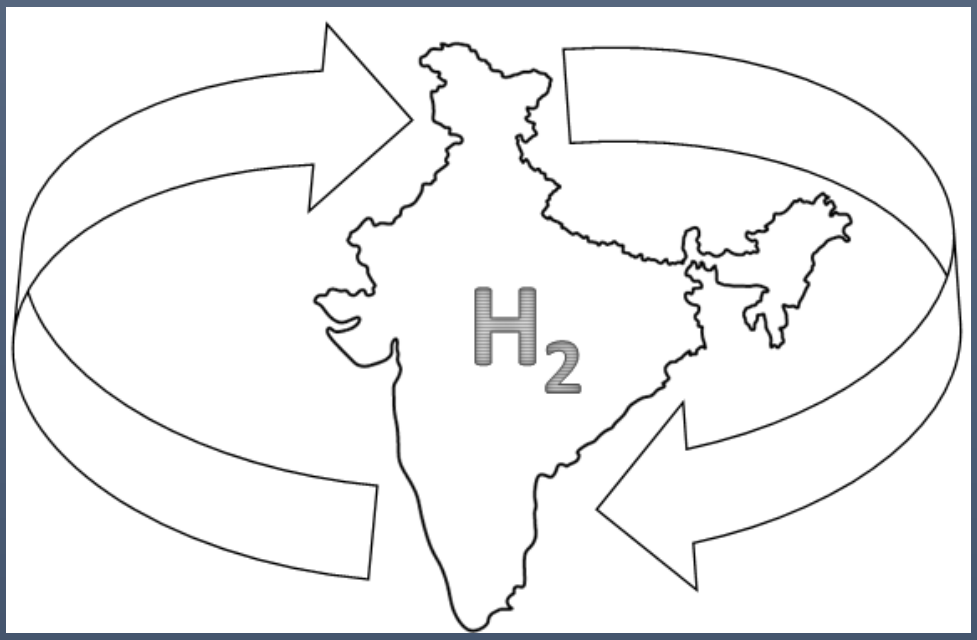

A report on

Hydrogen Production and Demand in India

NATIONAL INSTITUTE OF SOLAR ENERGY
HYDROGEN ENERGY DIVISION

NISE
National Institute of Solar Energy

Contents

Preface

Energy is a vital input for economic growth of a country. For meeting growing energy requirement, India continues to rely heavily on fossil fuels. Its import dependence on liquid and gaseous fossil fuels continues to grow. With a view to move towards low carbon pathways and energy security, India has undertaken several measures in the past four decades, including development and deployment of new and renewable energy sources. In this regard, hydrogen as a new energy vector has been attracting a considerable attention globally as well as in India in the recent years. For accelerating further development, the Government of India has announced in the Budget for the financial year 2021-22 its intent to launch hydrogen mission during 2021.

Hydrogen plays a critical role in fertiliser, petroleum refining, caustic soda, chemical, semiconductor, vegetable oil and other industries. Most of these industries produce hydrogen on-site for meeting their hydrogen demand. However, reliable information on hydrogen production capacity and actual demand for hydrogen of these industries is not available presently. This report prepared by a team consisting of Dr. M R Nouni, Sr. Consultant; Dr. Joydev Manna, Sr. Scientist; Shri Prakash Jha, Engineer and Shri Rudranath Sarkhel, Engineer of Hydrogen Division of National Institute of Solar Energy under the guidance of Dr. Chandan Banerjee, Dy Director General based on inputs received from different sources has estimated the total hydrogen production capacity in the country as on 1.4.2020 and also demand for hydrogen for the financial year 2019-20. Based on the production capacity and actual demand for hydrogen, the report also provides indication about availability of spare hydrogen in the country for initiating some demonstration project in the niche locations. These projects may play important role in providing visibility to non-industrial applications of hydrogen with existing hydrogen production infrastructure in the country.

