Green Hydrogen

Landscape and Technology

Abhijeet Gaikwad

Summary:

The worldwide hydrogen sector is currently experiencing a substantial shift, primarily motivated by the pressing need to eliminate carbon emissions from various businesses and mitigate the impact of greenhouse gases. Hydrogen, widely recognised as the environmentally friendly energy carrier of the future, is increasingly being acknowledged as a flexible and sustainable option. Nations globally are making significant investments in the development of hydrogen production, storage, and distribution infrastructure to fully exploit its potential. Dominantly nations have put forward the strategies to replace grey hydrogen used in refineries, fertilizer's and steel industries by green hydrogen. From Europe's ambitious hydrogen policy to Asia's significant role in increasing production, the momentum is growing. The advancements in electrolyser technology, along with the incorporation of renewable energy, are reducing expenses and enhancing the competitiveness of green hydrogen. In order to achieve a sustainable and low-carbon future, it is imperative for governments, companies, and academia to collaborate as the globe transitions to a hydrogen economy.

The objective of this article is to assess the global and national hydrogen landscape, the support mechanisms available for hydrogen industry and technologies involves in Green Hydrogen sector.

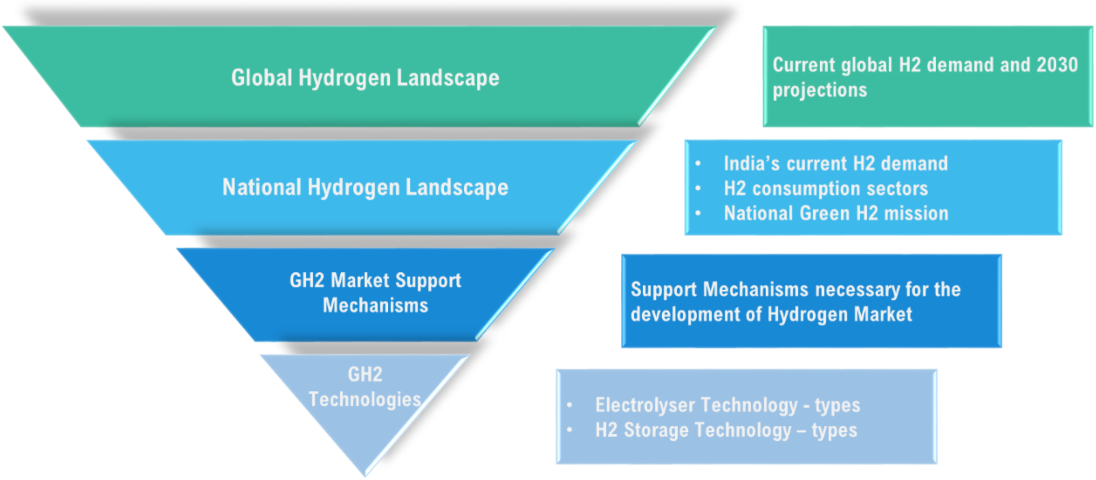

Figure 1: Top to bottom approach Green Hydrogen Ecosystem

This article is divided into ***four sections*** as shown in the above figure.

- *The **first section** delves into global hydrogen landscape which highlights the current hydrogen demand and future demand projections as world transits towards net zero economy.*
- *The **second section** focuses on India's current hydrogen demand, hydrogen consumption points and dives into National Green Hydrogen Missions (NGHM).*
- *The **third section** provides insight about necessary support mechanisms which are needed to drive up the demand for green hydrogen and how support mechanisms can help to reduce the cost of hydrogen technology and subsequently the cost of hydrogen production.*
- *The **last section** explores the available technologies in green hydrogen production and storage.*

Contents

Table 1: Abbreviation used in this paper

Abbreviation	Meaning
MMT	Million Metric Tons
DRI	Direct Reduced Iron
H_2	Hydrogen
IEA	International Energy Agency
NZE	Net Zero Emissions
NGHM	National Green Hydrogen Mission
FIT	Feed-in Tariff
LCOE	Levelised Cost of Energy
LCOH	Levelised Cost of Hydrogen
CfD	Contract for Difference
GVW	Gross Vehicle Weight
TSO	Transmission System Operator
DSO	Distribution System Operator
RFNBO	Renewable Fuels of Non-Biological Origin
CCS	Carbon Capture and Storage
SECI	Solar Energy Association of India
SMR	Steam Methane Reforming
PEM AEM SOEL	Proton Exchange Membrane Anion Exchange Membrane Solid Oxide Electrolyser
TRL	Technology readiness level
BOP	Balance of plant

1 Global hydrogen landscape:

This section explains current global hydrogen demand, where is this hydrogen being used i.e. application sectors and region wise share of hydrogen use. Furthermore, it contains some major tenders in green hydrogen across the globe.

Global cumulative hydrogen demand in 2022 was 95 million metric tons (MMT) refer Figure 2. Industrial H2 demand accounted for 53MMT of hydrogen in 2022, of the 53MMT of hydrogen used in industry in 2022, about 60% was for ammonia production, 30% for methanol and 10% for direct reduced iron (DRI) in the iron and steel industry. Hydrogen use in refining reached more than 41MMT in 2022.

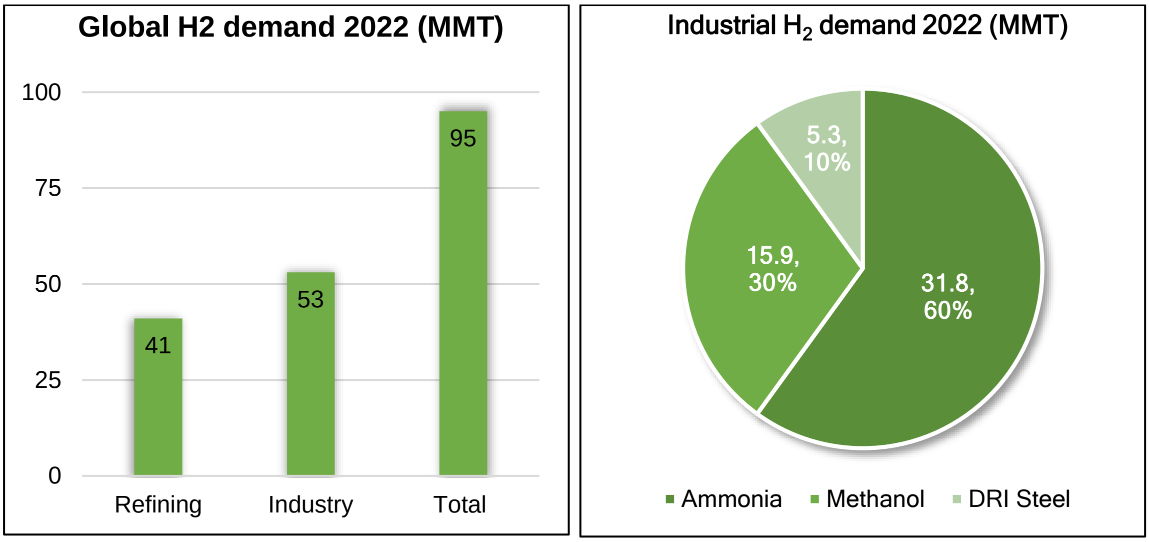

Figure 2: Current global H_2 demand in MMT

In 2022, the hydrogen demand in industry increased significantly compared with 2021, driven by rising global demand for ammonia, methanol and for steel making. China remains the main consumer of hydrogen, with 29% of global H2 demand, followed by the North America (17%), Middle East (13%), India (9%) and Europe (8%) as shown in the Figure 3. The region wise sectorial global demand of hydrogen is shown in Figure 4.

