	0.0	0.6	9.02	-	0.6	0.6

2.7 Rajasthan

Rajasthan is the largest state in the country with a total land area of 3, 42, 239 sq. km. (132139 sq. miles) and is the seventh largest by population. Rajasthan- the desert State of India is immensely diversified with dunes, hills, blistering heat and cold [32]. The state depends on thermal as well as renewable energy sources for power requirements. It has the highest installed capacity of renewable energy sources in the country, and most of it comes from solar sources [33]. Table 7 represents the installed capacity of electricity generation in GW from different energy sources in the state of Rajasthan.

Table 7: Installed capacity of electricity generation of Rajasthan in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	Res* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
0.43	10.97	0.0	21.17	32.57	4.68	16.34	21.02

2.8 Andhra Pradesh

Andhra Pradesh is located on the southeastern coast of India. It is the seventh largest state by land area of 162,975 km^2 (62,925 sq. mi) and the tenth most populous state with a population of 49,386,799. The state ranks first position for installed hydropower generation in the country but the majority of energy comes from thermal energy sources. The state ranks 7^{th} in the renewable energy scenario. Table 8 represents the installed capacity of electricity generation in GW from different energy sources in the state of Andhra Pradesh.

Table 8: Installed capacity for electricity generation of Andhra Pradesh in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	Res* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
1.67	12.30	0.0	9.35	23.32	4.1	4.5	8.6

2.9 Telangana

Telangana is located in the south-central part of the Indian peninsula. It is the eleventh largest state having a total land area of 112,077 km^2 (43,273 sq. mi) and the twelfth populated state of India has 35,193,978 people. The energy generated through coal is the major source of power in the state and renewable energy became the 2nd major source of energy [34]. Table 9 represents the installed capacity of electricity generation in GW from different energy sources in the state of Telangana.

Table 9: Installed capacity of electricity generation of Telangana in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	Res* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
2.48	7.19	0.0	5.1	14.77	0.13	4.65	4.78

2.10 Madhya Pradesh

Madhya Pradesh is a state situated in central India. It is the second-largest state and the fifth-most populated state with over 72 million residents. It has several coal projects and ranks 4th in the total installed capacity of thermal energy in the country but lags in the installation of renewable energy. Table 10 represents the installed capacity of electricity generation in GW from different energy sources in the state of Madhya Pradesh.

Table 10: Installed capacity for electricity generation in Madhya Pradesh in GW as of 31.12.2022.

Hydro (GW)	Thermal (GW)	Nuclear (GW)	Res* (GW)	Total (GW)	Green Sources		
					Wind Power (GW)	Solar Power (GW)	Total (GW)
1.70	11.80	0.0	5.87	19.37	2.84	2.77	5.61

Fig. 3 is a graphical representation of the total installed capacity of electricity (GW) in various states. It is observed that Gujarat has the most installed capacity of energy from all forms of energy and West Bengal Fig. 4 represents the total installed capacity of green energy sources (GW) in various states using a horizontal bar graph and it is evident from the graph that Rajasthan has the most amount of installed green energy sources in the country followed by Gujarat and Tamil Nadu.