(Dr. Arun K. Tripathi)
Director General

Executive Summary

- Hydrogen has been attracting a lot of attention of the policy makers, environment lovers, researchers, industrial organisations, including automobile companies and others for quite some years in view of its potential to play a significant role in providing low-carbon future solutions to many issues faced by the global energy system.
- Global demand for hydrogen is estimated in the range of 70 to 80 million tonnes (MT) during 2018 as per the different sources. 95% of all hydrogen was generated from natural gas and coal and remaining 5% was generated through electrolysis. Authentic information on hydrogen production capacity and demand for India is not available and this report makes an effort in this direction by collecting information from different sources.
- Hydrogen can be produced from any primary energy source, which according to the raw materials used could be divided into two major categories namely, conventional and renewable technologies. In the first category processes fossil fuels are reformed by steam reforming, partial oxidation, autothermal steam reforming and pyrolysis. The second category accommodates the methods which produce hydrogen from renewable resources, either from biomass or water. For splitting water, either electricity or some other primary energy source is required.
- Water electrolysis utilising renewable electricity is the principal method for producing green hydrogen. The most commonly used electrolyser is alkaline based with efforts for development and deployment of proton exchange membrane electrolyser and solid oxide electrolyser being aggressively pursued.
- Presently, a vast majority of hydrogen is produced for in-situ consumption by the industry. The production of ammonia and refining of petroleum are the prime examples of it, which account for nearly two-thirds of hydrogen consumption. The other applications of hydrogen are in vanaspati industry for hydrogenation of vegetable oil; use as a reduction agent in place of carbon in iron and steel industry; cooling of generators in thermal power plants; float glass industry; production of other chemicals such as hydrogen peroxide, methanol etc; space applications; semiconductor industry etc.

- Hydrogen production capacity has been estimated as 6.341 MTPA as 1.4.2020, as per details given in Fig. 1.

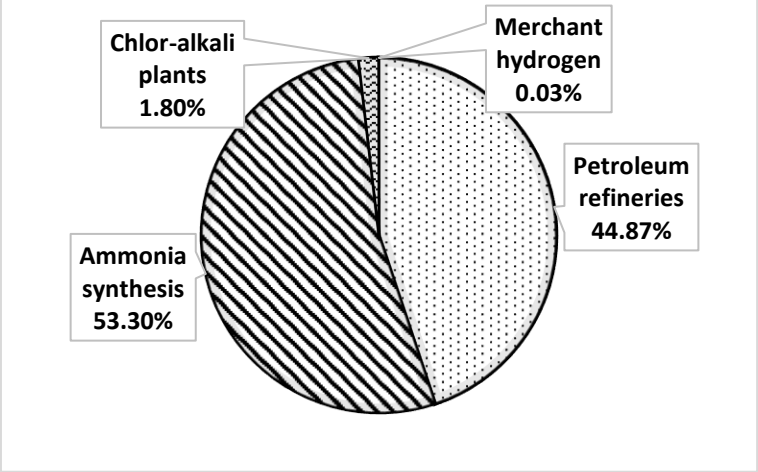

Fig. 1: Hydrogen production shared by various industrial sectors

- Hydrogen demand in petroleum refineries in India during 2019-20 could not be estimated because the petroleum refineries both in public and private sector did not share the information with the team involved from NISE in undertaking this study. Some of them from public sector cited this to be confidential and others from private sector did not share any information by not responding to queries from NISE team. Considering hydrogen demand in the petroleum refineries at 90% of the installed capacity, demand for hydrogen during 2019-20 was estimated at 2.5605 MT. For other industries the demand for hydrogen during 2019-20 was estimated about 2.84 MT, as per details given below:

- Petroleum refineries : 2.5605 MT
- Ammonia synthesis for fertiliser production : 2.647 MT
- Chlor-alkali units : 0.090 MT
- Merchant hydrogen : 0.00063 MT
- Space applications : 0.0242 MT
- Float glass : 0.0007 MT
- Thermal power plants : 0.0003 MT
- Hydrogen peroxide : 0.0098 MT
- Methanol production : 0.0663 MT#
- Total : 5.39943 MT

estimated based on the actual methanol produced in the country during 2019-20

- In addition, there would be demand for hydrogen for applications related to (a) stationary power generation; (b) transport sector; and (c) household sector in the immediate coming years. However, the demand for these applications during 2019-20 was negligible.
- Government of India has announced launching of hydrogen mission during 2021-22. Based on information obtained, it emerges that some surplus hydrogen is available from the major hydrogen production units. However, the exact amount would be known, if information relating to actual production is made available by the industry. The surplus hydrogen from the petroleum refineries, chlor-alkali units and merchant producers may be significant for initiating some demonstration projects without investing in creating new infrastructure for hydrogen production.
- Different renewable energy-based hydrogen production technologies are being supported in the country under R&D programme of the Government of India and are under different stages of development. These efforts have the potential for development of green hydrogen production technologies by utilising domestically available resources.