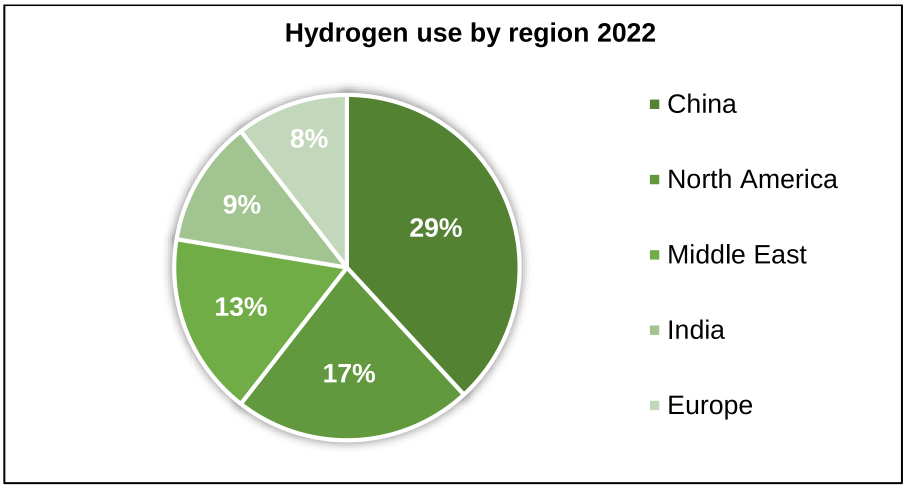

Figure 3: Hydrogen use by region 2022

The Figure 4 shows the region wise sectorial global hydrogen demand in 2022.

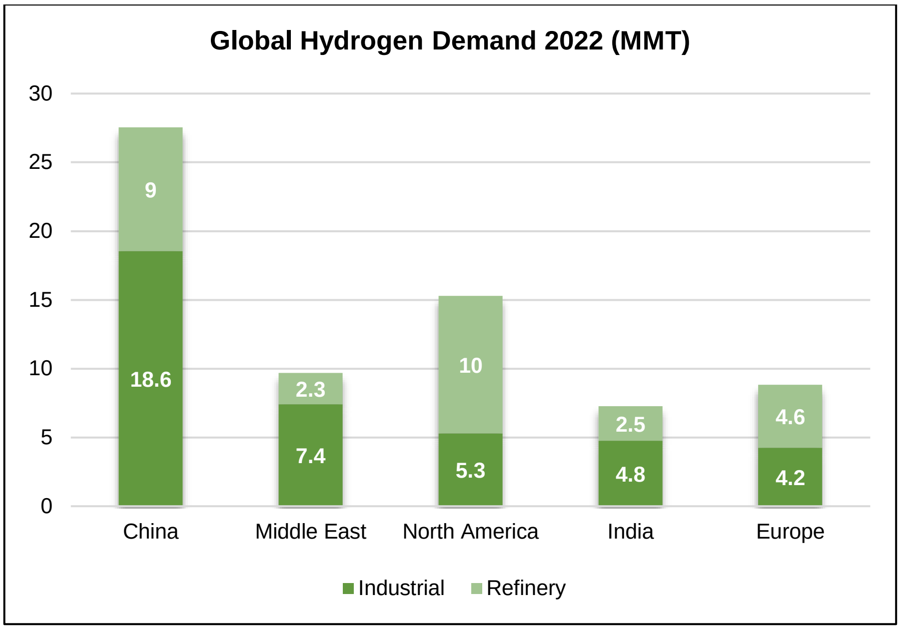

Figure 4: Global hydrogen demand by region in 2022[1]

According to International Energy Agency (IEA), the oil demand will reduce in 2030, as the world transits towards net zero economy. IEA projects the hydrogen demand in refinery to be 35MT by 2030. In the net zero emission (NZE) Scenario 2030, hydrogen use in industry is projected to be 70MMT. Transport, domestic heating and industrial using H_2 boilers, use of H_2 in gas turbine will further increase the H_2 demand of about 40-50MMT by 2030. The Figure 5 shows the sector wise projection of hydrogen in 2030.

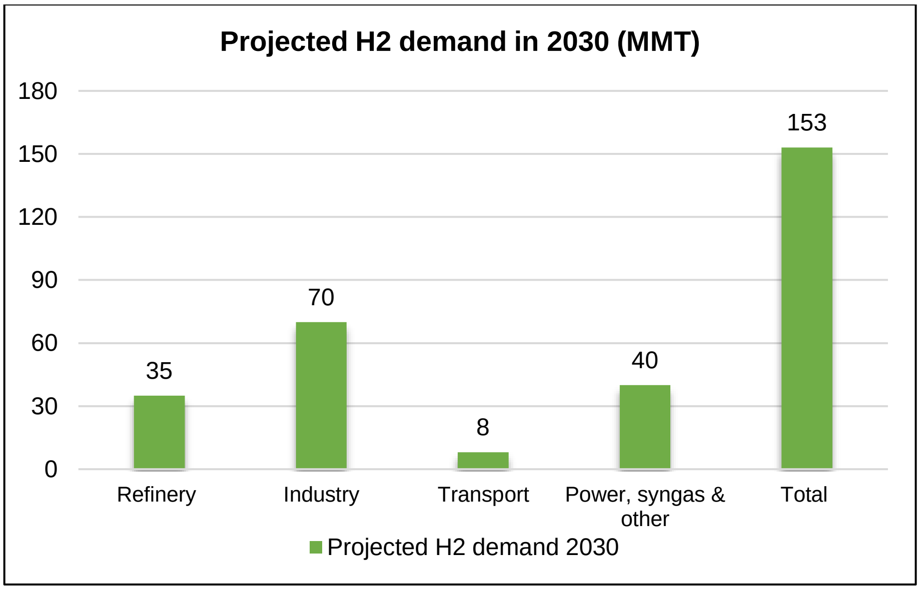

Figure 5: H2 demand projections 2030 in MMT

The hydrogen demand is projected to grow significantly. This will open new avenues and opportunities for business to cater.

[1] International Energy Agency (IEA) - Global Hydrogen Review

1.1 Major global green hydrogen tender list

This section contains the large hydrogen tenders which have significant importance regarding hydrogen market development initiatives across the globe.

- The European Commission held the first round of the "European Hydrogen Bank" auction on November 23, 2023 with a maximum price of *EUR4.50 (USD4.91)/kg*. The approved projects will receive subsidies for a decade, alongside revenue from hydrogen sales. The European Hydrogen Bank is a project aimed at facilitating renewable hydrogen generation and imports inside the EU. It intends to unlock private investment in the EU and third countries by tackling investment obstacles, reducing the funding gap, and connecting future renewable hydrogen supply to consumers, thereby contributing to the EU's target of 20MMT of hydrogen in the energy mix by 2030. The pilot auction for renewable hydrogen production in Europe attracted 132 bids from projects located in 17 European countries, representing a total planned electrolyser capacity of 8.5GW. The first auction under the European Hydrogen Bank mechanism came in significantly below expectations, with the seven successful projects bidding at 37-48euro cents/kg *(40-51USDcents/kg)* for a total of 1.5GW of electrolysis. Seven winners receive 720EUR million for 1.58MMT over 10 years, well below *Eur4.50/kg* price ceiling set for debut auction. The support structure is based on the well-established contract for difference (CfD) model.
- German steel producer Stahl-Holding-Saar (SHS) has launched a tender to buy up to 50,000Tons of locally produced renewable hydrogen for its Dillinger and Saarstahl plants in Saarland[2].
- The UK government launched its first electrolytic hydrogen allocation round (HAR1) in July 2022, and has selected 11 projects which represent 125MW of capacity with a weighted average strike price of £241/MWh. As anticipated, HAR2 has also been launched with support available for up to 875MW of low carbon hydrogen projects[3].
- The Dutch government plans to hold an auction in 2024 to allocate 1EUR billion in subsidies for green hydrogen projects. This ambitious goal is part of their plan to reach 8GW of green hydrogen production capacity by 2032[4].

[2] SPGlobal - Energy Transition

[3] Hydrogen Insights - UK Policy

[4] Hydrogen Insights - Nederland to hold 1 BL Auction

2 India's Hydrogen Landscape

This section explains current hydrogen demand in India, where is this hydrogen being used i.e. application sectors and National Green hydrogen mission.

Demand for hydrogen today is at around 6MMT per annum, coming solely from industry sectors, such as fertilizers (3.4MMT), refineries (2.5MMT), and methanol (0.05MMT) as shown in the Figure 6. This can increase to around 28MMT by 2050, driven by cost reductions in key technologies such as electrolysers, fuel cells, and compressed hydrogen storage, as well as the growing interest to decarbonize the energy system.

