GREEN HYDROGEN

1. INTRODUCTION

In a world where the pursuit of clean, sustainable energy sources has taken centre stage, Green Hydrogen has emerged as a shining beacon of hope. This remarkable substance holds the promise of revolutionizing our energy landscape by offering a clean and efficient solution to some of our most pressing environmental challenges. Green Hydrogen, often hailed as the fuel of the future, is hydrogen gas produced through a process that relies entirely on renewable energy sources, such as wind or solar power, resulting in a near-zero carbon footprint.

The production of Green Hydrogen represents a breakthrough in the quest to decarbonize our energy systems. Unlike conventional hydrogen production methods, which predominantly rely on fossil fuels and release significant greenhouse gas emissions, Green Hydrogen is produced through a process called electrolysis. During electrolysis, water is split into hydrogen and oxygen using electricity generated from renewable sources, leaving no harmful by-products. This fundamental shift in production methods holds the key to addressing some of the most pressing challenges of our time, including climate change and the transition away from fossil fuels.

The advantages of Green Hydrogen are manifold. Firstly, it serves as a versatile and efficient energy carrier. Hydrogen can be easily transported and stored, making it a viable option for a wide range of applications, from powering vehicles to industrial processes and even heating homes. Secondly, its production is inexhaustible, as long as renewable energy sources like sunlight and wind are available. This abundance ensures a reliable and sustainable energy supply, reducing our dependence on finite fossil fuels. Moreover, Green Hydrogen has the potential to create jobs and stimulate economic growth in regions with abundant renewable energy resources.

As we explore the prospects of Green Hydrogen, it becomes evident that this technology has the potential to reshape entire industries and foster a cleaner, more sustainable future. In the transportation sector, hydrogen fuel cells are emerging as a viable alternative to traditional internal combustion engines, offering longer ranges and quicker refuelling times while emitting only water vapour as a by-product. In industry, Green Hydrogen can replace the carbon-intensive processes that currently underpin manufacturing and chemical production. Additionally, it can serve as an energy storage solution, helping to balance the intermittency of renewable energy sources and provide stability to the grid.

However, realizing the full potential of Green Hydrogen requires overcoming numerous challenges, including the high initial costs of electrolysis equipment, the need for further advancements in renewable energy technology, and the development of a robust infrastructure for hydrogen production, distribution, and utilization. Despite these challenges, governments, industries, and researchers worldwide are investing heavily in the development and scaling of Green Hydrogen technology, recognizing its pivotal role in the global transition to a sustainable, low-carbon future.

Apart from Green Hydrogen, there exists a whole colour spectrum of Hydrogen:

a. **Blue Hydrogen:** Blue hydrogen is primarily generated from natural gas through a method known as steam reforming, wherein natural gas is combined with heated steam to yield hydrogen as the primary product. However, this process also results in the production of carbon dioxide as a secondary output. Consequently, the concept of blue hydrogen encompasses the utilization of carbon capture and storage (CCS) to capture and store this carbon.

   At times, blue hydrogen is referred to as 'low-carbon hydrogen' since the steam reforming procedure does not completely prevent the generation of greenhouse gases.

b. **Grey Hydrogen:** At present, this represents the prevalent method of hydrogen generation. Grey hydrogen is derived from natural gas, specifically methane, through steam methane reformation, but it does not involve the capture of the greenhouse gases produced during the process. Essentially, grey hydrogen is identical to blue hydrogen, except it lacks the implementation of carbon capture and storage.

c. **Black and Brown Hydrogen**: By employing black coal or lignite, also known as brown coal, in the hydrogen production process, both black and brown hydrogen occupy the extreme end of the hydrogen spectrum and are highly detrimental to the environment.

   To add to the complexity, any hydrogen generated from fossil fuels through the gasification process is occasionally referred to as either black or brown hydrogen interchangeably. A recent announcement from Japan and Australia revealed a new initiative involving the utilization of brown coal in Australia to produce liquefied hydrogen. This hydrogen will subsequently be transported to Japan for low-emission applications.

d. **Pink Hydrogen**: Pink hydrogen is produced via electrolysis that is powered by nuclear energy. Hydrogen generated from nuclear sources can also be termed as either purple hydrogen or red hydrogen. Furthermore, the exceedingly high temperatures produced by nuclear reactors have the potential to be harnessed in alternative hydrogen production methods. This can involve generating steam for more efficient electrolysis or facilitating steam methane reforming, which may be based on fossil gas.

e. **Turquoise Hydrogen**: This represents a recent addition to the hydrogen color spectrum, and its large-scale production is yet to be demonstrated. Turquoise hydrogen is manufactured using a technique known as methane pyrolysis, which yields hydrogen and solid carbon as its output. In the future, the value of turquoise hydrogen may hinge on whether the thermal process is driven by renewable energy and whether the carbon is either permanently stored or put to use, potentially positioning it as a low-emission hydrogen source.

f. **Yellow Hydrogen:** Yellow hydrogen is a recently coined term referring to hydrogen produced through electrolysis powered by solar energy.

g. **White Hydrogen**: White hydrogen is a naturally formed hydrogen that occurs in underground reservoirs and is generated through hydraulic fracturing (fracking). Currently, there are no plans to harness this hydrogen.

2. SIGNIFICANCE OF GREEN HYDROGEN

Green hydrogen is produced through the electrolysis of water using renewable energy sources such as wind or solar power. This process emits no greenhouse gases, making it a clean and environmentally friendly energy carrier. Hydrogen can be used as a means of energy storage, allowing excess renewable energy to be stored and used when needed, helping to balance grid fluctuations and support energy security. It can be used in a wide range of applications, including transportation, industry, heating, and electricity generation, making it a versatile energy carrier. Hydrogen has a high energy density by weight, which makes it suitable for applications where energy storage needs to be compact, such as in fuel cells for vehicles. Green hydrogen can play a crucial role in transitioning to a sustainable energy future. It can be produced in large quantities and used to replace fossil fuels in sectors that are difficult to decarbonize.

When used in fuel cells, hydrogen produces only water vapour as a by-product, reducing local air pollution and improving air quality in urban areas. Producing green hydrogen locally using renewable resources can enhance a region's energy independence and reduce reliance on imported fossil fuels. Hydrogen can act as a buffer for intermittent renewable energy sources, helping to stabilize the electricity grid and ensure a consistent power supply. Green hydrogen can be transported and traded globally, fostering international cooperation on clean energy solutions. The development and scaling up of green hydrogen technologies can drive innovation in renewable energy, electrolysis, and fuel cell technologies as well.

Hydrogen can be produced from water, which is abundant, reducing concerns related to resource scarcity that can be associated with other energy carriers. Hydrogen can be produced

Figure 1: Significance of green hydrogen

at various scales, from small-scale electrolysers for local applications to large industrial facilities, allowing for decentralized production and distribution. In transportation, hydrogen fuel cells offer fast refuelling, long driving ranges, and compatibility with heavy-duty vehicles like buses and trucks. Hydrogen can be used in industries like steel, chemicals, and aviation, where direct electrification may be challenging, helping to reduce emissions in these sector. The green hydrogen industry can create new jobs in manufacturing, infrastructure development, and research and development, helping stimulate economic growth.

3. UNDERSTANDING GREEN HYDROGEN

Hydrogen, the most abundant element in the universe, has long been recognized for its potential as a clean energy carrier. Green hydrogen, unlike its grey or blue counterparts, is produced using renewable energy sources, primarily wind and solar power. The process of generating green hydrogen involves the electrolysis of water, where electricity from renewable sources is used to split water molecules into hydrogen and oxygen. This method ensures that the production process is emissions-free and environmentally friendly.

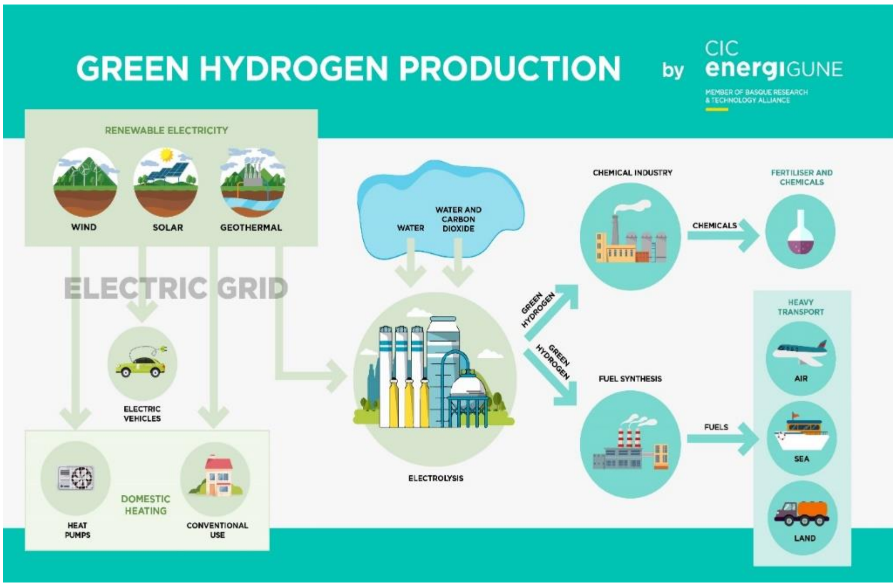

Figure 2: Understanding Green Hydrogen (Source: https://cicenergigune.com/en/blog/electrolysis-water-sustainable-produce-green-hydrogen)

Steps involved in the production:

a) Water purification:

The water used for electrolysis must be purified to remove impurities such as minerals and salts. This is important to prevent damage to the electrolyser and to ensure the production of high-purity hydrogen. Water purification can be done using a variety of methods, such as reverse osmosis, ion exchange, and distillation.

b) Electrolyser:

The electrolyser is the device that is used to split water into hydrogen and oxygen. Electrolysers are typically made of stainless steel or titanium and contain two electrodes, a cathode and an anode. The electrodes are immersed in water and an electric current is applied. The electric current causes the water molecules to split into hydrogen and oxygen atoms. The hydrogen atoms are collected at the cathode, while the oxygen atoms are collected at the anode.