1. Introduction

Hydrogen derives its name from the Greek words *hydro* for "water" and *genes* for "forming". It makes up more than 90 percent of all the atoms, which equals three quarters of the mass of the universe. Hydrogen is essential for life, and it is present in nearly all the molecules in living things. It is also occurring in the stars and powers the universe through the proton-proton reaction and carbon-nitrogen cycle. Pure hydrogen gas is scarce in the earth's atmosphere and it occurs mainly in water, in organic matter such as living plants, petroleum and coal. Therefore, it is the most abundant element in the universe.

Hydrogen is the lightest and the simplest element. It is colourless, odourless, and flammable gas. Hydrogen is non-toxic and much lighter than air and it dissipates when released. Its energy content at lower heating value is 120.7 MJ/kg, which is much higher than the most gaseous and liquid fuels on gravimetric basis. However, its volumetric energy density is poor and therefore, it is needed to be stored at very high pressure. Liquid hydrogen has lower energy density compared to liquid fuels like petrol and diesel. Moreover, liquefaction and raising pressure to store adequate hydrogen consume significant energy. Hydrogen offers the option of producing it from a wide range of resources using different feedstocks, including conventional and renewable employing different technologies.

The carbon-based fuels have played a remarkable role in the economic growth in the light of increasing population and urbanisation ever since the beginning of the industrial era. Growth in consumption of fossil fuels in turn contributed to higher concentration of the greenhouse gases in the earth’s environment, which have negatively impacted the climate change by way of global warming. Realising the importance of decarbonising the energy sources, development and deployment of the renewable energy sources have come to the forefront of the global energy scene. With increasing penetration in the global energy mix of variable renewable energy resources such as wind and solar, which have grown from 48 GW to 651 GW and 2.2 GW to 633 GW during the period 2004 to 2019, the role of hydrogen as an energy storage medium for balancing the power system have been increasingly recognized. Hydrogen is a versatile energy carrier as not only it can be produced from a number of energy sources but it also storable, transportable and utilisable across different sectors of the economy.

Hydrogen has been attracting a lot of attention of the policy makers, environment lovers, researchers, industrial organisations, including automobile companies and others for quite some years in view of its potential to play a significant role in providing low-carbon future solutions to many issues faced by the global energy system. Firstly, hydrogen can decarbonise several sectors that covers chemical, petroleum refineries, iron and steel and long-haul transport. Secondly, it could be produced from any energy source and thirdly, it offers a long-term viable electricity storage medium with variable renewable energy sources such as solar and wind. Hydrogen looks promising for transport applications on three counts: GHG emissions reduction, energy security and reduction of local air pollution.

Authentic information relating to global demand for hydrogen is not available. Different source estimated its demand during 2018 from 70 to 80 MMT. As per IRENA, around 120 million tonnes of hydrogen were produced during 2018, of which two-thirds was pure hydrogen and one-third was in mixture form with other gases. As per IEA, around 70 MMT of dedicated hydrogen was produced in 2018 from natural gas (76%) and coal (23%). About 2% of hydrogen was produced through electrolysis. On this issue, IRENA is of the view that about 95% of all hydrogen was generated from natural gas and coal and remaining 5% was generated as a by-product from chlorine production through electrolysis. In the iron and steel industry, coke oven gas is used, and it also contains a high hydrogen share, some of which is recovered. Currently there is hardly any significant hydrogen production from renewable sources at global level. It has been stagnating in the range of 0.35 to 0.37 MT/year during the period 2015-2019, as per IEA. By the end of 2019, electrolysers of an aggregate capacity of 25 MW were in operation for production of clean hydrogen.