Demand will continue to be largely focused in industry sectors, either expanding in existing sectors, such as fertilizers and refineries, or growing into new sectors, such as steel. Hydrogen is expected to play important role in the transport sector in heavy-duty and long-distance segments, as batteries increases the Gross Vehicle Weight (GVW) of heavy duty vehicles significantly.

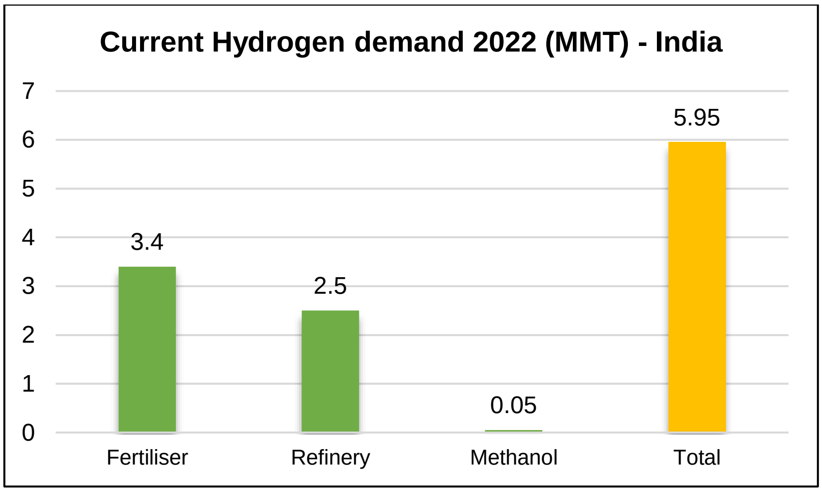

Figure 6: Current hydrogen demand in India 2022

Hydrogen has a wide range of applications across various sectors, including energy, transportation, industry, and more. Hydrogen is currently being consumed in refineries, fertilizer's and process industries at large scale; it is predominantly produced from natural gas via process a called "steam methane reforming" which emits large quantities of CO2 emissions. This hydrogen produced from natural gas is called grey hydrogen.

2.1.1 National Green Hydrogen Mission

India has launched the National Green Hydrogen Mission (NGHM) with an outlay of ***19,744INR crores (2.3USD billions)*** with a target of 5MMT production capacity of Green Hydrogen per annum alongside adding renewable energy capacity of about 125GW (gigawatt) in India by 2030. It aims to entail over ***800,000INR crores*** of total investments and generate six lakh jobs. This may lead to a cumulative reduction in fossil fuel imports by over ***100,000INR crores*** and an abatement of nearly 50MMT of annual greenhouse gas emissions. The figure 7 below shows the allocation of funds in nation green hydrogen mission.

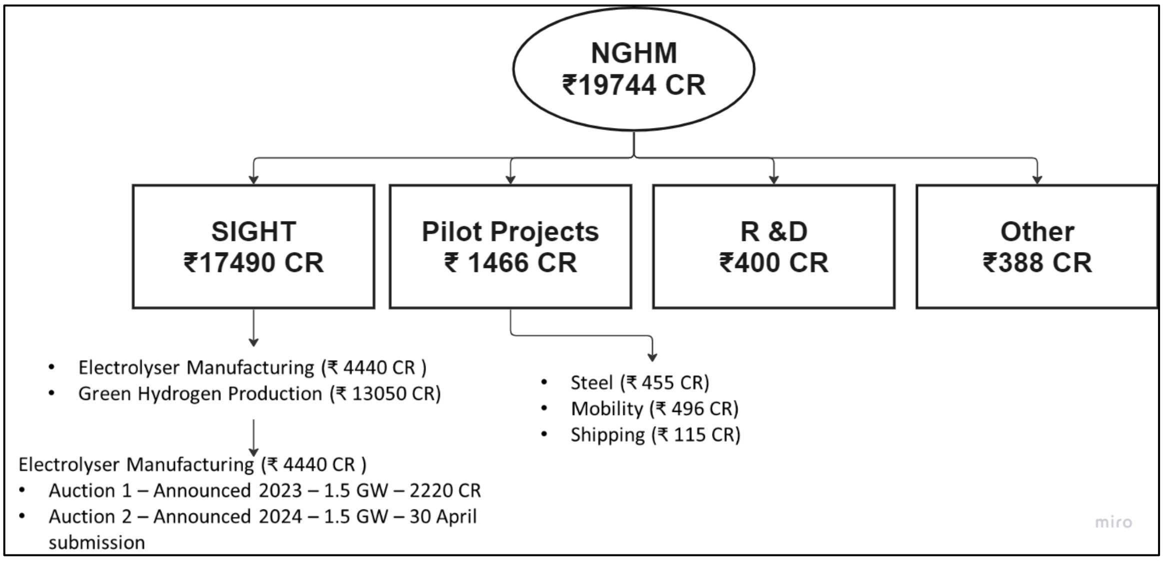

Figure 7: Allocation of Green Hydrogen Mission Fund

Objective of NGHM is to make India the Global Hub for production, usage and export of Green Hydrogen and its derivatives. This mission will lead to significant decarbonisation of the economy, reduced dependence on fossil fuel imports, and enable India to assume technology and market leadership in Green Hydrogen.

2.1.2 Existing tenders on green hydrogen in India

- ***Gas Authority of India Limited (GAIL)*** has floated an open tender in Dec 2021 to set up 4.3Ton per day (TPD) Green Hydrogen production unit, based on principle of electrolysis of water using PEM at GAIL Vijaipur site for its refinery application.
- ***Gujarat Industries Power Company Ltd. (GIPCL)*** has floated Invitation for Expression of Interest (EOI) for setting up 5 & 10MW electrolyser based Green Hydrogen Project along with associated facilities in April 2022 for surrounding refineries, fertilisers and chemical industries.
- ***Hindustan Petroleum Corporation Ltd. (HPCL)*** issued notice inviting tender (nit) for supply of electrolyser system for green hydrogen production at Hindustan Petroleum Corporation Limited at Visakh refinery in the state of Andhra Pradesh dated Oct 2021.
- The ***Solar Energy Association of India (SECI)*** issued the tender of Green Hydrogen Produced in India. The tender is for selection of Green Hydrogen Producers for setting up Production Facilities for Green Hydrogen in India under the Strategic Interventions for Green Hydrogen Transition (SIGHT) Scheme (Mode-1-Tranche-I), and has been awarded on 9th January, 2024 to 10 companies for a total capacity of 0.4MMT per annum.
- The ***SECI*** issued one more tender for selection of Electrolyser Manufacturers (EM) for setting up Manufacturing Capacities for Electrolysers in India under SIGHT Scheme (Tranche-I), and has been awarded on 12th January, 2024 to 8 companies for a total capacity of 1.5GW per annum.

3 Green Hydrogen Market Development:

This section explains the need of support mechanism for hydrogen industry, what are the available support mechanism and explains the working of major mechanisms.

Currently there are more than 1000projects[5] announced worldwide for green hydrogen and this represents a total of 38MMT per year. However, because of market uncertainty, high technological prices, and a multitude of additional challenges, only a limited number of projects have reached final investment choices.

At this stage of the hydrogen market's development, it is crucial for investors and legislators to back efforts that aim to reduce technology costs and accelerate the industry's learning process. In order to establish a market, it is necessary to have a well-functioning supply and demand infrastructure. Support mechanisms are essential tools that can significantly drive market development. For instance, the implementation of feed-in-tariff policies played a crucial role in facilitating the widespread adoption of solar photovoltaic (PV) technology in Germany and the UK. Similarly, the use of contract for difference mechanisms was pivotal in the successful deployment of wind energy technology in the UK.

3.1 Mechanisms that can enable green hydrogen market:

3.1.1 Feed-in-Tariff

A feed-in tariff (FIT) is a policy designed to support the development of renewable energy sources by providing a guaranteed, above-market price for producers. FITs usually involve long-term contracts, from 15 to 20 years.

Similar to feed-in schemes for renewable energy, green hydrogen producers can receive a remuneration either through a fixed feed-in tariff (FIT) or through a feed-in premium (FIP). Referring to the Levelised Cost of Energy (LCOE) approach commonly used for FIT, the remuneration level can be determined by the Levelised Cost of Hydrogen (LCOH).