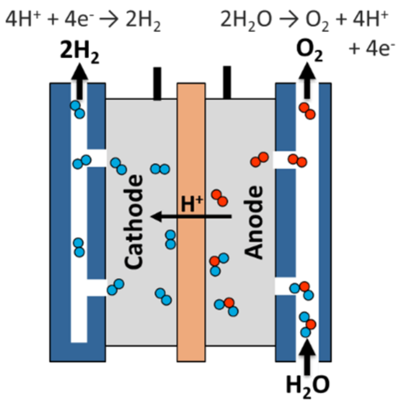

Figure 3: Electrolyser (Source: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis)

c) Electrolysis process:

The electrolysis process is a two-step process. In the first step, water molecules are split into hydrogen and oxygen ions. In the second step, the hydrogen ions are reduced to hydrogen gas at the cathode, while the oxygen ions are oxidized to oxygen gas at the anode. The following chemical reactions show the electrolysis process:

$$H2O + e- \rightarrow \frac{1}{2} H2 + OH- \quad (1)$$

$$2OH- \rightarrow \frac{1}{2} O2 + H2O + 2e- \quad (2)$$

d) Hydrogen collection and storage:

Once the hydrogen gas has been produced, it needs to be collected and stored. Hydrogen gas can be stored in a variety of ways, including compressed gas tanks, liquid hydrogen storage tanks, and metal hydrides. The most common method of hydrogen storage is compressed gas tanks. Compressed gas tanks are made of strong materials such as steel or carbon fibre and can withstand high pressures. Liquid hydrogen storage tanks are used to store hydrogen gas in liquid form. Liquid hydrogen is very cold (-253°C) and must be stored in insulated tanks. Metal hydrides are materials that can absorb and release hydrogen gas. Metal hydrides are still under development, but they have the potential to be a very efficient way to store hydrogen gas.

- **Biomass Gasification**: This method involves heating biomass (organic materials like wood, agricultural residues, or algae) in the presence of limited oxygen or steam to produce a syngas (a mixture of hydrogen and carbon monoxide), which can then be separated to obtain hydrogen.

4. APPLICATIONS

Figure 4: Applications of green hydrogen

Green hydrogen holds immense potential across a diverse range of applications.

- Firstly, it serves as a scalable solution for large-scale energy storage, harnessing excess renewable energy during periods of low demand and converting it into hydrogen via electrolysis. This stored hydrogen can then be transformed back into electricity through fuel cells or other methods when demand is high, ensuring a stable and reliable energy supply.
- In the realm of transportation, hydrogen fuel cells have emerged as a promising option to power various vehicles, from cars and buses to trucks and trains. These fuel cells emit only water vapour as a by-product, making them an attractive choice for mitigating greenhouse gas emissions in the transportation sector.
- Moreover, green hydrogen finds its place in industrial processes, benefiting sectors like steel manufacturing, chemical production, and ammonia synthesis. As a cleaner alternative to conventional hydrogen production methods often reliant on fossil fuels, it can serve as both a feedstock and fuel in various industrial applications, contributing to emissions reduction.
- In the domain of power generation, hydrogen can be directly combusted in gas turbines or integrated into combined-cycle power plants, offering a consistent power supply. This proves particularly valuable in areas where renewable energy generation is intermittent, providing stability to the grid.
- For heating and cooling, green hydrogen can replace natural gas in residential, commercial, and industrial systems. Additionally, it can be used in absorption chillers, effectively reducing emissions in heating and cooling sectors.
- To support the burgeoning adoption of hydrogen-powered vehicles, hydrogen refuelling stations are being deployed, with green hydrogen as the supply source. This facilitates vehicle refuelling with minimal carbon emissions, advancing cleaner transportation options.
- In agriculture, green hydrogen plays a crucial role in the production of ammonia-based fertilizers, essential for modern farming practices. This contributes to reducing the carbon footprint of the agricultural sector, aligning with sustainability goals.
- In space exploration, green hydrogen emerges as a clean and efficient propellant for rockets, offering a promising avenue to minimize the environmental impact of space missions.

5. GREEN AMMONIA

Green ammonia is a term used to describe ammonia production methods that prioritize environmental sustainability and reduced carbon emissions. Unlike traditional ammonia production, which relies heavily on fossil fuels and is associated with significant greenhouse gas emissions, green ammonia is produced using renewable energy sources and environmentally friendly processes. It represents a more sustainable and eco-friendly approach to ammonia production.

The key characteristics of green ammonia include:

a. Renewable Energy Sources: Green ammonia production utilizes renewable energy sources such as wind, solar, hydro, or geothermal power to generate hydrogen, a critical component in ammonia synthesis. This contrasts with conventional ammonia production, which typically relies on fossil fuels like natural gas.

b. Electrolysis: One of the primary methods for producing green ammonia involves electrolysis, a process in which water is split into hydrogen and oxygen using electricity from renewable sources. The hydrogen generated through this process is then used in ammonia synthesis.

c. Reduced Carbon Emissions: Green ammonia production significantly reduces carbon dioxide (CO_2) emissions compared to traditional ammonia manufacturing methods. This reduction in carbon emissions is achieved by replacing fossil fuels with clean energy sources and by implementing carbon capture and utilization technologies.

d. Sustainable Nitrogen Sources: In addition to green hydrogen, green ammonia production also considers the source of nitrogen. Sustainable sources of nitrogen, such as air capture or the utilization of nitrogen from renewable feedstocks, can further enhance the environmental sustainability of the process.

e. Diverse Applications: Green ammonia has a wide range of applications, including serving as a carbon-free fuel for transportation, a storage medium for renewable energy, and a sustainable source of nitrogen for agriculture as a fertilizer.

f. Alignment with Sustainability Goals: Green ammonia aligns with global sustainability and climate change mitigation goals by reducing greenhouse gas emissions, supporting the transition to renewable energy, and promoting sustainable agriculture.

5.1. Traditional Method of Ammonia Production – Haber Bosch Process

The Haber-Bosch process is a critical industrial chemical reaction used to synthesize ammonia (NH3) from nitrogen (N2) and hydrogen (H2) gases. It was developed by Fritz Haber and Carl Bosch in the early 20th century, and it has had a profound impact on modern agriculture and the production of fertilizers.

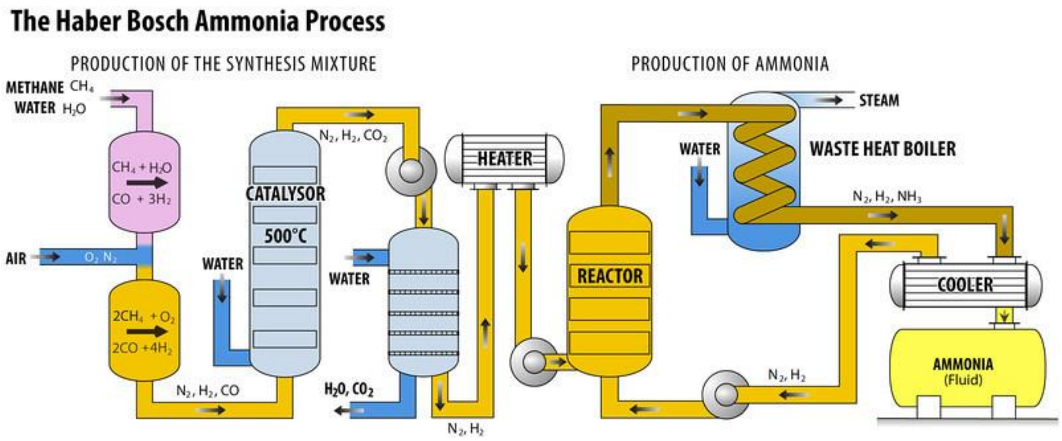

Figure 5: Haber Bosch Ammonia Process (Source: https://www.theengineeringconcepts.com/haber-process-ammonia-manufacturing/)

Here's an overview of the process:

Nitrogen and Hydrogen Sources: The process begins with the sources of nitrogen and hydrogen. Nitrogen is typically obtained from the air (which is about 78% nitrogen), and hydrogen is usually produced by steam reforming of natural gas or other hydrocarbon sources.

Compression: Both the nitrogen and hydrogen gases are compressed to increase their pressure, which is a crucial step for the reaction to proceed efficiently. High pressure is necessary because the reaction between N2 and H2 to form NH3 is an equilibrium reaction, and increasing the pressure shifts the equilibrium towards the formation of ammonia.