Presently, a vast majority of hydrogen is produced for in-situ consumption by the industry. The production of ammonia and refining of petroleum are the prime examples of it, which account for nearly two-thirds of hydrogen consumption. Other major industrial uses of hydrogen include production of methanol and steel. Use of hydrogen for synthesis of ammonia-based fertiliser and in petroleum refining dates back to the mid-20th century. Recently use of hydrogen in petroleum refining has been growing very rapidly due to a combination of factors relating to changes in crude; environmental regulations such as limits of sulphur in diesel, allowable limits of NO_x, and SO_x, in off-gas emissions to the atmosphere, aromatic and light hydrocarbon concentrations in the gasoline etc. It has been estimated

that hydrogen demand in refineries will grow by 7% and reach 41 MT by 2030. Around 31 MT of hydrogen was consumed in 2018 for ammonia synthesis. Most of the synthesised ammonia (80%) is used to produce fertilisers (urea, ammonium nitrate/phosphate etc.). In the chemical industry, a small amount of hydrogen is also used in some other chemical synthesis such as polymers (ethylene, propylene) and solvents (benzene, toluene) etc. Other applications of hydrogen are in glass, semiconductor, synthetic fuel, and food processing industries.

So far as India is concerned, no reliable data for hydrogen demand and its production through different resources is available in public domain. As per the global practice, hydrogen is mostly produced for in-situ consumption by fertiliser, petroleum refining and chlor-alkali industry. Hydrogen market in India was valued at US$ 50 million in 2017, and is expected to reach US$81 million by 2025, growing at a CAGR of 6.3% from 2018 to 2025.

Govt. of India has announced to launch a hydrogen mission for green hydrogen production during 2021. The hydrogen mission is going to play a catalytic role for development of activities related to production and utilisation of hydrogen in the country. In this context, availability of information relating to existing hydrogen production capacity and the present demand for it for various applications would provide information to the different stakeholders about any spare/surplus capacity that is available presently and could be utilised for initiating some demonstration projects on the ground. In this report, an effort has been made to put together estimate of hydrogen production capacity and demand for India for the financial year 2019-20 based on information gathered from a variety of sources. The report also provides a brief account of various hydrogen production methods and its uses in India. In majority of applications where hydrogen is used as a reactant, hydrogenation takes place to insert hydrogen to saturate the molecule or to cleave the molecule to remove heterogeneous atoms such as sulphur and nitrogen. In most of these applications, the reaction depends on hydrogen partial pressure and hence high purities and high pressures are employed in the process. Majority of hydrogen is used as a reactant in the chemical and petroleum industries.

2. Overview on hydrogen production methods

Hydrogen can be produced from any primary energy source. A wide variety of processes are available for hydrogen production which according to the raw materials used could be divided into two major categories namely, conventional and renewable technologies, as shown in Fig. 2. In the first category processes fossil fuels are utilised and includes the methods of hydrocarbon reforming and pyrolysis. In hydrocarbon reforming process, the participating chemical techniques are steam reforming, partial oxidation and autothermal steam reforming. The second category accommodates the methods which produce hydrogen from renewable resources, either from biomass or water. Currently most of the hydrogen is produced from fossil fuels/hydrocarbons due to the well-developed production techniques and low-cost of hydrogen produced by such processes. In the following section of this report an overview on the various hydrogen production methods is outlined and discussed.