- To incentivize the early adoption of green hydrogen, a feed-in-tariff mechanism can be implemented in the gas grid until the production costs of hydrogen are on par with natural gas prices.
- The expenses associated with maintaining this mechanism should be allocated among gas consumers.
- Implementing a legislative framework will allow hydrogen producers to inject hydrogen into the natural gas system for the purpose of mixing.
- The individuals will have the right to a 20-year contract to purchase hydrogen at a price that guarantees a satisfactory profit on their investment.
- The off-taker can either be a Transmission System Operator (TSO) for large-scale, high-pressure bulk hydrogen or a Distribution System Operator (DSO) for small-scale, medium-pressure hydrogen. The DSO and TSO have the ability to transfer the marginal cost, which represents the difference between the local hydrogen tariff and the market price for hydrogen, to a hydrogen clearing pool, specifically a designated fund.

[5] IEA Global Hydrogen Review 2023

3.1.2 Effect of FIT on biogas industry in UK

The UK implemented FIT in 2010. The scheme had many technologies covered including biogas. As it can be seen in Figure 8, since 2010, the installation of biogas plants has increased in UK. Furthermore, UK has implemented additional mechanisms to support biogas industry which includes Renewable Heat Incentive (RHI) since 2011, and Green Gas Support Scheme (GGSS) since 2021. Total number of biogas plants increased from 50 in 2011[6] to 723 in 2023 due to various support mechanisms[7].

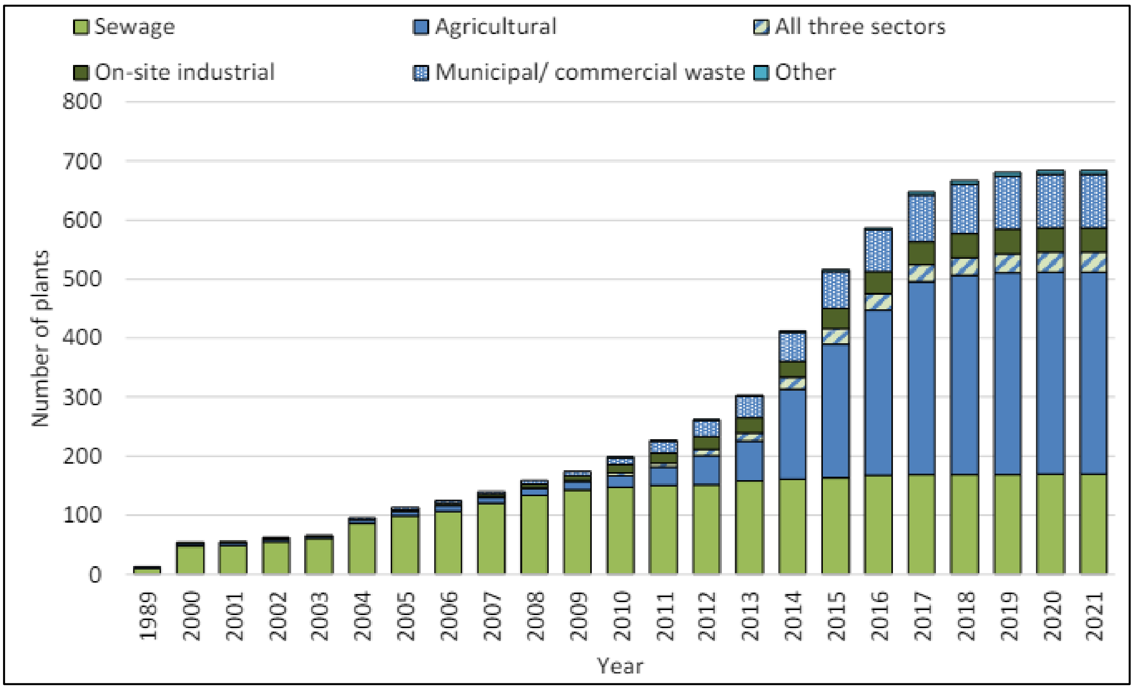

Figure 8: Number of biogas plants by feedstock in UK

3.1.3 Effect of FIT on Solar PV industry in India

Since the implementation of FIT in 2010, solar PV industry has grown significantly in India. From 2.82MW in 2009 to 37,627MW in 2020 the growth of solar industry is a good example of effect of government support to develop a market. Refer Figure 9 below to understand the effect of FIT government support in solar PV industry development in India.

[6] Gov.UK - Anaerobic digestion action plan

[7] HRS - can UK meet its AD targets

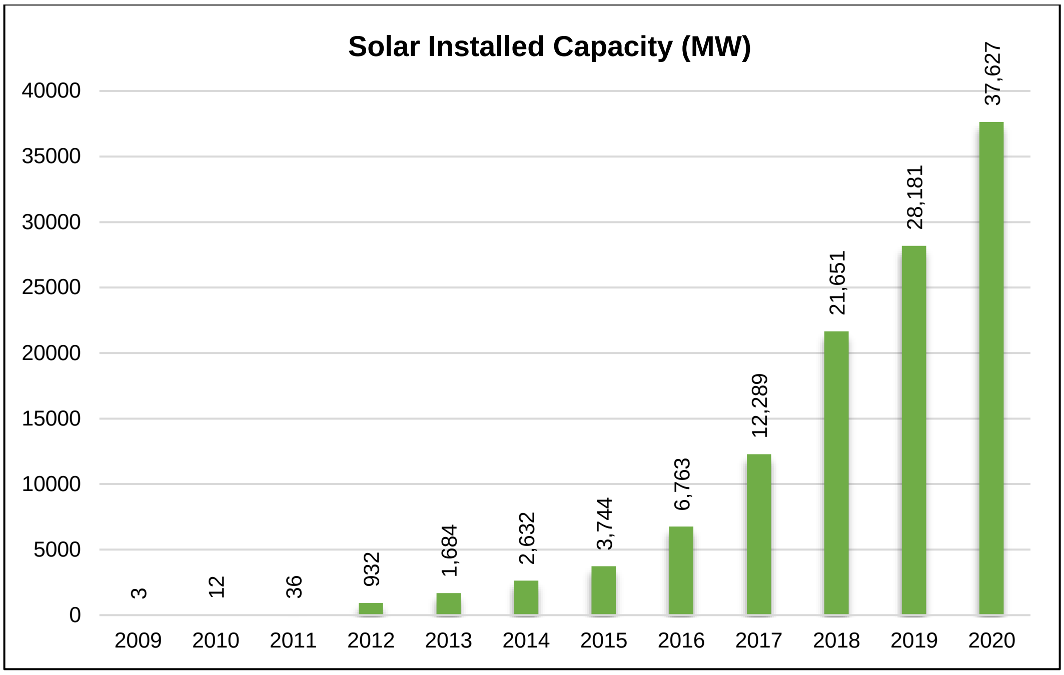

Figure 9: Solar installed capacity in MW

3.1.4 Contract for Difference (CfD)

Contract for Difference is a mechanism that provides financial support to low-carbon renewable energy and hydrogen projects. It aims to incentivize the production of low-carbon hydrogen by offering a guaranteed price for the hydrogen produced. It is a financial instrument that mitigates the risk associated with the price volatility of a specific asset (e.g., hydrogen or electricity). A bilateral agreement is established between a buyer (typically a government or a major consumer) and a seller (typically a hydrogen producer). Contracts for Difference give recipients a top-up subsidy that represents the difference in cost between the green option and the existing polluting option.

A CfD involves a consumer or a government agreeing to purchase hydrogen at a fixed price for a specified period of time, regardless of the market price. Hydrogen producers' benefit from a steady stream of revenue, which facilitates the acquisition of financing necessary for their operational activities and the purchaser obtains a dependable provision of hydrogen at a consistent cost, thereby enabling them to reduce their ecological impact and fulfil their sustainability goals.

The government will set a reference price for hydrogen, and generators will receive an extra payment if the market price drops below the reference price. The reference price will be that of natural gas (NG). Conversely, when the market price is higher than the reference price, companies are obligated to compensate the government for the difference.

How the price will be set?

Strike Price: It is often found through a competitive bidding mechanism, such as a tender or auction when producers compete against each other to determine the minimum set price that allows them to proceed with their individual projects. Therefore, these fixed prices are typically referred to as the 'strike price' (the price at which the auction was won).