Reaction: The compressed nitrogen and hydrogen gases are then introduced into a reactor vessel, where they come into contact with a catalyst. The most common catalyst used in the

Haber-Bosch process is iron with small amounts of other promoters like potassium oxide. The catalyst helps facilitate the reaction between N2 and H2 to form ammonia:

$N_2 + 3H_2 \rightleftharpoons 2NH_3$

This reaction is exothermic, meaning it releases heat. The reaction is typically conducted at high temperatures (around 400-500°C) to optimize the ammonia production rate.

Cooling and Separation: After the gases have reacted, the resulting mixture contains ammonia, unreacted nitrogen and hydrogen, and other byproducts. This mixture is then cooled, which helps to condense the ammonia into a liquid phase, which can be separated from the remaining gases.

Recycle: To improve the overall yield and efficiency of the process, unreacted nitrogen and hydrogen gases are usually recycled back into the reactor, allowing for further ammonia synthesis.

Product Purification: The separated liquid ammonia is further purified to remove any remaining impurities or by-products. This typically involves processes like distillation.

Ammonia Storage and Distribution: The purified ammonia is then stored and distributed for various industrial and agricultural applications. Ammonia is a crucial component in the production of fertilizers, explosives, and various chemicals.

The Haber-Bosch process revolutionized agriculture by making it possible to produce synthetic fertilizers on a large scale. This increased food production and played a significant role in the Green Revolution of the 20th century, which helped alleviate global food shortages.

5.2. Needs and Advantages of Green Ammonia

Green ammonia is gaining attention as an environmentally friendly alternative to conventional ammonia production methods, such as the Haber-Bosch process, due to its potential to reduce greenhouse gas emissions and other environmental impacts. Here are some key reasons for the need and advantages of green ammonia:

Reducing Carbon Emissions: The conventional Haber-Bosch process relies on the production of hydrogen, which is often derived from fossil fuels, leading to significant carbon emissions.

Green ammonia, on the other hand, is produced using renewable or low-carbon hydrogen sources, such as electrolysis of water using renewable electricity or hydrogen from biomass or waste, significantly reducing carbon emissions associated with its production.

Renewable Energy Integration: Green ammonia can serve as a means to store and transport renewable energy, particularly excess electricity generated from wind and solar power when demand is low. This energy can be used to produce hydrogen through electrolysis, which is then converted into ammonia and stored for later use or transport.

Clean Energy Carrier: Ammonia is an efficient carrier of hydrogen, as it has a higher energy density by volume compared to gaseous hydrogen. This makes it a practical option for the long-distance transport of hydrogen, which is challenging to achieve efficiently using gaseous hydrogen due to its low density.

Reducing Nitrogen Pollution: The production of green ammonia can incorporate technologies to capture and manage nitrogen emissions, reducing the environmental impact associated with the release of excess nitrogen compounds, which can lead to water pollution and ecosystem damage.

Sustainable Agriculture: Green ammonia can be used as a more environmentally friendly source of nitrogen for agricultural fertilizers, reducing the carbon footprint of food production and minimizing nitrogen pollution.

Decarbonizing Industry: Ammonia is a key feedstock in the production of various chemicals, and green ammonia can be used as a sustainable source of ammonia for industrial applications, helping to decarbonize these sectors.

International Energy Trade: Green ammonia can be transported globally and used as an energy carrier, potentially reducing dependence on fossil fuels in regions that lack access to renewable energy resources.

Innovation and Research: The development of green ammonia production methods encourages innovation in clean energy technologies, including advanced electrolysis, renewable energy integration, and carbon capture and utilization.

While green ammonia holds significant promise as an environmentally friendly alternative, there are also challenges to overcome. These include the development of cost-effective and efficient green hydrogen production methods, the scaling up of green ammonia production infrastructure, and addressing safety and transportation considerations, as ammonia is toxic and requires specialized handling. Overall, the need for green ammonia is driven by the imperative to reduce greenhouse gas emissions, transition to a more sustainable energy and chemical industry, and address environmental challenges associated with conventional ammonia production. Research and investment in green ammonia technologies are essential to realize its potential benefits fully.

5.3. Applications of Green Ammonia

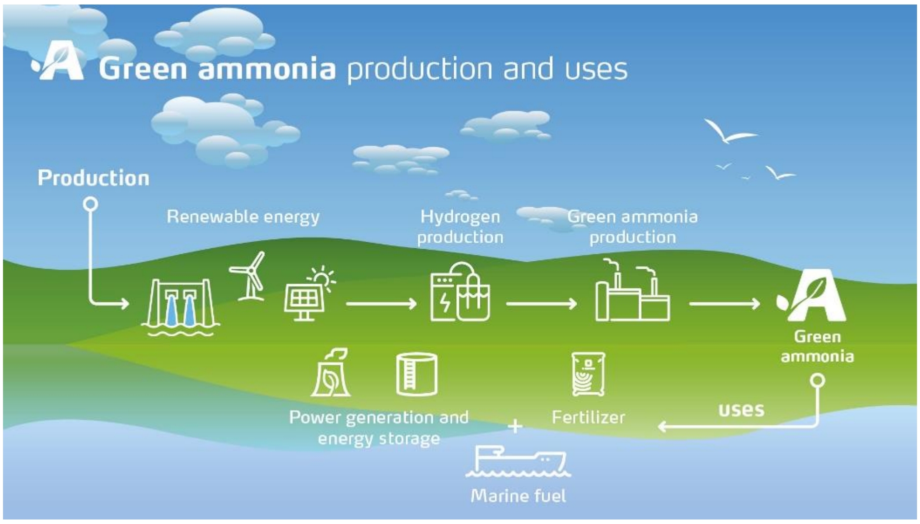

Figure 6: Applications of Green NH3 (Source: https://www.weforum.org/agenda/2021/01/green-ammonia-stop-fossil-fuels/)

a. **Agriculture and Fertilizers**: One of the primary uses of ammonia is in agriculture as a nitrogen fertilizer. Green ammonia can replace conventionally produced ammonia in fertilizers, reducing the carbon footprint of agricultural practices and minimizing the environmental impact associated with nitrogen runoff and pollution.

b. **Clean Energy Carrier**: Green ammonia can serve as an efficient carrier of hydrogen, making it suitable for storing and transporting renewable energy. Excess electricity generated from wind, solar, or other renewable sources can be used to produce green hydrogen, which is then converted into green ammonia for later use or transport. This helps in balancing energy supply and demand and supports the integration of renewable energy into the grid.

c. **Power Generation**: Green ammonia can be used as a fuel in power plants, particularly in gas turbines and internal combustion engines. When burned, it releases nitrogen and water as byproducts, making it a cleaner alternative to traditional fossil fuels.

d. **Maritime and Shipping:** The maritime industry is exploring green ammonia as a potential fuel for ships to reduce emissions and comply with stricter environmental regulations. Ammonia can be used in fuel cells or combustion engines to power ships.

e. **Chemical Industry**: Ammonia is a critical feedstock in the chemical industry for the production of various chemicals, including fertilizers, explosives, and synthetic materials. Green ammonia can replace conventionally produced ammonia in these processes, reducing the carbon footprint of the chemical sector.

f. **Hydrogen Production**: Green ammonia can be a source of green hydrogen, which has applications in a wide range of industries, including transportation, industrial processes, and energy storage. Green hydrogen can be obtained by dissociating ammonia back into hydrogen and nitrogen.

g. **Carbon Capture and Utilization (CCU):** Green ammonia can play a role in carbon capture technologies. It can be used as a solvent for capturing carbon dioxide (CO2) from industrial emissions. This captured CO2 can then be utilized in various applications, such as enhanced oil recovery or the production of synthetic fuels and chemicals.

h. **International Energy Trade**: Green ammonia can be transported globally and used as an energy carrier, potentially reducing dependence on fossil fuels in regions that lack access to renewable energy resources. This makes it a valuable resource for international energy trade.

i. **Industrial Heat and Cooling**: Ammonia can be used as a refrigerant in industrial cooling systems and air conditioning. Using green ammonia in these applications reduces the environmental impact compared to traditional refrigerants like hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs).

j. **Hydrogen for Mobility**: Green ammonia can serve as a source of hydrogen for fuel cell vehicles, particularly in areas where hydrogen infrastructure is limited. Ammonia can be converted back into hydrogen and used to power fuel cell electric vehicles.

k. **Space Exploration**: Ammonia is used as a coolant in space applications and can be produced in space using green ammonia production methods, reducing the need to transport ammonia from Earth.

As green ammonia production technologies continue to advance and become more economically competitive, the range of applications is likely to expand, contributing to a more sustainable and environmentally friendly future across multiple industries.