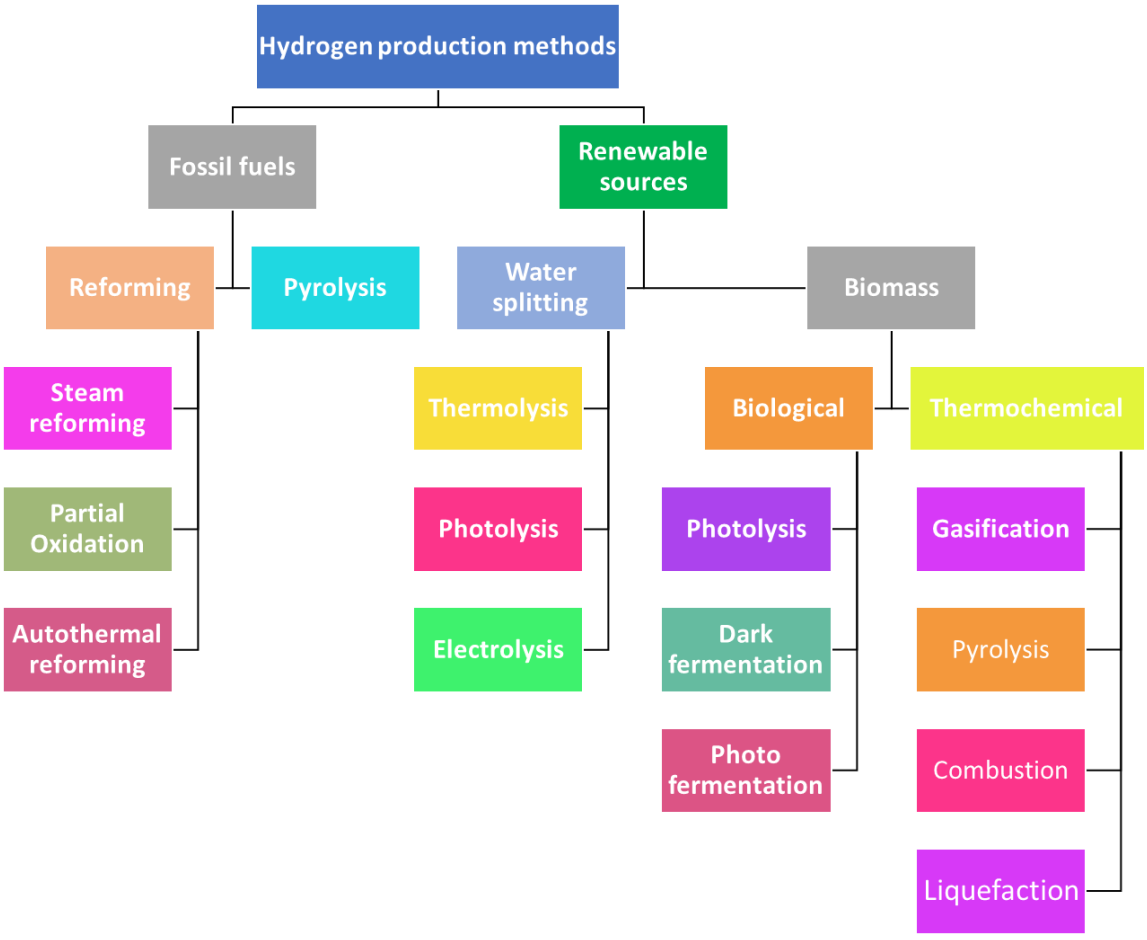

Fig. 2: Hydrogen production methods using fossil fuels and renewable sources

2.1. Hydrogen production from fossil fuels

Fossil fuels (hydrocarbons) are good source of hydrogen and can be reformed to produce hydrogen. Coal is generally gasified before reforming processes. Most hydrocarbon fuels contain at least some amount of sulphur and it can poison the fuel processing catalyst. Thus, desulphurisation is performed to remove the sulphur content before commencing the reformation process. In case of coal, gasification process is performed prior to desulphurisation and reforming processes. A flow diagram of the hydrogen production methods employing reformation process is shown in Fig. 3.