Reference price: Reference price will be the price of natural gas.

e.g. Assume 5 producers submitted their bids in the auction.

Table 2: H2-CfD bids (conceptualised for illustration)

Producer	Bid (USD $/kg)
A	11
B	8
C	5
D	5.8
E	7

The strike price here is assumed[8] to be 7.36USD $/kg which represent the average price of the bids submitted. The reference price is the price of natural gas and it is variable.

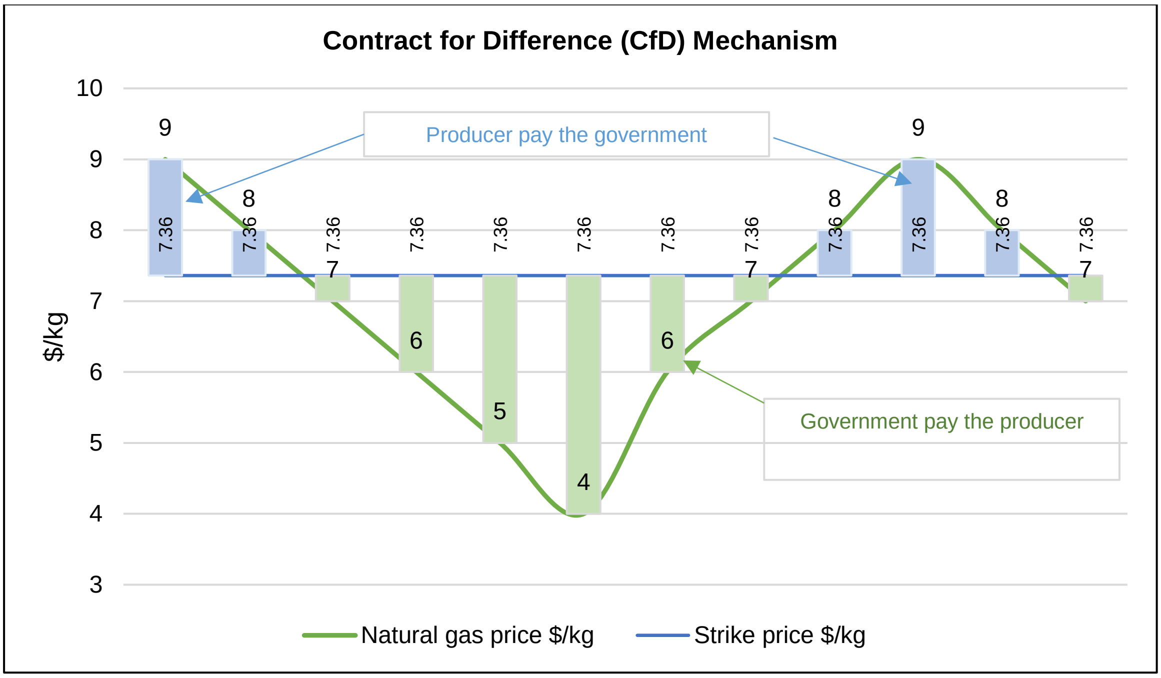

Figure 10: Working of CfD Mechanism

As shown in the Figure 10, when the natural gas price is above strike price the difference is paid by producer to the government and when the natural gas price is below the strike price government pays the difference to producer. The CfD seeks to reduce the price disparity by offering financial support to hydrogen producers with lower carbon emissions, so enhancing their competitiveness and promoting wider adoption

3.1.5 Requirements for implementing CfD mechanism:

- The hydrogen generated by qualifying projects must have a carbon intensity ranging from 2 to 4kilogrammes of CO_2 per kilogramme of hydrogen.
- Projects must have the capacity to generate a minimum of few thousand metric tonnes of hydrogen per year. The minimal capacity requirement ensures that the CfD programme only provides funding to larger projects that have a significant impact on the hydrogen market.

[8] The method used here to calculate the strike price is for illustration purpose.

- Projects must have a minimum operational lifespan of 15 years. The project's long-term commitment demonstrates its viability and fosters sustainable development.
- Projects are required to have offtake agreements with customers for a minimum of seventy percent of the hydrogen they produce. This ensures a demand for the hydrogen generated, reducing the risk for project creators.

3.1.6 Effect of CfD on price reduction

Since the implementation of CfD mechanism in the UK, the strike prices for offshore wind has reduced significantly; that means the cost to develop offshore wind farms have reduced drastically. This is because governments support to develop the industry led to competitive bidding auctions which made developers to bid with lowest cost to win the government support for projects. As shown in the Figure 11 the strike prices of offshore wind auctions have reduced significantly and this led the government to spend less on supporting the new industry development.

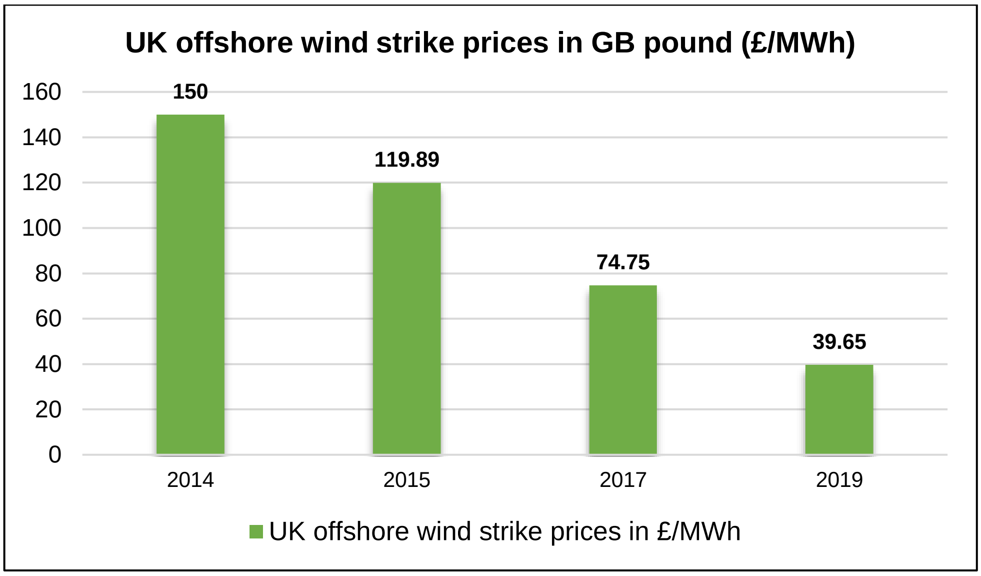

Figure 11: Effect of CfD in offshore wind industry in UK

3.1.7 Demand Side support mechanisms:

Many countries across the globe are going to place mandatory targets regarding the demand for hydrogen in transportation and industry, as well as synthetic fuel mandates in aviation. For example, The EU has implemented the FuelEU Maritime rule with the aim of increasing the proportion of renewable and low-carbon fuels in the fuel composition of international maritime transport inside the EU. The FuelEU Maritime initiative encompasses the potential implementation of a 2% renewable fuel of non-biological origin (RFNBO) target in maritime fuels beginning in 2034 to support the uptake of the renewable fuels.

In 2021, India declared its intention to implement quotas for steel, fertilisers, and refining. Although these quotas were ultimately excluded from the National Green Hydrogen Mission, they continue to be deliberated upon and may be implemented in the near future. The consultation on a consumption rebate scheme scheduled to commence in 2025 has been initiated in New Zealand, while the United States has declared a ***1USD billion*** initiative to promote the demand for low-emission hydrogen, the specifics of which are expected to be disclosed later this year.

4 Hydrogen production and storage technologies:

There are several existing hydrogen production technologies, and new ones are in development stage. The new technologies aim to achieve zero or minimal emissions during production processes. Colours are used by industry to differentiate between carbon-intensive (grey and black/brown) and clean (green, blue, turquoise, and pink) hydrogen technologies refer Figure 12.