6. GLOBAL GREEN HYDROGEN SCENARIO

Green hydrogen is hydrogen that is produced using renewable energy sources, such as solar and wind power. It is a clean and sustainable fuel that can be used to decarbonize a variety of sectors, including industry, transportation, and power generation

The global green hydrogen market size was valued at USD 4.02 billion in 2022 and is expected to hit over USD 331.98 billion by 2032**,** poised to grow at a CAGR of 54.98% from 2023 to 2032**.**

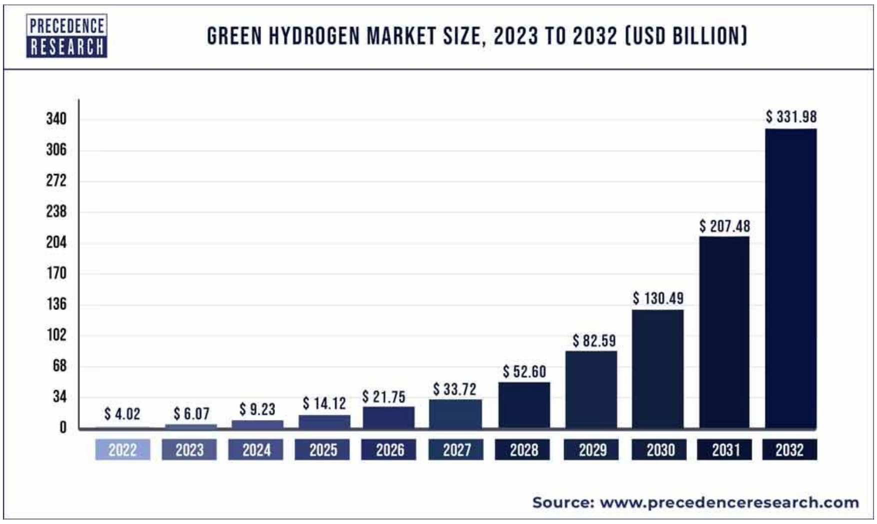

Figure 7: Green hydrogen Market Size (Source:www.precedenceresearch.com)

The growth of the green hydrogen market is being driven by a number of factors. Governments worldwide are taking proactive measures, both financial and policy-driven, to facilitate the development and widespread adoption of green hydrogen. Notably, the European Union has set an ambitious target of producing a substantial 10 million tonnes of green hydrogen annually by 2030. This commitment demonstrates the global recognition of green hydrogen as a linchpin in the pursuit of sustainable and carbon-neutral energy solutions.

Simultaneously, many corporations and organizations are charting an ambitious course towards decarbonization, aiming to dramatically reduce their carbon emissions. In this endeavour, green hydrogen emerges as a pivotal enabler of these lofty decarbonization goals. The significance of this transition is underscored by the world's largest oil and gas company, Saudi Aramco, which has laid out formidable plans to generate 6.5 million tonnes of green hydrogen each year by 2030, thereby signalling the transformation of even traditionally fossil fuel-centric industries towards cleaner energy alternatives.

Furthermore, the prospects for green hydrogen are bolstered by a substantial reduction in production costs. Technological advancements and the realization of economies of scale are driving a swift decline in the cost of manufacturing green hydrogen. This cost reduction trajectory not only enhances the competitiveness of green hydrogen but also underscores its growing feasibility as a clean energy source.

As we look to the future, the trajectory of green hydrogen's global influence will be influenced by several factors, including the rate of technological innovation, the extent of governmental support, and the level of private sector investment. If these factors align favourably, green hydrogen stands poised to play a transformative role in the global energy transition, steering us closer to the coveted goal of achieving net-zero emissions on a global scale by 2050.

Here are some of the key trends that are expected to shape the global green hydrogen scenario in the coming years:

- **Increased investment in green hydrogen production:** The global green hydrogen market is expected to attract significant investment in the coming years, as governments and companies look to scale up production. This investment will be needed to drive down costs and make green hydrogen more competitive with other fuels.

- **Development of new green hydrogen production technologies:** New green hydrogen production technologies are being developed all the time, which could further reduce costs and improve efficiency. For example, companies are developing new types of electrolysers that can produce hydrogen more efficiently.
- **Expansion of green hydrogen infrastructure:** As the green hydrogen market grows, there will be a need to expand the associated infrastructure, such as hydrogen pipelines and storage facilities. This will allow green hydrogen to be transported and used more widely.
- **Growing demand for green hydrogen in a variety of sectors:** Green hydrogen is expected to be used in a variety of sectors in the coming years, including industry, transportation, and power generation. For example, green hydrogen can be used to produce steel and other industrial products without emitting greenhouse gases. It can also be used to fuel fuel cell vehicles and to store renewable energy.

The global green hydrogen scenario is very promising. Green hydrogen has the potential to play a major role in the global energy transition and help to achieve net zero emissions by 2050.

7. CHALLENGES AND CONSTRAINTS

The production and adoption of green hydrogen, a promising clean energy carrier, come with a multitude of challenges. The high production costs associated with green hydrogen, primarily generated through water electrolysis, make it more expensive compared to alternative hydrogen forms, such as grey or blue hydrogen derived from natural gas with carbon capture and storage (CCS).

Green hydrogen's reliance on intermittent renewable energy sources like wind and solar introduces issues of uneven production and supply due to the intermittency and location-dependent nature of these resources.

The process of converting electricity into hydrogen via electrolysis incurs energy losses, rendering it less efficient than direct electricity use for certain applications. Furthermore, establishing the necessary infrastructure for hydrogen production, storage, and distribution is a formidable challenge, encompassing the construction of new electrolysis facilities and hydrogen pipelines.

Moreover, hydrogen's low energy density complicates its storage and transportation, necessitating high-pressure tanks or cryogenic storage, which adds complexity and cost to the distribution system. Safety concerns arise due to hydrogen's highly flammable nature, mandating robust safety measures throughout its production, storage, and transportation phases.

The scalability of green hydrogen production to meet global energy demands is another substantial hurdle, demanding significant investments in renewable energy infrastructure for large-scale projects. Additionally, the versatility of hydrogen as an energy carrier, suitable for various sectors like transportation, industry, and power generation, may result in competition for its use, potentially impacting its availability and price.

Furthermore, a lack of standardized processes and technologies for green hydrogen production hinders widespread adoption, making it challenging for companies and industries to adopt a

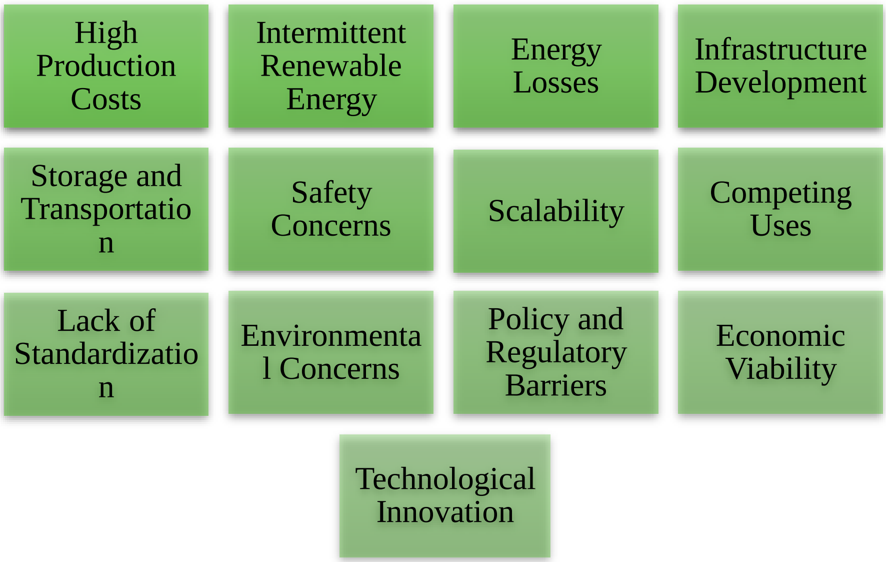

Figure 8: Challenges and constraints of green hydrogen

common approach. Environmental concerns also need careful consideration as scaling up green hydrogen production may impact land use and resource requirements, despite its environmental friendliness when produced using renewable energy sources.

Policy and regulatory barriers can significantly influence the development and deployment of green hydrogen, with inconsistent or inadequate policies potentially impeding its growth.

Additionally, the economic viability of green hydrogen production is heavily reliant on government incentives, subsidies, and carbon pricing mechanisms, potentially making it non-competitive with fossil fuels in their absence.

The ongoing technological innovation is essential to enhance the efficiency and reduce the costs of green hydrogen production technologies. In conclusion, addressing these multifaceted challenges is paramount to realizing green hydrogen's full potential as a clean and sustainable energy source.

Type of Risk	Risk categorisation	Risk Management/Mitigation Measures
Strategic Risks	Supply Chain Disruptions in Critical Inputs	Diversification in Supply Chains
Technological Risk	Technology Disruptions and Unforeseen Developments	Diversification of technology options, Technology agnostic approach in funding support. Funding of multiple R&D and pilot threads, Collaborative platforms for industry, academia and startups
Operational/Project Level Risks	Water Availability	Optimizing location of Renewable Energy and Green Hydrogen production plants
	Land Availability	States to be requested to create land banks for Renewable Energy and Green Hydrogen deployment
	Safety Concerns	Rigorous safety standards and regulatory mechanisms
Financial and Market Risks	Sustainable Demand	Demand creation efforts in identified sectors
	Availability of Affordable Renewable Energy (RE)	Integrated planning of RE capacity addition
	Availability of Electrolysers and other key components	Incentives to create domestic manufacturing ecosystem
	Additional infrastructure costs and capital expenditure	Ramp up of capacities to achieve economies of scale
	Availability of accessible Credit	Risk sharing framework in procurement, Facilitating projects to access FDI, bond markets, MFAs

Figure 9: Risks associated with green hydrogen and its mitigation measures (Source: National Green Hydrogen Mission, India)

8. INTERVENTIONS FOR GREEN HYDROGEN ADVANCEMENT

The advancement of green hydrogen technology is driven by several key trends and innovations. High-efficiency electrolysis techniques, such as Proton Exchange Membrane (PEM) and Solid Oxide Electrolysis Cells (SOEC), are significantly enhancing hydrogen production efficiency. PEM electrolysis, with its quick response time, is particularly well-suited for grid balancing and intermittent renewable energy sources like wind and solar.