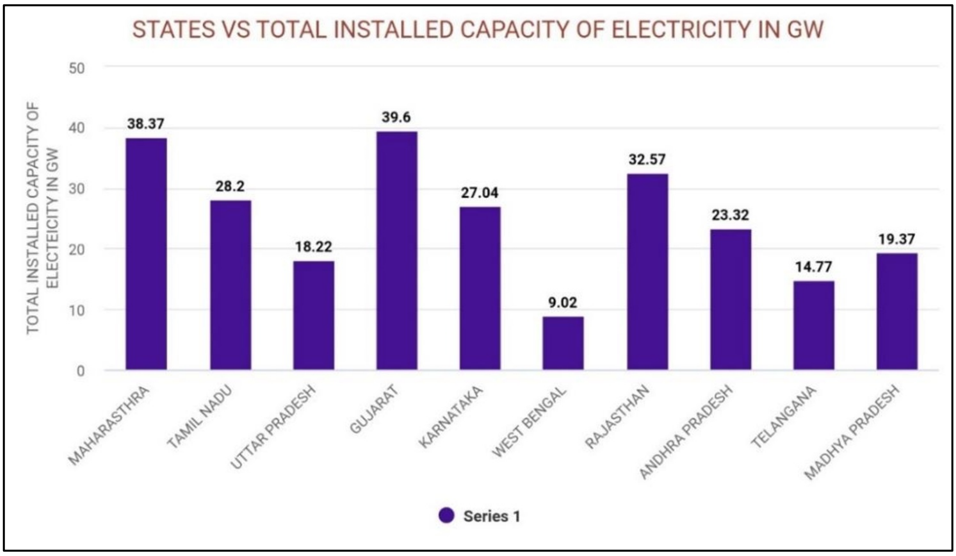

Figure 3: Representation of total installed capacity of electricity (GW) in various states using a bar graph.

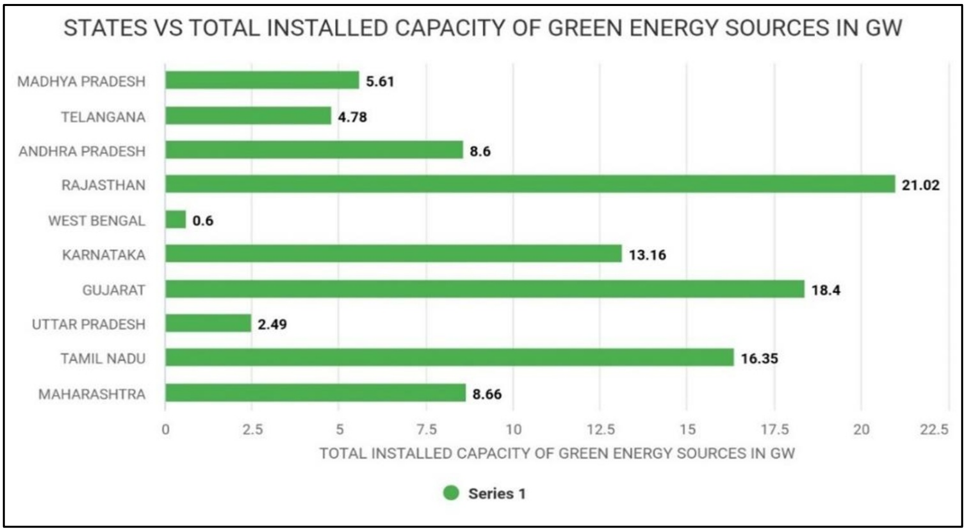

Figure 4: Representation of total installed capacity of green energy sources (GW) in various states using a horizontal bar graph.

3 Available potential of green energy sources in major indian states

India's potential for renewable energy is vast and the majority of it is left untapped. Table 11 clearly shows us the potential of both solar and wind energy we can utilize in our country if we give more prominence to setting up solar power plants and wind farms. The energy generated will help India to meet its domestic, agricultural and industrial energy requirements, thus leading the country to transit into net zero emissions by reducing the emission of CO_2 produced by human activities [35].

Table 11: Comparison between installed capacity (GW) and potential capacity (GW) of solar and wind energy.

States	Solar Energy		Wind Energy	
	Installed Capacity(GW)	Potential Capacity(GW)	Installed Capacity(GW)	Potential Capacity(GW) At 100 M
Maharashtra	3.65	64.32	5.01	45.39
Tamil Nadu	6.41	17.63	9.94	33.79
Uttar Pradesh	2.49	22.83	-	-
Gujarat	8.5	35.77	9.9	84.43
Karnataka	7.89	24.76	5.27	55.85
Rajasthan	16.34	142.33	4.68	18.77
Andhra Pradesh	4.5	38.66	4.1	44.23
Telangana	4.65	20.41	0.13	4.24
West Bengal	0.6	6.36	-	-
Madhya Pradesh	2.77	62.66	2.84	10.48
Total(GW)	**57.8**	**435.73**	**41.87**	**297.18**

The potential capacity available in these states is obtained through various articles and government websites which are based on the studies conducted by various officials concerning the geography of India. With time and the right policies, India can harness all of this available potential and establish a bigger green hydrogen ecosystem. Fig. 5 shows a graphical representation of the comparison between installed and available potential capacity in GW of solar energy. It is clear from the graph that most of the solar energy in Rajasthan is left untapped and if utilized electively will bring about major changes in the energy scenario of the country. Fig. 6 shows a graphical representation of the comparison between installed and available potential capacity in GW of wind energy. The graph shows that Gujarat has major potential for wind energy and few states like Uttar Pradesh and West Bengal have negligible.