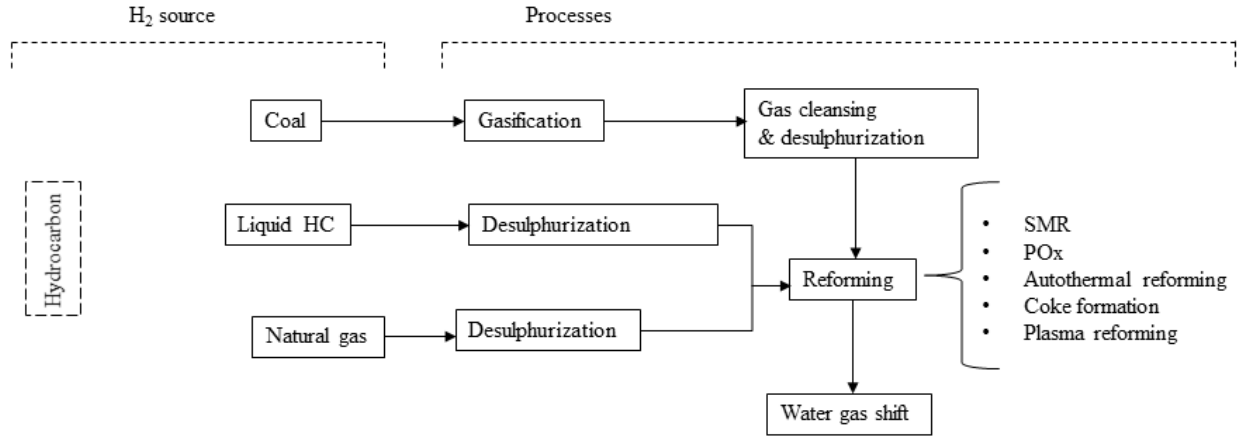

Fig. 3: Hydrogen production methods involving hydrocarbon reforming

Desulphurisation processes can be categorized as (a) chemical reaction technologies, and (b) adsorptive technologies. Chemical reaction technologies include hydrodesulphurisation (HDS) and alkylation processes. In commercial scale mainly HDS is used where the used catalyst partially or completely hydrogenates the sulphur-bearing molecules and forms hydrogen sulphide (H_2S) gas which can easily be removed from the flow gas mixture. Another chemical reaction approach is selective alkylation of organo-sulphur molecules. This technology is still in demonstration stage and yet to be implemented on a large commercial scale. In this technology, the molecular weight of the sulphur bearing molecules is increased and accordingly boiling point of sulphur containing molecules increases. Through distillation approach it becomes easy to remove the sulphur.

The adsorptive approaches for desulphurisation employ adsorbents of sulphur to remove the sulphur content from the fuel. Most often two types of materials are used: (a) high

surface area materials, and (b) metals. High surface area materials such as activated carbon, modified zeolites or other materials can adsorb the entire sulphur containing molecule on their surfaces. On the other hand, metals such as nickel react with the sulphur containing molecules to form metal sulphide e.g., nickel sulphide. The high surface area approach is easily operable and can be carried out at ambient temperature and pressure using conventional fixed-bed equipment. The metal-based approach is comparatively complicated and requires high temperatures and pressures. Generally, for low sulphur fuels (<50 ppm sulphur), adsorbent technologies are generally used. Sometime a mix of chemical and absorptive technologies may be necessary to ensure the complete sulphur removal.

Reforming processes of fuels are generally performed after gas cleansing and desulphurisation. There are three primary techniques used to produce hydrogen from hydrocarbon fuels: steam reforming (SR), partial oxidation (POX), and autothermal reforming (ATR). Other reforming processes under development are plasma reforming and aqueous phase reforming (APR). Pyrolysis of hydrocarbons is also used to produce hydrogen. SR is generally the most preferred process for hydrogen production in industry. Advantages and disadvantages of the three primary reforming processes are summarised in Table 1.

Table 1: Advantages and disadvantages of SR, POX and ATR process for hydrogen production

Reforming process	**Advantages**	**Disadvantages**
SR	• Mature technology with extensive industrial experience • Oxygen is not needed • Lowest process temperature • Best H_2/CO ratio for H_2 production	• Highest air emissions
POX	• Desulphurisation requirement is minimum • Catalyst is not required • Low methane slip	• Low H_2/CO ratio • High processing temperatures • Soot formation
ATR	• Lower process temperature than POX • Low methane slip	• Limited industrial experience • Requires air or oxygen

Since all the three processes produce large amounts of carbon monoxide, one or more water-gas-shift (WGS) reactors are used to generate more hydrogen after reforming process. In the WGS process, the generated carbon monoxide reacts with water vapour and produces one mole of hydrogen and carbon dioxide as per the Eq. 1. The reactors are generally combination of a high temperature reactor and a low temperature reactor. The high temperature (>350°C) reactor has fast kinetics but is limited by thermodynamics to the amount of carbon monoxide that can be converted. Therefore, a lower temperature reactor (210–330°C) is used to higher conversion of carbon monoxide. High temperature WGS reactors commonly use an iron catalyst, and lower temperature reactors often use a copper catalyst.