Moreover, the integration of renewable energy sources like wind, solar, and hydropower into hydrogen production is essential, supported by smart grid technologies, advanced inverters, and efficient grid management systems to ensure a stable and reliable power supply to electrolysers. Scaling up the size and capacity of electrolysers is another critical trend, as it reduces the cost per unit of hydrogen produced, enhancing the competitiveness of green hydrogen.

Innovations in catalysts and materials, including platinum-free catalysts and advanced materials like graphene, aim to reduce costs and improve the durability of electrolysers. Additionally, advanced energy storage solutions, such as large-scale batteries and hydrogen storage technologies like metal hydrides and underground caverns, play a crucial role in storing excess green hydrogen during periods of oversupply and maintaining a continuous hydrogen supply.

Hydrogen transportation is evolving with innovations like high-pressure hydrogen tanks, liquefaction, and solid-state hydrogen storage, making it easier to transport and distribute hydrogen efficiently. Advancements in hydrogen fuel cell technology are driving the adoption of green hydrogen in various sectors, including transportation, industrial processes, and power generation.

The development of a robust hydrogen infrastructure, including pipelines, refuelling stations, and distribution networks, is essential to support the growth of green hydrogen markets. Research continues to improve the efficiency and durability of electrolysers, reducing electrode corrosion, extending equipment lifespan, and optimizing maintenance procedures.

Safety measures and technologies are being developed to address potential concerns associated with hydrogen production, storage, and transportation. Furthermore, AI and machine learning are increasingly employed to optimize hydrogen production facility operations, predict equipment failures, and enhance system efficiency.

Government incentives, subsidies, and regulations are pivotal in driving green hydrogen advancement, with many countries introducing policies to support its development and adoption. Lastly, international collaboration among countries, research institutions, and private companies is accelerating research and development efforts and helping establish global standards and best practices in the green hydrogen sector

9. GREEN HYDROGEN ECONOMY:

The Green Hydrogen Economy represents a transformative shift in the global energy landscape, driven by the production, distribution, and utilization of hydrogen generated through environmentally sustainable methods. This emerging economic paradigm holds immense potential to address various energy and environmental challenges, creating new opportunities for industries, regions, and economies.

Figure 10: Green hydrogen economy (Source: National Green Hydrogen Mission, India)

Here's an exploration of the economic aspects of the Green Hydrogen Economy:

a) **Job Creation**:

The transition to a green hydrogen economy has the potential to generate millions of new jobs across various sectors. This includes research and development, manufacturing of electrolysers and fuel cells, construction and maintenance of hydrogen infrastructure, and renewable energy production. These jobs can provide economic stability and growth, particularly in regions previously reliant on fossil fuels.

b) **Energy Security**:

As countries invest in domestic green hydrogen production, they reduce their dependence on imported fossil fuels. This enhances energy security by mitigating the risks associated with global energy supply disruptions, price volatility, and geopolitical tensions.

c) **Industrial Growth**:

Green hydrogen can serve as a clean feedstock for numerous industries, including chemicals, steel, and transportation. By substituting conventional fossil fuels with green hydrogen, industries can lower their carbon footprint, comply with stricter environmental regulations, and potentially increase competitiveness in international markets.

d) **Export Opportunities**:

Countries blessed with abundant renewable energy resources can become major exporters of green hydrogen and related technologies. This can create new revenue streams, strengthen trade relationships, and boost economic growth. For example, countries like Australia and Saudi Arabia are eyeing green hydrogen exports to Asia and Europe.

e) **Infrastructure Investments**:

Developing a robust hydrogen infrastructure, including pipelines, storage facilities, and refuelling stations, necessitates significant investments. These projects can stimulate economic growth in both urban and rural areas, particularly during the construction phase.

f) **Technology Innovation**:

The green hydrogen sector promotes innovation in hydrogen production, storage, and transportation technologies. Public and private investments in research and development can lead to breakthroughs that not only advance the green hydrogen industry but also have broader applications, further stimulating economic growth.

g) **Economic Diversification**:

Regions and nations traditionally dependent on fossil fuel industries can diversify their economies by transitioning to green hydrogen. This diversification can mitigate economic vulnerabilities linked to fluctuations in fossil fuel prices and promote more sustainable, resilient economies.

h) **Cost Reduction**:

As the green hydrogen industry scales up, the cost of hydrogen production is expected to decline, making it more economically competitive with fossil fuels. This cost reduction is critical for the widespread adoption of green hydrogen across various applications, including transportation and power generation.

i) **Financial Incentives**:

Many governments are offering financial incentives, subsidies, and tax benefits to encourage the growth of the green hydrogen industry. These incentives can stimulate private sector investments and further accelerate the transition.

j) **International Collaboration**:

The global nature of the green hydrogen economy fosters international collaboration and partnerships. Countries and companies are increasingly working together to share knowledge, technologies, and best practices, creating a global network that can drive economic growth and environmental sustainability.

The Green Hydrogen Economy represents a promising economic pathway towards a more sustainable and environmentally friendly future. However, realizing these economic benefits will require concerted efforts from governments, industries, and stakeholders to overcome technical, regulatory, and financial challenges.

10. GREEN HYDROGEN IN DEVELOPING COUNTRIES

Green hydrogen can benefit developing countries in several ways:

Decarbonization: Green hydrogen can help developing countries reduce their greenhouse gas emissions and meet their climate commitments. It can decarbonize hard-to-abate sectors like heavy industry, buildings, and transport, which are major contributors to carbon emissions.

Energy Security: Developing countries without access to fossil fuel resources can use locally produced green hydrogen to enhance their energy security. By utilizing their abundant renewable resources, they can create a domestic, renewable fuel that reduces their dependence on imported fossil fuels.

Economic Opportunities: Green hydrogen production and its associated industries, such as hydrogen infrastructure, transport, construction, and agriculture, can create job opportunities and stimulate economic growth in developing countries. It can also attract investment and support the development of local industries.

Sector Coupling: Green hydrogen offers developing countries the opportunity to exploit sector coupling, where different sectors like agriculture, water, and power can be interconnected through the use of renewable-generated electricity and water to produce green hydrogen. This integration can lead to greater economic efficiencies and transform domestic industries.
Energy Access and Resilience: Green hydrogen can provide decentralized energy solutions, covering all energy needs in buildings, transport, and industry. It can improve energy access in remote areas and help shield critical infrastructure from power supply disruptions, enhancing climate and extreme weather resilience.

Overall, green hydrogen provides developing countries with a zero-carbon energy solution that supports their sustainable energy objectives, generates economic opportunities, increases energy security, and contributes to global decarbonization efforts.
The development finance institutions can play a crucial role in the adoption of green hydrogen in developing countries. They can provide support and financing to accelerate the uptake of green hydrogen projects and create the necessary policy and regulatory enabling environment. Here are some specific roles that development finance institutions can play:

1. Funding First-of-a-Kind Projects: Development finance institutions can provide innovative co-financing and concessional funds to support first-of-a-kind green hydrogen projects in developing countries. These projects often involve new technologies or components that do not have a sufficient scale or track record. By blending commercial financing with concessional funds, the financing cost of the electrolysis plant can be reduced, making the project more economically viable.
2. Mobilizing Private Capital: Development finance institutions can work in tandem with private investors to mobilize private capital for green hydrogen projects. They can provide financial instruments, such as loans, guarantees, and equity investments, to attract private sector participation and mitigate investment risks. This can help bridge the financing gap and unlock additional investment in green hydrogen infrastructure and technologies.
3. Capacity Building and Technical Assistance: Development finance institutions can support capacity building efforts in developing countries by providing technical assistance and knowledge sharing. This can include training programs for engineers and technicians to install, monitor, operate, and maintain integrated fuel cell and hydrogen systems. By building local expertise, developing countries can overcome the shortage of qualified professionals and accelerate the deployment of green hydrogen technologies.

4. Policy and Regulatory Support: Development finance institutions can work with governments and policymakers to develop national strategies, policy frameworks, and regulatory environments that support the adoption of green hydrogen. They can provide guidance on best practices, international standards, and regulatory frameworks to create a favourable investment climate for green hydrogen projects. This can include establishing clear national strategies, setting targets, and implementing supportive policies and regulations.

Overall, development finance institutions can provide the necessary financial resources, technical expertise, and policy support to accelerate the adoption of green hydrogen in developing countries. Their involvement can help overcome barriers and create an enabling environment for the successful deployment of green hydrogen projects, contributing to sustainable energy development and climate change mitigation efforts.

11. INFLATION REDUCTION ACT

The Inflation Reduction Act, 2022 includes the largest hydrogen subsidies in the world, marking a significant development for the hydrogen market. The act reduces the projected timeline for green hydrogen cost competitiveness and incentivizes the growth of the hydrogen ecosystem. The US is expected to become a major exporter of green hydrogen by 2030, with competitive production costs. The current state of the US market includes various players, such as pure hydrogen players, RE/utility firms, and oil and gas/chemical players. Key geographies for green hydrogen development include Texas, Florida, California, and Pennsylvania. The US has also initiated the development of hydrogen hubs, with several government-led and private initiatives proposed. The growth trajectory for green hydrogen in the US is expected to drive domestic demand and attract foreign players. The US Department of Energy has published a draft national clean hydrogen strategy and roadmap to further support green hydrogen development. EY, with its expertise in the hydrogen ecosystem, can assist companies in accelerating their journey in hydrogen. The states with high green hydrogen potential in the US are Texas, Florida, California, and Pennsylvania. These states have access to low Levelized Cost of Electricity (LCOE), existing hydrogen infrastructure, and proximity to large hydrogen demand centres. Texas, in particular, has high regulatory support and has become a first mover in setting up large-scale green hydrogen projects.