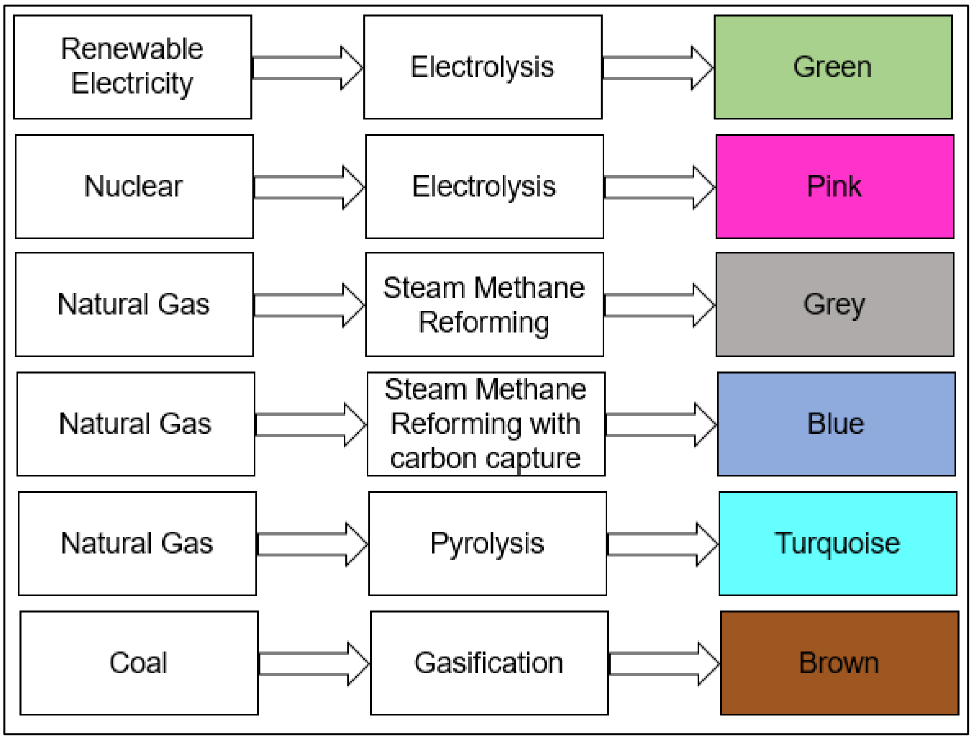

Figure 12: Colour scheme for hydrogen production

The

Table 3 provides the types of hydrogen produced from various technologies and it describes the significance of the colour.

Table 3: Types of Hydrogen and its description

Type of Hydrogen	Description
Brown/Black Hydrogen:	▪ Hydrogen originating in a process of coal gasification is called black (from black coal) or brown (from brown coal) hydrogen. Coal gasification involves conversion of coal from its solid state into gaseous form. ▪ The process disintegrates coal into its chemical constituents, which includes methane gas. The coal then reacts with oxygen and steam under high temperature and pressure, which results in the formation of syngas, a blend of hydrogen, carbon dioxide, and carbon monoxide.
Grey Hydrogen	▪ Grey hydrogen refers to hydrogen produced from fossil fuels, using the most commonly applied concept of gas reforming. ▪ In this process, natural gas and steam at high temperature and pressure are converted to hydrogen and carbon dioxide through a catalytic chemical reaction, which is endothermic and uses steam at 700 °C to 1000 °C. Since a large amount of carbon dioxide is emitted during the production process, it is referred to as “grey".
Blue Hydrogen	▪ Using the steam methane reforming or auto thermal reforming process that mixes natural gas with very hot steam and catalysts and produces H_2 and CO_2. ▪ This CO_2 can be then captured and stored underground by CCUS to make the process carbon-neutral, and the resulting H_2 is called blue hydrogen
Turquoise Hydrogen	▪ Turquoise hydrogen production uses a modified pathway when compared with blue hydrogen production. ▪ A pyrolyser splits the natural gas feedstock to produce hydrogen and solid carbon without any need for carbon emission abatement. ▪ The turquoise colour fits in between the green and the blue colours because even though natural gas is used as the raw material, the low carbon intensity of the process makes it an attractive option
Green Hydrogen	▪ Green hydrogen is the hydrogen produced without greenhouse gas emissions. ▪ It is made through the electrolysis of water using renewable energy sources such as solar or wind power. ▪ Electrolysis entails an electrochemical reaction to split water into oxygen and hydrogen, releasing no carbon-dioxide in the process.
Pink Hydrogen	▪ Like green hydrogen, it is generated through electrolysis of water but using nuclear energy as a power source.

4.1 Emissions from hydrogen production via different routes[9]

Today, Natural gas is the main source of hydrogen production globally, accounting for 62% of production. The direct emissions of hydrogen production from natural gas without carbon capture and storage (CCS) using steam methane reforming (SMR) are around 11kg CO_2-eq/kg H_2. Applying CCS to the various direct CO_2 sources at the SMR hydrogen plant can reduce the direct emissions to 1.5-6.2kg CO_2-eq/kg H_2 (capture rate 93%). Hydrogen production from coal gasification without CCS results in total emissions of 22-26kg CO_2-eq/kg H_2. Applying CCS with a total capture rate of 93% reduces the emissions intensity of the coal pathway to 2.6-6.3 kg CO_2-eq/kg H_2. Figure 13 below shows the emission intensity of various H_2 production pathways.

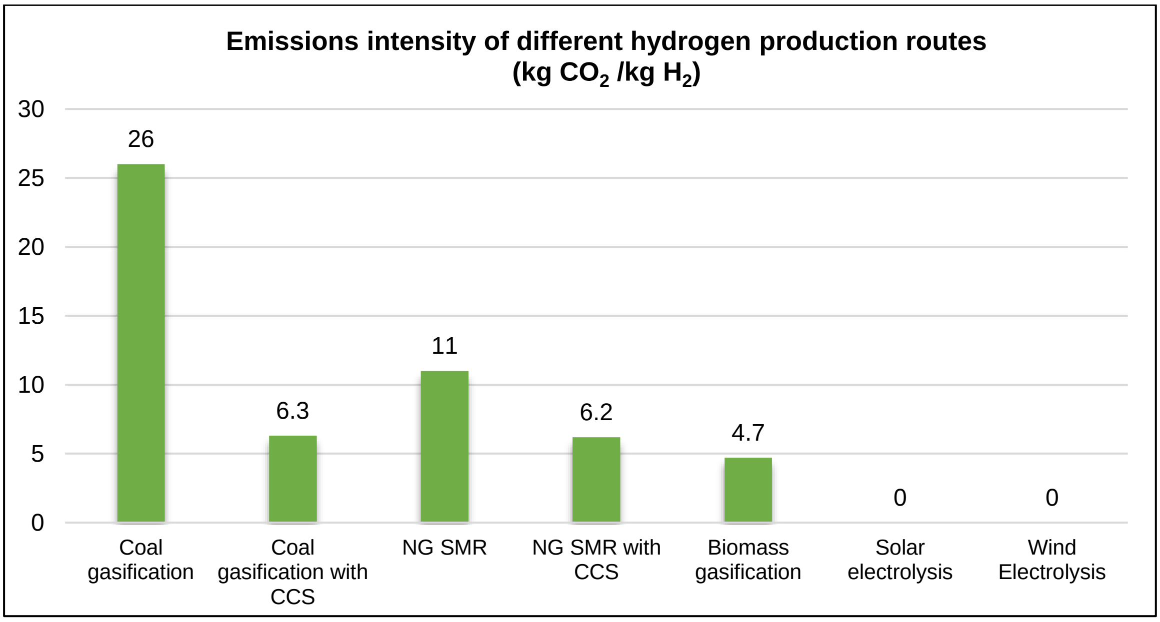

Figure 13: Emissions intensity of different hydrogen production

4.2 Green Hydrogen production

Hydrogen, when produced from clean sources such as solar, wind, and hydro etc., is called green and it is a critical enabler of the global transition to sustainable energy and a vital component of achieving net-zero emissions economies. Renewable hydrogen is obtained through the process of electrolysis where electricity is used to split water into its components – oxygen and hydrogen. Electrolysis occurs in a device called an electrolyser, which splits water. The Figure 14 represents simple diagram of green hydrogen production.