$$CO + H_2O = H_2 + CO_2 \qquad (1)$$

2.1.1. Steam reforming

SR of hydrocarbons is an endothermic process and requires an external heat source. SR does not require oxygen. It has a lower operating temperature than POX and ATR and produces reformate with a high H_2/CO ratio (3:1) which is beneficial for hydrogen production. However, it does have the highest emissions of the three processes. Reaction involved in SR process of hydrocarbons can be expressed by Eq. 2.

$$C_mH_n + mH_2O = mCO + (m + \frac{1}{2}n)H_2 \qquad (2)$$

SR can be performed at modest temperatures (>180°C) for methanol, DME, and other oxygenated hydrocarbons that can be readily activated. However, most of the conventional hydrocarbons require operating temperatures of greater than 500°C. In SR, hydrocarbons like methane reacts with steam under 3–25 bar pressure. Both non-precious metal (such as nickel) and precious metals (e.g., platinum or rhodium) are used as catalysts for SR process. In general, less expensive nickel catalysts are used almost universally in the industry. Promoters, such as magnesia or potassium or other alkaline components, are used as catalyst support to minimise the coke formation during reforming process. SR is commonly used in industry to produce hydrogen from methane and is known as steam methane reforming (SMR). Typically, thermal efficiency of SMR process is 70-85%.

2.1.2. Partial oxidation

POX converts hydrocarbons to hydrogen by partially oxidising the hydrocarbons with limited amount of oxygen (Eq. 3). The heat is provided by the ‘‘controlled’’ combustion. With less than the stoichiometric amount of oxygen available, the reaction products contain primarily hydrogen and carbon monoxide (and nitrogen, if the reaction is carried out with air rather than pure oxygen), and a relatively small amount of carbon dioxide and other compounds. POX is, typically, much faster than SR and requires a smaller reactor vessel. It does not require a catalyst for operation and is more sulphur tolerant than the other processes. The process occurs at high temperatures with some soot formation and the H_2/CO ratio (1:1 to 2:1) is favoured for the feeds to hydrocarbon synthesis reactors such as Fischer-Tropsch.

$$C_mH_n + \frac{m}{2}O_2 = mCO + \frac{n}{2}H_2 \qquad (3)$$

POX of hydrocarbons can be performed with or without a catalyst. The non-catalytic POX of hydrocarbons in the presence of oxygen typically occurs with flame temperatures of 1300–1500°C to ensure complete conversion and to reduce soot formation. Catalysts can be added to the POX system to lower the operating temperatures. For POX of natural gas, the catalysts are typically based on nickel or rhodium. Typically, the thermal efficiencies of POX reactors with methane fuel are around 60–75%, based on the higher heating values.

2.1.3. Autothermal reforming

ATR uses the POX to provide the heat and steam reforming to increase the hydrogen production resulting in a thermally neutral process as per Eq. 4. ATR is typically conducted at a lower pressure than POX reforming. Since POX is exothermic and ATR incorporates POX, these processes do not need an external heat source for the reactor. However, they require either an expensive and complex oxygen separation unit to feed pure oxygen to the reactor or the product gas is diluted with nitrogen thereby necessitating gas separation and purification processes.

$$C_mH_n + mH_2O = mCO + (m + \frac{1}{2}\,n)H_2 \qquad (4)$$

In ATR process, steam is used in the catalytic partial oxidation (CPOX) process. It consists of a thermal zone where POX or CPOX is used to generate the heat needed to drive the

downstream steam reforming reactions in a catalytic zone. Therefore, the temperature profile in the reactor is characterised by a sharp rise in the thermal zone, and then the temperature steadily decreases in the catalytic zone due to the endothermic reactions. The heat from the POX negates the need for an external heat source, simplifying the system and decreasing the start-up time. A significant advantage of this process over SR is that it can be stopped and started very rapidly while producing a larger amount of hydrogen than POX alone. For ATR to operate properly both the oxygen to fuel ratio and the steam to carbon ratio must be properly always controlled in order to control the reaction temperature and product gas composition while preventing coke formation. For methane reforming the thermal efficiency of ATR is comparable to that of POX reactors (60–75%), based on the higher heating values.