By 2030, the expected production cost of US green hydrogen, including the tax benefits provided by the Inflation Reduction Act (IRA), is projected to be in the range of $0.5-1.5 per kilogram of hydrogen (KgH2). This would make the US the region with the lowest production cost in the world. The IRA incentives have made green hydrogen production competitive with existing gray hydrogen, reducing the earlier projected timeline for cost competitiveness by more than a decade. EY is uniquely positioned to assist companies in accelerating their journey in the hydrogen market. With significant experience and a deep understanding of the entire hydrogen ecosystem, EY's global hydrogen team is actively involved in shaping, financing, and optimizing hydrogen ecosystems and business models across the world. EY has already supported over 30 clients in over 50 hydrogen projects, developing hydrogen policy and strategy, building out hydrogen applications, and investing in green and blue hydrogen production. By bringing together business, technical, tax, legal, regulatory, and modelling specialists, EY's globally connected hydrogen team is ideally placed to support clients in their day-to-day queries and provide comprehensive assistance in navigating the complexities of the hydrogen market.

12. GREEN HYDROGEN INITIATIVES IN INDIA

a) National Green Hydrogen Mission

India's National Green Hydrogen Mission aims to establish a comprehensive action plan for the production, usage, and export of green hydrogen. The mission objectives include making India a global hub for green hydrogen production, replacing fossil fuels with renewable fuels, and achieving significant decarbonization of the economy. The mission will be implemented in a phased approach, starting with demand creation and domestic consumption, and later expanding to new sectors of the economy. The mission will also focus on sourcing green hydrogen through decentralized renewable energy generation, building the required infrastructure for storage and delivery, and promoting international cooperation and partnerships. The mission governance framework includes an empowered group, advisory group, and mission secretariat to oversee and coordinate the implementation of the mission.

Objective:

The objective of India's National Green Hydrogen Mission is to make India the global hub for the production, usage, and export of green hydrogen and its derivatives. The mission aims to achieve significant decarbonization of the economy, reduce dependence on fossil fuel imports, and establish India as a leader in technology and manufacturing of electrolysers and other enabling technologies for green hydrogen. It also aims to replace fossil fuels and fossil fuel-based feedstocks with renewable fuels and feedstocks based on green hydrogen in various sectors such as ammonia production, petroleum refining, city gas distribution systems, steel production, and transportation. The mission seeks to create a comprehensive action plan for the establishment of a green hydrogen ecosystem and catalyse a systemic response to the opportunities and challenges of this emerging sector.

Strategy:

The National Green Hydrogen Mission will be governed and coordinated through a structured governance framework. The mission will be overseen by an Empowered Group (EG) chaired by the Cabinet Secretary and comprising key stakeholders from various ministries, departments, and experts from the industry. The EG will provide guidance, monitor progress, recommend policy interventions, and approve mid-course corrections if required. The Mission Director will serve as the Secretary of the EG.

Additionally, there will be a National Green Hydrogen Advisory Group chaired by the Principal Scientific Adviser to the Government of India. This group will consist of experts from academic and research institutions, industry, and civil society. The Advisory Group will advise the EG on science and technology-related matters, technology gap analysis, R&D roadmap, and evaluation of proposals for financial support.

The Mission Secretariat, headquartered in the Ministry of New and Renewable Energy (MNRE), will coordinate the day-to-day activities of the mission. It will be headed by the Mission Director and comprise subject matter experts and professionals. The Secretariat will formulate policies, guidelines, and schemes, as well as manage pilot and R&D projects. It will also assist the EG and the Advisory Group, as required. The Mission Secretariat will continuously monitor the sector's exposure to various risks, categorize and address them in a timely manner, with the guidance of the EG from time to time. A specific portion of the Mission budget will be earmarked for program management activities to support the Secretariat.

The mission will ensure coordination and collaboration among all stakeholders, avoiding duplication of efforts and optimizing resource utilization. It will also leverage existing institutions, industry-academia-government networks, and international collaborations to support the implementation of the mission objectives. The Ministry of New and Renewable Energy (MNRE) will be the nodal coordinating ministry for the mission, responsible for overall policy formulation and program implementation.

Implementation Roadmap:

The phased approach of India's National Green Hydrogen Mission involves implementing the mission objectives in a planned and coordinated manner. The first phase, from 2022-23 to 2025-26, focuses on creating demand and increasing domestic electrolyser manufacturing capacity. It aims to enable the indigenization of the value chain and increase the production and uptake of green hydrogen. This phase also includes pilot projects in sectors already using hydrogen and the establishment of a regulatory framework and R&D ecosystem.

The second phase, from 2026-27 to 2029-30, aims to drive down costs and accelerate the growth of green hydrogen production. It explores the potential for commercial-scale projects in sectors such as steel, mobility, shipping, railways, and aviation. R&D activities will be scaled up, and penetration across all potential sectors will be enhanced to achieve deep decarbonization of the economy.

The phased approach allows for a gradual and systematic implementation of the mission, starting with foundational activities and expanding to new sectors in subsequent phases. It ensures a coordinated and strategic approach to achieve the mission objectives and drive the transition to a green hydrogen economy

Key components:

The key components of India's National Green Hydrogen Mission are as follows:

Demand Creation: The mission aims to create demand for green hydrogen by making it competitive for exports and through domestic consumption. This involves promoting the use of green hydrogen in various sectors and capturing global demand.

Incentivizing Supply: The mission includes an incentive framework to address supply-side constraints. It aims to encourage the production of green hydrogen and the development of a domestic manufacturing ecosystem for related equipment and technologies.

Building an Enabling Ecosystem: The mission focuses on building an enabling ecosystem to support scaling and development. This includes ensuring the availability of affordable renewable energy, electrolysers, and other key components. It also includes the provision of accessible credit and risk-sharing frameworks.

International Cooperation: The mission emphasizes active engagement in international collaborative efforts for hydrogen and fuel cell development. It aims to forge strategic partnerships, explore joint investments and collaborative projects, and develop long-term trade agreements for green hydrogen and its derivatives.

Research and Development: The mission recognizes the importance of research and development in advancing green hydrogen technologies. It supports R&D activities, technology gap analysis, and the development of a phased R&D roadmap. It also encourages industry-academia collaboration and the establishment of centers of excellence.

Mission Governance Framework: The mission establishes a governance framework to ensure effective implementation and coordination. It includes an Empowered Group chaired by the Cabinet Secretary, a National Green Hydrogen Advisory Group, and a Mission Secretariat. The governance structure oversees the mission activities, provides guidance, monitors progress, and recommends policy interventions.

Expected Outcomes:

Economy-Wide Benefits: The mission will lead to the decarbonization of industrial, mobility, and energy sectors, reducing dependence on imported fossil fuels. It will also contribute to the development of indigenous manufacturing capabilities, creating employment opportunities across the value chain, and fostering cutting-edge technologies and innovation in the country.

Green Hydrogen Production Capacity: The mission aims to achieve a green hydrogen production capacity of at least 5 million metric tonnes (MMT) per annum by 2030, with the potential to scale up to 10 MMT per annum with the growth of export markets. This will be accompanied by an associated renewable energy capacity addition of about 125 GW.

Job Creation: The implementation of the mission is expected to create over 6 lakh full-time jobs across the green hydrogen value chain.

CO2 Emissions Reduction: The various green hydrogen initiatives under the mission are expected to avert nearly 50 MMT per annum of CO2 emissions, contributing to significant decarbonization in the identified industrial sectors.

Investments: The mission is likely to leverage over ₹8 lakh crore in total investments, fostering economic growth and attracting both public and private investments.