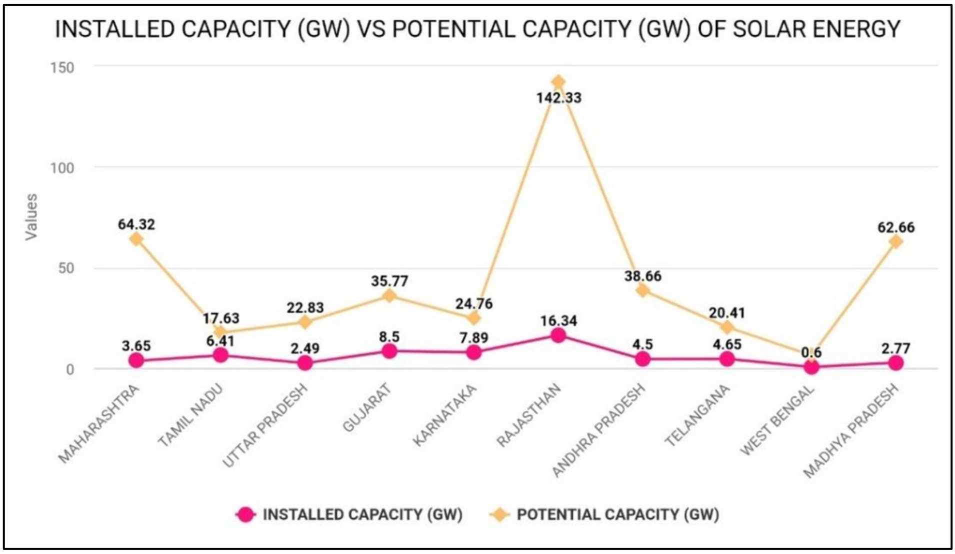

Figure 5: Installed Capacity (GW) vs Potential Capacity (GW) of solar energy.

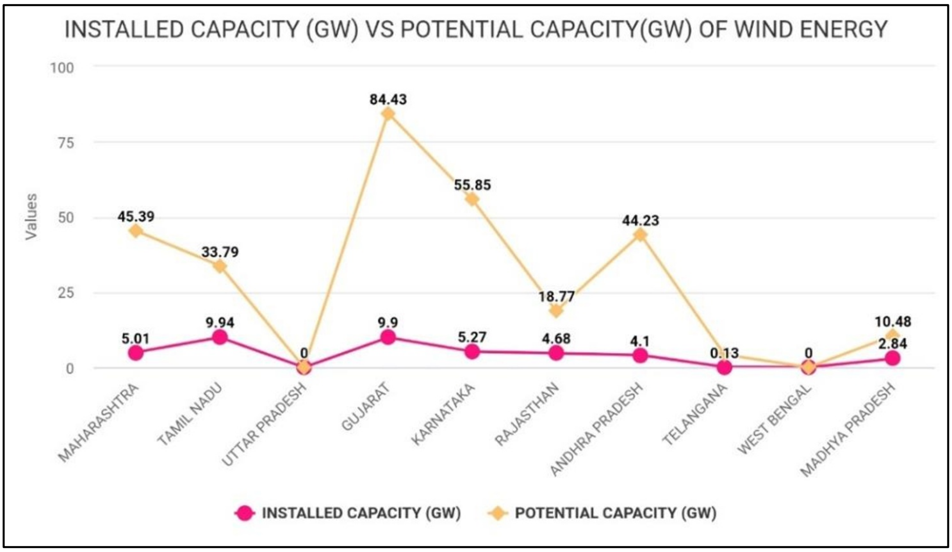

Figure 6: Installed Capacity (GW) vs Potential Capacity (GW) of wind energy.

4 Requirements for the production of green hydrogen and opportunities for its use

With all the benefits of green hydrogen and energy diversification, emerging countries like India should make efforts to implement a hydrogen economy. By 2030, green hydrogen should be able to supply at least 10% of our present energy needs (as of 2022). So, to generate the necessary green hydrogen, we must utilize the potential zones of solar and wind energy resources extensively.