[9] IEA (international energy agency) – Global Hydrogen Review 2023

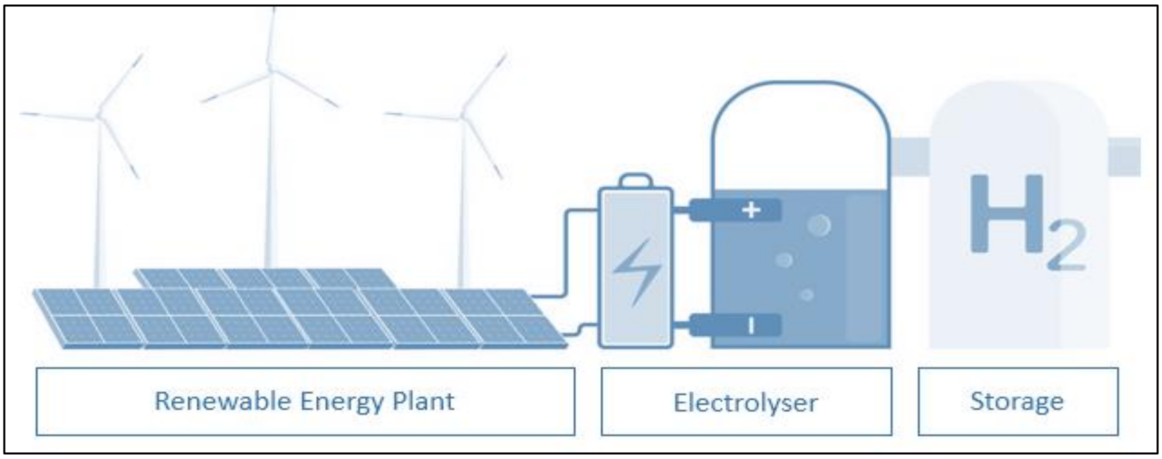

Figure 14: Green Hydrogen simple schematic diagram[10]

This energy source has merits and demerits that we must be aware of. Following are some of its most important merits:

- **100 % sustainable:** green hydrogen does not emit polluting gases either during combustion or during production.
- **Storable:** hydrogen is easy to store, which allows it to be used subsequently for other purposes and at times other than immediately after its production.
- **Versatile:** green hydrogen can be transformed into electricity or synthetic gas and used for commercial, industrial or mobility purposes.

However, green hydrogen also has some demerits;

- **High cost**: energy from renewable sources, which are key to generating green hydrogen through electrolysis, is more expensive to generate, which in turn makes hydrogen more expensive to obtain.
- **High energy consumption:** the production of hydrogen in general and green hydrogen in particular requires more energy than other fuels.
- **Safety issues:** hydrogen is a highly volatile and flammable element and extensive safety measures are therefore required to prevent leakage and explosions.
- **Low volumetric density:** hydrogen gas at atmospheric pressure has very low energy density compared to other fuels.

[10] Source – Witty Images

4.3 Electrolyser Technology

Hydrogen from renewable power has a potential to highly contribute to the global energy decarbonisation. Renewable hydrogen is obtained through the process of electrolysis where electricity is used to split water into its components – oxygen and hydrogen. Electrolysers can be classified on the basis of electrolyte used as alkaline if potassium hydroxide is used and PEM if a solid polymer membrane is used as electrolyte. Although promising, solid oxide and anion exchange membrane (AEM) technologies are still in their early stages of development. The **Table 4** summarises the characterisation of electrolyser technologies.

Table 4: Characterisation of electrolyser technologies

Parameter	Alkaline	PEM	AEM	Solid Oxide
Operating Temp	70-90 ˚C	50-80 ˚C	40-60 ˚C	700-850 ˚C
Operating pressure	1-30 bar	< 70 bar	<35 bar	1 bar
Electrolyte	*KOH / NaOH* (5-7 mol/L)	Solid polymer electrolyte *(PFSA)*	DVB polymer support with (1 *mol/L*) *KOH / NaOH*	Yttria stabilized Zirconia *(YSZ)*
Separator	Asbestos/Zirfon/Ni	Nafion	Fumatech	Solid electrolyte *YSZ*
Electrode/Catalyst (Hydrogen side)	Nickel coated perforated stainless steel	Iridium oxide	Nickel	*Ni / YSZ*
Electrode/Catalyst (Oxygen side)	Nickel coated perforated stainless steel	Platinum carbon	Nickel or *NiFeCo* alloys	Perovskites *(LSCF, LSM)* *(La,Sr,Co,FE)* *(La,Sr,Mn)*
Gas Diffusion layer	Nickel mesh	Titanium mesh/carbon cloth	Nickel foam/carbon cloth	Nickel mesh/foam
Nominal current density	0.2–0.8 A/cm^2	1–2 A/cm^2	0.2–2 A/cm^2	0.3–1 A/cm^2
Voltage range	1.4–3 *V*	1.4–2.0 *V*	1.4–2.5 *V*	1.0–1.5 *V*
Efficiency	50%–78%	50%–83%	57%–59%	89%
Lifetime (stack)	60,000 *h*	50,000–80,000 *h*	>30,000 *h*	20,000 *h*
Commercial Status	Mature	Commercial	Small scale demonstration 1 MW	Demonstration

Capex 10 MW [US$/kWe]	500 - 1000	700 - 1400	1500-2500	>2300

The Figure 15 below shows the key equipment needed for green hydrogen projects,which include renewable energy plant. It may be solar PV, wind or hydro. Then electctrolsyer which produced hydrogen from electricity and water, and then produced hydrogen is stored in storage.

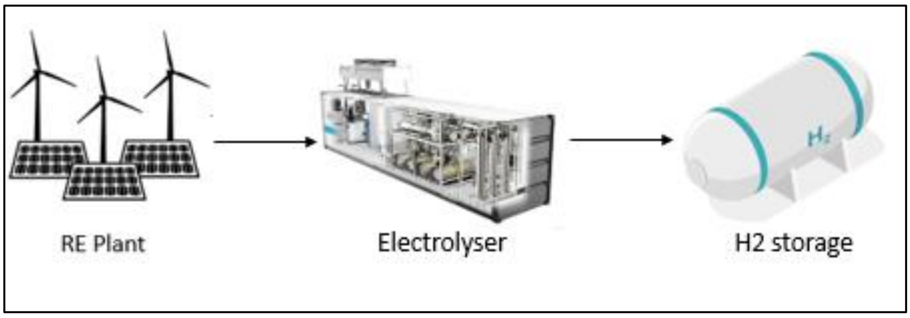

Figure 15: Basic Schematic of Electrolyser System

4.3.1 Balance of Plant:

The balance of plant (BoP) for an electrolyser system refers to all the components and systems necessary for the operation of the electrolyser that are not directly part of the electrolyser stack itself and is represented in block diagram in Figure 16.

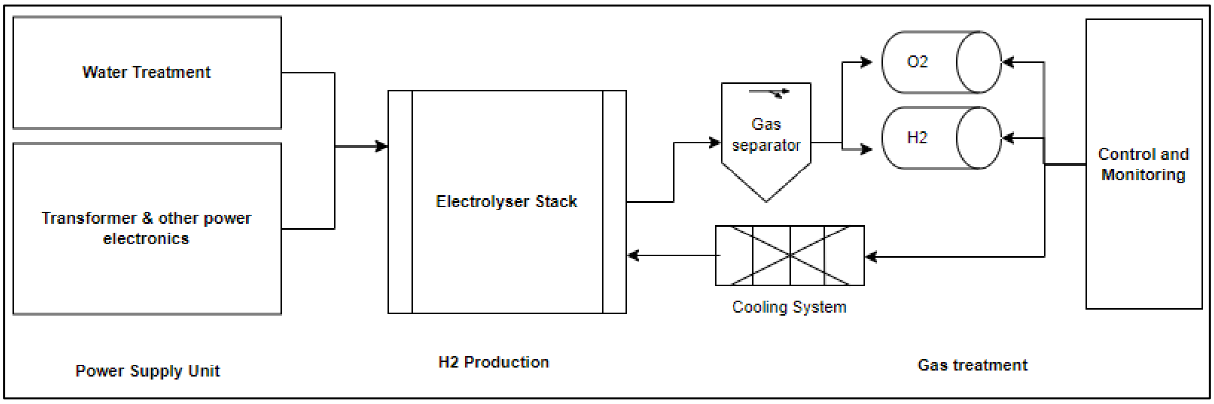

Figure 16: Typical Electrolyser balance of plant (BoP) diagram

For an electrolyser system used for hydrogen production, the balance of plant typically includes components such as:

- Power Supply: Often an external component providing the necessary electrical power for the electrolysis process. This can include transformers, rectifiers, and other power electronics.
- Water Treatment System: To provide high-quality water for the electrolysis process, which is crucial for efficiency and longevity of the electrolyser.
- Gas Treatment System: For purification and drying of the hydrogen and oxygen gases produced by the electrolyser, ensuring they meet the required purity standards. It includes pressure regulation, control and monitoring system.