The National Green Hydrogen Mission aims to achieve these outcomes by promoting the production, usage, and export of green hydrogen and its derivatives, driving the transition to a clean energy economy, and positioning India as a global leader in green hydrogen technology and manufacturing.

b) Sample analysis - State wise Green Hydrogen Policy

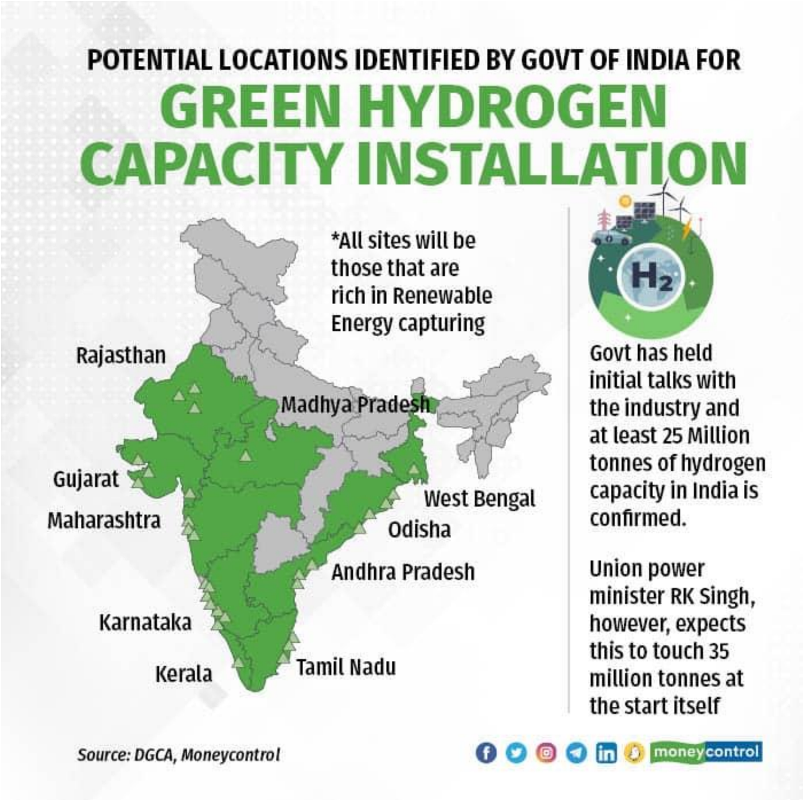

Figure 11: Indian government has identified states which have the potential to become green hydrogen manufacturing hubs.(Source: https://www.moneycontrol.com/news/business/economy/government-lists-10-states-for-green-hydrogen-manufacturing-9439561.html)

1. Uttar Pradesh:

The Uttar Pradesh Green Hydrogen Policy 2022 aims to promote green hydrogen and ammonia production, market creation, and demand aggregation in the state. The policy set targets to reduce the cost of green hydrogen, achieve green hydrogen blending in existing sectors, and establish a state centre of excellence for research and development. It also provides fiscal incentives and establishes a state level committee to oversee the implementation of the policy.

In the near term, the Uttar Pradesh Green Hydrogen Policy 2022 will primarily focus on two major sectors in the state of Uttar Pradesh - Nitrogenous (N-) Fertilizers and Refinery. These sectors have a significant contribution to the state's industrial emissions, with the chemicals & fertilizers sector accounting for nearly 50 percent and the refinery sector contributing around 5 percent of UP's industrial emissions. By promoting green hydrogen/ammonia in these sectors, the policy aims to address more than 50 percent of the state's industrial emissions. Additionally, the policy envisions covering other emerging industries and applications of green hydrogen in the future.

The Uttar Pradesh Green Hydrogen Policy 2022 aims to achieve the following targets:

1. Reduce the cost of green hydrogen to $2.0 per kilogram in the policy period and make efforts to further reduce it to $1.0 per kilogram in the long term.
2. Achieve 20 percent green hydrogen blending in the total hydrogen consumption of the state by 2028 for existing fertilizer and refinery units, reaching 100 percent by 2035.
3. Set up a state centre of excellence (CoE) to lead research, development, and techno-economic innovation activities.
4. Achieve the number one rank in the ease of doing business index based on the Business Reform Action Plan (BRAP) recommended by the Department of Industrial Policy and Promotion (DIPP).

The implementation of the Uttar Pradesh Green Hydrogen Policy 2022 is overseen by the State Level Committee. This committee is responsible for coordinating with various government departments and agencies, assigning roles and responsibilities to different stakeholders, monitoring the progress of the policy and institutions involved, approving incentives for beneficiaries, revisiting targets for progress tracking, and interpreting and modifying any provision of the policy. The State Level Committee is chaired by the Additional Chief Secretary/Principal Secretary of the Department of Additional Sources of Energy, Government of Uttar Pradesh. It also includes members from the Finance Department, Revenue Department, Planning Department, Agriculture Department, Law Department, Chief Executive Officer of Invest UP, Subject Matter Expert of state/central government, and the Director of UPNEDA (Uttar Pradesh New and Renewable Energy Development Agency).

2. **Maharashtra:**

The Maharashtra state cabinet has approved the Green Hydrogen Policy to promote renewable energy and green hydrogen projects. The policy will provide incentives to projects that procure renewable energy through open access, from in-state or out-of-state power distribution companies, power exchanges, for self-consumption. The state cabinet also approved Rs 8,562 crore for the implementation of this policy. The current hydrogen demand of the state is 0.52 million tonnes per annum and may reach 1.5 million tonnes by 2030. Green hydrogen and related production projects will be registered with the Energy Office.

3. **Andhra Pradesh:**

Andhra Pradesh boasts a thriving, rapidly expanding economy, thanks to its government's welcoming stance toward investors. It ranks second in the nation for its extensive coastline, featuring six operational ports and additional ones in the developmental pipeline to boost exports. The state boasts a robust network of roads and railways, facilitating connectivity to major industrial hubs. Abundant water resources from the Godavari and Krishna rivers, along with rich natural resources, further enhance its appeal.

Moreover, East Asian countries are increasingly embracing Net Zero strategies, where Green Hydrogen plays a pivotal role. To make Green Hydrogen affordable, the availability of cost-effective renewable energy power sources within our nation is essential. Fortunately, Andhra Pradesh can produce cost-effective Green Hydrogen within the state. The ports across the state are equipped with facilities for storing liquid nitrogen, which can also be repurposed for storing Green Hydrogen, making it economically viable for end users in other countries. In light of these factors, Andhra Pradesh offers an ideal environment for the establishment of Green Hydrogen/Green Ammonia projects.

Objectives:

i. To leverage the renewable energy potential within the state and achieve Green Hydrogen production of up to 0.5 MTPA (Million Tonnes Per Annum) or Green Ammonia production up to 2.0 MTPA within the next five years.

ii. To facilitate the growth of an ecosystem that supports the production of Green Hydrogen and Green Ammonia.

iii. To attract investments, generate employment opportunities, and enhance the state's economy.

iv. To create 12,000 jobs for every Million Tonne Per Annum (MTPA) of Green Hydrogen production in the state.

v. To encourage the establishment of manufacturing facilities for Green Hydrogen and Green Ammonia equipment within the state.

vi. To position Andhra Pradesh as the preferred choice for the production and export of Green Hydrogen and Green Ammonia.

4. Rajasthan

On September 16, 2023, Ashok Gehlot, the Chief Minister of Rajasthan, unveiled the preliminary version of the 'Rajasthan Green Hydrogen Policy-2023.' The aim is to encourage investors and seek out clean energy sources, aligning with the state's commitment to clean energy production, future energy demands, and climate change mitigation. This policy has received approval, and the Energy Department will soon release an official notification.

Under this initiative, companies engaged in green energy production within the state will be eligible for a range of subsidies. Furthermore, this decision is expected to bolster employment opportunities within Rajasthan.

It's noteworthy that Rajasthan possesses abundant renewable energy resources, making it an ideal location for green hydrogen production. To incentivize investors, the state government will provide various facilities under the policy. For instance, renewable energy plants with a capacity of 500 KTPA established on the state's transmission system will enjoy a 50 percent exemption in transmission and distribution charges for a decade. Additionally, there will be a complete exemption from additional and cross-subsidy surcharges when purchasing renewable energy from third parties for ten years.

The policy also includes a 30 percent (up to Rs 5 crore) grant for land allocation and the establishment of research centers dedicated to green hydrogen production from treated or brackish water. Moreover, it offers various discounts, water availability, and banking facilities as part of the Rajasthan Investment Promotion Scheme-2022 (RIPS-2022). The policy removes restrictions on the capacity of captive power plants and allows the banking of generated electricity. It also eliminates the ban on power withdrawal during peak hours.

Within the framework of the 'Rajasthan Green Hydrogen Policy-2023,' there will be full reimbursement or waiver of wheeling and transmission charges for power plants. Additionally, banking charges for power plants will be reimbursed or waived for periods ranging from seven to ten years. The policy categorizes the green hydrogen sector as a thrust sector under the Rajasthan Investment Promotion Scheme-2022 and designates it as a Sunrise Sector, making it eligible for the benefits of the Manufacturing Standard Package. It's worth noting that the Energy Department solicited feedback from stakeholders by releasing a draft of the policy for public input, and important suggestions have been incorporated.

Lastly, the state government has set an ambitious target of achieving 2000 KTPA energy production by 2030 under this policy, with projects falling into four categories, including renewable energy extraction through the power grid network, co-production of renewable energy and hydrogen (700 KTPA), round-the-clock renewable energy generation through RTC power (800 KTPA), and the integration of renewable energy through the RVPN network (500 KTPA).

13. SOME GLOBAL INITIATIVES AND DEVELOPMENTS

Here are some outstanding accomplishments and partnerships that are catapulting green hydrogen into the mainstream:

- In 2023, the world's first green hydrogen powered train was launched in Germany. The train is powered by a fuel cell that uses green hydrogen to generate electricity.
- In 2023, the EU Commission signed a joint declaration on renewable hydrogen research and innovation, to step up and accelerate joint action in research, development, demonstration and deployment of Hydrogen Valleys.
- In 2023, the world's largest green hydrogen production facility opened in Saudi Arabia. The project's total value of USD 8.4 billion is being financed with USD 6.1 billion non-

recourse financing from 23 local, regional and international banks and financial institutions.