If we consider that 10% of our current demand will be met by green hydrogen in 2030, we can estimate the amount of hydrogen needed. To find that we have, Total Consumption of electricity (FY 2021-2022): 1379812 GWh

10% of total Consumption: 137981.2 GWh. Hydrogen has an energy density of around 39 KWh/kg. This means we can produce 39KWh of electricity using 1Kg of hydrogen. This is feasible if fuel cells had 100% efficiency, which they do not. Currently, their efficiency stands at 45%.

At 45% efficiency, 1 kg of hydrogen can produce around 16KWh of electricity.

To produce 13798.1 GWh,

The hydrogen required in Kg $= \frac{137981.2 \times 10^6}{16}$

The total quantity of hydrogen required is 862,38,25,000 Kg or 86,23,825 Ton

To make green hydrogen we need to produce the above-required hydrogen using only electricity produced by renewable energy. We can produce it using commonly used methods like alkaline water electrolysis or Polymer electrolyte membrane (PEM) electrolysis, which have efficiencies of around 67%.

At 67% efficiency, 50 KWh of electricity is required to produce 1 kg of Hydrogen.

Estimates of the electricity required to produce 862,38,25,000 Kg of hydrogen.

Total Electricity required in KWh $= 862{,}38{,}25{,}000 \times 50$

We will need 43,11,91,250000 KWh of electricity, or 4,31,191.25 GWh, to produce the hydrogen we will need If we assume that hydrogen will be able to satisfy 10% of our present demand in 2030. In GW, we need **50 GW** of electricity from renewable energy sources.

With their combined production, we may produce the above-mentioned power using 60% and 40% of solar and wind energy. Furthermore, these energies can be produced following the state's respective energy potential. Also, possible locations for this generation can be suggested using various factors such as solar irradiance, average temperature, amount of installable space available, wind speed, wind patterns, wind density etc. Table 12 and Fig. 7 show the amount of solar capacity that should be installed in each state to meet the 10% of green hydrogen requirements. Table 13 and Fig. 8 provide a list of locations where wind capacity should be installed in GW to meet the 10% green hydrogen requirement. Therefore, green hydrogen production for any application will be solely provided by these locations without disturbing the regular pattern of operations of electricity supply thus not hindering daily requirements of other purposes.

Table 12: Solar capacity to be installed in GW and their possible locations for installation.

States	Solar Capacity To Be Installed (GW)	Possible Locations for Installation
Maharashtra	4.428	Pune, Solapur, Kolhapur, Sangli
Tamil Nadu	1.212	Erode, Salem, Tirupur, Vellore
Uttar Pradesh	1.569	Lucknow, Fatehpur, Gonda, Banda
Gujarat	2.462	Bhavnagar, Gir Somnath
Karnataka	1.704	Raichur, Bidar, Gulbarga, Belgavi, Uttar Kannada
Rajasthan	9.798	Udaipur, Bhilwara, Tonk
Andhra Pradesh	2.661	Guntur, Nandyal, Annamayya, Chittoor
Telangana	1.404	Narayanpet, Nalgonda, Khammam
West Bengal	0.435	Paschim Medinipur
Madhya Pradesh	5.598	Jabalpur, Panna, Rajgarh

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Table 13: *Wind capacity to be installed in GW and their possible locations for installation.*

States	Wind Capacity To Be Installed (GW)	Possible Locations for Installation
Maharashtra	3.05	Nashik, Jalgaon, Pune, Aurangabad, Ahmednagar
Tamil Nadu	2.274	Chennai
Uttar Pradesh	-	-
Gujarat	5.682	Surat, Navsari
Karnataka	3.758	Dakshina Kannada, Udupi, Hassan, Chikkamagalur
Rajasthan	1.262	Jalore, Pali
Andhra Pradesh	2.976	East Godavari, West Godavari, Bapatla
Telangana	0.848	Kamareddy, Nizambad
West Bengal	-	-
Madhya Pradesh	3.52	Sagar, Chhatarpur, Raisen