The balance of plant is critical for the efficient and safe operation of an electrolyser system, and its design can significantly impact the overall performance and cost-effectiveness of hydrogen production.

4.3.2 Comparison of electrolyser technologies

- For water electrolysis, there are four main technologies available: Alkaline water electrolysis (AEL), proton exchange membrane (or polymer electrolyte membrane) electrolysis (PEMEL), Anion Exchange Membrane (AEM) and solid oxide electrolysis (SOEL). Among them proton exchange membrane (PEM) and alkaline electrolyser technologies are currently commercially available and are above Technology Readiness Level (TRL) 7.
- PEM water electrolysis has great advantages such as compact design, high current density (above 2A/cm^2), high efficiency, fast response, and small footprint. In addition, it can be operated at low temperatures (20–80 degrees Celsius) to produce ultra-pure hydrogen and oxygen, which have a significant economic value. However, platinum group metals (PGMs) like platinum, iridium, and ruthenium as catalysts make PEM electrolysis the most expensive electrolysis method because of initial capital expenditure (CAPEX).
- Alkaline technologies are likely to be used in projects that have fewer electricity price restrictions, little space limitations, and low renewable variabilities, such as large, GW-scale industrial projects connected to hydropower. On the other hand, PEM technologies are better suited for projects with high renewable variability and limited space, such as offshore projects.

4.4 Storage

Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell technologies in applications including stationary power, portable power, and transportation. Hydrogen can be stored physically as either a gas or a liquid. Hydrogen has a high energy per unit mass content of 120.1MJ/kg. However, its low density at environment temperature yields an extremely low energy density (0.01MJ/L). As a result, larger volumes of hydrogen must be required to meet the same energy demands as other fuels.

Hydrogen storage can be divided according to whether it is based on physical or material storage. Under physical storage, it is stored as a gas or liquid as a pure molecular compound with no significant physical or chemical bonding to other materials.

The most suitable storage vessel will be determined by the application of the storage, the volume to be stored, the time required for storage, the required discharge rate, the geographical availability of different options and whether the storage is small-scale or large-scale. For large-scale storage, the energy density issue and filling time are not constraints, whereas for small-scale storage, the energy density issue and charging times are crucial. The purity of the hydrogen is an additional important factor, as a high purity of hydrogen is of utmost importance for its use in fuel cells, whilst for burning purposes, purity will not be a critical point. The Figure 17 below shows various types of hydrogen storage and table 5 consists the comparison of these storage technologies.

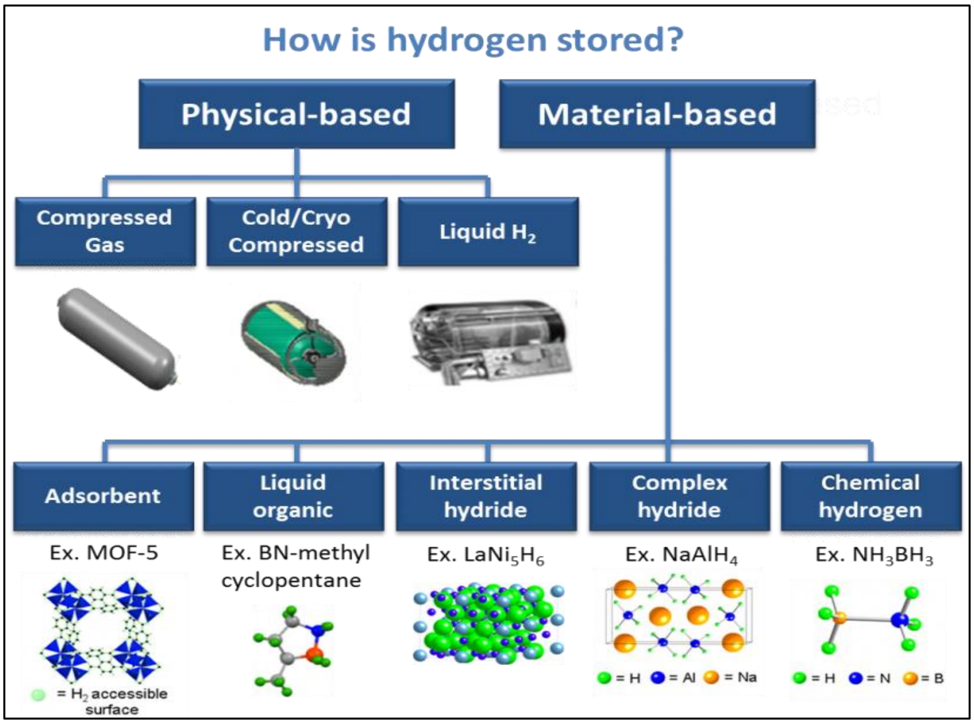

Figure 17: types of Hydrogen Storage[11]

4.4.1 Comparison of Hydrogen Storage:

Table 5: Comparison of hydrogen storage types

Types of Hydrogen Storage	Volumetric energy density	Advantages	Drawbacks
Gas Hydrogen	25-30 kg/m^3	High efficiency, convenient, mature technology.	High pressure can cause safety issues, Heat management required
Liquid	50 kg/m^3	High liquid density and storage efficiency	Costly, Large consume of energy and time, low temperature
Metal hydrides	50-175 $kg.m^3$	High safety, high purity of hydrogen, good reversible cycle performance, large volume of hydrogen density	Absorbing impurities, Low hydrogen storage capacity owed to the weight of metallic hydrides

Compressed gas storage is mature, easy to handle and install and highly efficient among other storage technologies for green hydrogen plants. Hydrogen can also be stored underground i.e. in salt caverns or gas depleted caverns however, this type of storage is restricted to fewer locations and suitable for large scale hydrogen storage.

[11] Science Direct - https://doi.org/10.1016/B978-0-12-818487-5.00010-8

5 Sgurr Energy's Scope

Service	Description
Pre-feasibility Analysis	• Our consultancy specializes in providing comprehensive prefeasibility and feasibility reports for Green Hydrogen projects. Leveraging our expertise in renewable energy, we offer tailored solutions to meet your specific needs, ensuring the viability and success of your Green Hydrogen initiatives. • **Resource Assessment:** Thorough analysis of renewable energy potential (solar, wind, etc.) for hydrogen production, considering local climatic conditions and available land. • **Economic Feasibility**: Indicative High Level Financial modelling to assess the economic viability of the project, including capital expenditure, operational costs, and revenue projections. • **Demand and Application Assessment**: Analysis of consumption points for hydrogen and evaluating its suitability to various application.
Detailed feasibility Analysis	• **Technology Evaluation:** In-depth review of electrolysis technologies to determine the most suitable option based on efficiency, scalability, and cost-effectiveness. • **Plant Design**: Customized plant design considering the selected technology, local conditions, and project requirements, ensuring optimal performance and efficiency. • **Performance Modelling**: Come up with a digital twin or a representative mathematical model of hydrogen equipment to align with application requirements and precisely optimize the CAPEX and revenue streams. • **Hourly yield assessments:** These are generated in parallel with the solar and wind generation profiles, to understand the efficiency of hydrogen technology (Electrolyser, Storage and Fuel cells) integration with solar/wind power plants. • **Economic Analysis:** Financial modelling to assess the economic feasibility of the project, including cost estimations, revenue projections, and financial indicators (LCOE, LCOH etc.) • **Risk Analysis:** Identification of potential risks associated with the project, including supply chain disruptions, and technology risks. • **Layouts and Schematics:** Develop feasibility stage layouts, process flow diagrams, BIM designs, electrical schematics and interconnection diagrams etc.