- L&T Construction awarded contracts for the world's largest green hydrogen plant. The project that will integrate 4GW of renewable energy to enable the production of up to 600 tonnes of carbon-free hydrogen per day.
- In 2023, the United States Department of Energy announced plans to invest $8 billion in green hydrogen projects. This investment is part of the Biden administration's plan to create a clean energy economy and reduce greenhouse gas emissions

THE CENTRAL QUEENSLAND HYDROGEN PROJECT: PIONEERING A SUSTAINABLE HYDROGEN INDUSTRY

The Central Queensland Hydrogen Project is a ground-breaking initiative aimed at establishing a large-scale renewable hydrogen supply chain between Central Queensland, Australia, and Japan. This case study explores the key objectives, findings, and potential impact of the project, highlighting its significance in the transition to a sustainable and commercially viable renewable hydrogen industry.

Objective:

The primary objective of the Central Queensland Hydrogen Project is to assess the commercial, technical, and strategic viability of establishing a renewable hydrogen supply chain. The project aims to position Central Queensland as a preferred Australian renewable hydrogen hub by leveraging the region's renewable energy resources and infrastructure. It also seeks to secure offtake agreements, achieve target hydrogen pricing, and improve technology and commercial readiness through partnerships with Japanese energy, gas, trading, and technology companies.

Project Feasibility:

The feasibility study conducted for the Central Queensland Hydrogen Project yielded several key findings:

1. Technical Feasibility: The project is technically feasible, with suitable land, power supply, water resources, and wastewater disposal solutions available in Central Queensland. There are no major project-limiting impacts associated with regulatory approvals.

2. Commercial Viability: The project is potentially commercially viable with appropriate government support. Phase 1 of the project is considered commercially viable, and Phase 2 is expected to be commercially viable as an independent standalone project.

3. Social and Stakeholder Impacts: The study identified key areas of community interest and considerations, including sustainable employment, training, and supply opportunities, industry benefit sharing strategies, environmental impacts, growth of the local hydrogen and renewable energy industry, and potential social impacts.

4. Government Support: The project has received strong support from various levels of government, including the Queensland Government. The project aligns with government policies and strategies pertaining to hydrogen initiatives and emissions reduction.

5. Financial Analysis: The financial analysis of the Central Queensland Hydrogen Project includes the development of a financial model that incorporates financial statements and key project metrics. These metrics include the Levelised Cost of Hydrogen (LCOH), Net Present Value (NPV), and Internal Rate of Return (IRR) for the two structuring options being considered. The financial model considers three scenarios: the Base Case, Optimised Case, and Stretch Case. The Base Case reflects the current market environment, while the Optimised Case takes into account expected developments and cost efficiencies in the renewable hydrogen market. The Stretch Case represents an optimistic scenario with significant improvements in technology. The financial analysis also considers cost structures, revenue models, and debt financing options. It assesses the financial and commercial viability of the project and includes considerations for grant funding opportunities, tax and accounting implications, and the treatment of government grants. The analysis provides cost estimates for both Phase 1 and Phase 2 of the project and evaluates the levelised costs based on the stand-alone costs and production of each phase.

6. Commercialization Pathway: The project's commercialization pathway involves securing local community acceptance, regulatory approvals, and managing construction risks. It also includes establishing exclusivity for offtake agreements, developing a joint venture structure

with consortium partners, refining the financial model, and securing agreements for land and port facilities.

Implementation Roadmap:

The timeline for the completion of Phase 1 of the Central Queensland Hydrogen Project is as follows:

- FEED (Front End Engineering and Design): Scheduled to commence in Q3 2022.

- FID (Final Investment Decision): Planned for Q3 2023.

- Detailed design, construction, and commissioning: Expected to take place from Q3 2023 to Q4 2026.

- Commercial production: Anticipated to begin in Q1 2027.

Phase 2 of the project is planned to commence in 2031. The specific timeline for Phase 2 will be further developed during the FEED stage, which will occur following the execution of Phase 1. Planning activities for Phase 2 execution will begin during Phase 1 operations, with the anticipated start date for Phase 2 planning being Q4 2026.

Impact and Future Prospects:

The Central Queensland Hydrogen Project has the potential to make a significant contribution to the development of a sustainable and commercially viable renewable hydrogen industry. By harnessing the region's renewable energy resources, the project aims to position Central Queensland as a preferred Australian renewable hydrogen hub. The establishment of a large-scale renewable hydrogen supply chain between Central Queensland and Japan will not only support the transition to renewable energy but also contribute to the development of a low-carbon export industry for Australia.

The project's success will depend on securing offtake agreements, achieving target hydrogen pricing, and further developing the technology and commercial readiness of the project. With strong government support and partnerships with Japanese energy companies, the Central Queensland Hydrogen Project is well-positioned to drive the growth of the renewable hydrogen industry and establish a green hydrogen hub in Gladstone.

The Central Queensland Hydrogen Project represents a significant step towards a sustainable and commercially viable renewable hydrogen industry. The project's feasibility study has confirmed its technical feasibility and potential commercial viability, with positive social and stakeholder impacts. With government support and strategic partnerships, the project aims to position Central Queensland as a preferred renewable hydrogen hub and contribute to the development of a low-carbon export industry. The successful implementation of the project will pave the way for a greener and more sustainable energy future

14. CONCLUSION

The exploration of green hydrogen represents a promising and transformative pathway towards a sustainable and decarbonized future. The step-by-step production process, involving renewable energy sources and electrolysis, underscores the importance of an integrated approach to clean energy generation. While the global green hydrogen landscape is still in its nascent stages, we have witnessed encouraging initiatives and developments worldwide, demonstrating a collective commitment to its advancement.

However, it is crucial to acknowledge that the journey towards a hydrogen-powered future is not without its challenges and constraints. From the cost of production to storage and transportation hurdles, addressing these issues demands innovative solutions and sustained investments. Governments, industries, and research institutions must collaborate closely to drive down costs and overcome technical barriers. Moreover, the establishment of a robust green hydrogen economy necessitates supportive policies, financial incentives, and regulatory frameworks that encourage its widespread adoption.

Looking ahead, green hydrogen has the potential to reshape the global energy landscape, reducing our reliance on fossil fuels and mitigating the climate crisis. It holds promise not only as a clean fuel for various sectors but also as a means of energy storage and grid stabilization, enhancing the reliability of renewable energy sources. As we stand at the precipice of a green hydrogen revolution, it is imperative that we seize this opportunity to usher in a new era of sustainability, innovation, and global cooperation. The future of green hydrogen is, quite literally, in our hands, and our choices today will determine the course of our planet for generations to come. It is a journey worth embarking upon, for the sake of a greener, cleaner, and more prosperous world.

15. REFERENCES

a) MINISTRY OF NEW AND RENEWABLE ENERGY ,GOVERNMENT OF INDIA. (2023, January). *NATIONAL GREEN HYDROGEN MISSION*. Retrieved September 17, 2023, from https://mnre.gov.in/img/documents/uploads/file_f-1673581748609.pdf

b) NITI Aayog. (2022, June). *Harnessing GREEN HYDROGEN OPPORTUNITIES FOR DEEP DECARBONISATION IN INDIA*. Retrieved September 17, 2023, from https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf

c) *Green Hydrogen Market Size to Hit USD 331.98 Billion by 2032*. (n.d.). https://www.precedenceresearch.com/green-hydrogen-market#:~:text=The%20global%20green%20hydrogen%20market,of%20over%2066.8%25%20in%202022.

d) *Hydrogen - IEA*. (n.d.). IEA. https://www.iea.org/energy-system/low-emission-fuels/hydrogen

e) https://documents1.worldbank.org/curated/en/953571597951239276/pdf/Green-Hydrogen-in-Developing-Countries.pdf

f) https://documents1.worldbank.org/curated/en/953571597951239276/pdf/Green-Hydrogen-in-Developing-Countries.pdf

g) https://upneda.org.in/MediaGallery/UPGH2_policy_II.pdf

h) https://indianexpress.com/article/cities/mumbai/maharashtra-introduces-hydrogen-policy-country-8749801/

i) *Hydrogen*. (n.d.). Energy. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en#:~:text=EU%20hydrogen%20initiatives,-The%20EU%20has&text=On%201%20March%202023%2C%20the,and%20deployment%20of%20Hydrogen%20Valleys.

j) (2022, August 27). *Germany introduces world's first hydrogen-powered trains*. The Economic Times. https://economictimes.indiatimes.com/industry/transportation/railways/germany-introduces-worlds-first-hydrogen-powered-trains/hydrogen-powered-train/slideshow/93813401.cms

k) *NEOM Green Hydrogen Company completes financial close at a total investment value of USD 8.4 billion in the world's largest carbon-free green hydrogen plant*. (n.d.). https://www.neom.com/en-us/newsroom/neom-green-hydrogen-investment

l) *h*ttps://www.energy.gov/articles/doe-launches-bipartisan-infrastructure-laws-8-billion-program-clean-hydrogen-hubs-across#:~:text=WASHINGTON%2C%20D.C.%20%E2%80%94%20The%20U.S.%20Department,hubs%20(H2Hubs)%20across%20America.

m) https://www.manufacturingtodayindia.com/sectors/lt-construction-awarded-contracts-for-the-worlds-largest-green-hydrogen-plant

n) https://www.stanwell.com/wp-content/uploads/Feasibility-Study-Report-CQ-H2-Project-Public-Final-071222.pdf

o) https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum#:~:text=Blue%20hydrogen%20is%20produced%20mainly,produced%20as%20a%20by%2Dproduct.