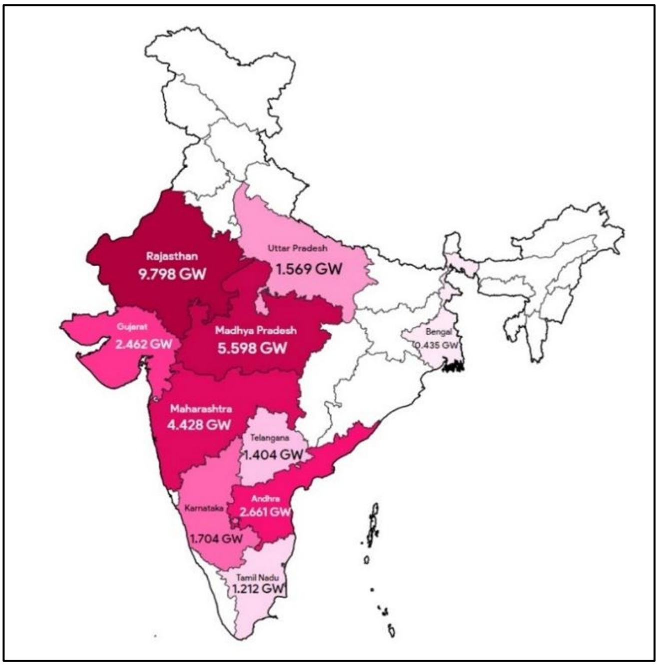

Figure 7: Potential Solar capacities that can be installed in different states in GW.

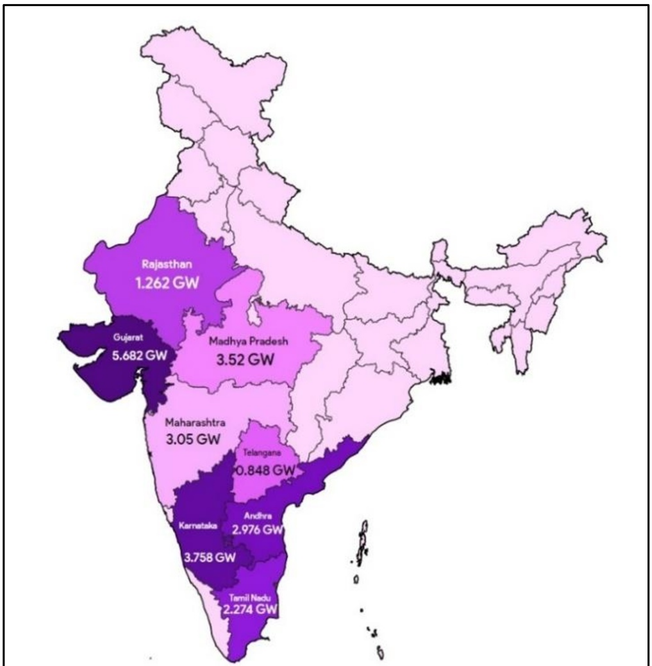

Figure 8: *Potential wind capacities that can be installed in different states in GW.*

5 CONCLUSION

A detailed study on the production, requirements and applications was carried out and it can be observed how green hydrogen can be used and its virtues in our diversification of energy. However, it is not perfect and has its caveats. Despite being the most abundant, hydrogen requires a lot of energy to convert into useful energy, which results in a significant amount of energy waste. Even technologies related to hydrogens such as electrolysis and fuel cells are in the developing stages. So, hydrogen is currently exceedingly inefficient and expensive.

Despite all of this, green hydrogen has many benefits over other existing fuel sources, such as fossil fuels. Firstly, it is a clean and renewable energy source; therefore, there is no chance of environmental damage from burning or atmospheric carbon dioxide release. It can also offer energy security because it can be produced locally without having to be imported from another nation.

Currently, the mentioned Indian states generate a total solar energy of about 57.6 GW out of the total potential of 435.73 GW which translates the utilization to 13.24%. These states produce about 41.87GW wind energy out of 297.18 GW total potential which is about 14.05% utilization. This data suggests that India still has a large amount of untapped renewable energy sources. Proper investments and schemes need to be implemented to extract this potential.

Through all this, we can move one step closer towards an independent, efficient, and sustainable energy economy.

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