2.1.4. Plasma reforming

In plasma reforming the overall reforming reactions are the same as conventional reforming. However, energy and free radicals used for the reforming reaction are provided by plasma typically generated with electricity or heat in the presence of a suitable catalyst. When water or steam is injected with the fuel, H, OH, and O radicals in addition to electrons are formed. Plasma reforming can also be configured to operate at lower temperatures than traditional reforming process. There are essentially two main categories of plasma reforming: thermal and non-thermal. The main reported disadvantages of plasma reforming include the electrical requirements and high electrode erosion at elevated pressures.

In thermal plasma reforming, a high electric discharge (>1 kW) is used. A great deal of power is consumed in raising both the electrons and the neutral species to a very high temperature (5000–10,000 K). Even more power is required to cool the electrodes to stop the metals from vaporising at these high temperatures. For example, around 16 MJ of energy is consumed to produce one kg of hydrogen from methane feedstock. Reduction in power consumption is a significant challenge for this technology.

In non-thermal plasmas, only temperature of the electron is increased (>5000 K), while the temperature of the bulk species does not increase significantly. Since only the electrons are directly excited, only a few hundred watts of power are required for this process. Four types of non-thermal plasma reformers have been described in the literature: gliding arc plasma,

dielectric barrier discharge (DBD), microwave plasma, and corona discharge. The first three processes use dynamic discharge to create the plasma, while the corona discharge generates the plasma with a static discharge.

2.1.5. Aqueous phase reforming

APR to produce hydrogen from oxygenated hydrocarbons or carbohydrates is currently under development. These reactors often operate at pressures up to 25–30 MPa and temperatures ranging from 220 to 270°C. The reforming reactions are rather complex and can be summarised to follow the reaction pathways as in Eq. (2) for reforming, followed by Eq. (1) for the WGS. A suitable catalyst is needed for this process and catalyst selection is important to avoid methanation, which is thermodynamically favourable, along with Fischer Tropsch products such as propane, butane, and hexane. As of now Pt-containing catalysts have shown highest activity while nickel-based catalysts are less active in this process. The advantages of APR reactors include elimination of the need to vaporise water and feedstock which eliminates a system component and enables fuels that cannot be vaporised such as glucose to be processed without first degrading them. APR occurs at low temperatures which favours WGS to increase the hydrogen yield while suppressing CO. Thus, the reforming and WGS occur in a single step eliminating multiple reactors. APR based process with efficiency of greater than 55% has been achieved.

2.1.6. Pyrolysis

Pyrolysis is another hydrogen-producing technology where the hydrocarbon is decomposed (without presence of water or oxygen) into hydrogen and carbon. Pyrolysis can be done with any organic material and can be used to produce hydrogen and carbonaceous compounds (e.g., hydrocarbons, CNTs etc.). Since no water or air is present, no oxides of carbon (e.g., CO or CO_2) are formed, eliminating the need for secondary reactors for WGS. Consequently, this process offers significant reduction in emissions. The advantages of this process are fuel flexibility, relative simplicity and compactness, clean carbon by-product, and reduction in CO_2 and CO emissions. The reaction that occurs during pyrolysis of hydrocarbons can be represented in the following form:

$$C_m H_n \rightarrow mC + \frac{n}{2} H_2 \qquad (5)$$

One of the challenges with this approach is the potential for fouling by the carbon formed, but proponents claim that this can be minimised by appropriate reactor design. Since it has the potential to lower CO and CO_2 emissions and it can be operated in such a way as to recover a significant amount of solid carbon which can be economically utilised, pyrolysis process for hydrogen production may play a significant role in the future. Technically, it is feasible to exploit concentrated solar thermal technologies for pyrolysis of gaseous hydrocarbons such as methane for hydrogen production.

2.2. Hydrogen production from water

Hydrogen can be generated from water molecules as one mole of hydrogen can be obtained by splitting one mole of water. Hydrogen could be produced from water by three processes: electrolysis, photolysis and thermolysis. While electrolysis process requires electricity, other two processes require solar energy (i.e., photon and thermal) for splitting water. These three processes are discussed in brief in the following sections.

2.2.1. Electrolysis

Water electrolysis was first demonstrated in 1789 and it was commercially used to produce hydrogen from 1890s. Early electrolysers utilised aqueous alkaline solutions as their electrolytes, and this technology persists to this day. Water electrolysers are electrochemical devices that are used to split water molecule into hydrogen and oxygen by using electricity. It is essentially the conversion of electrical energy to chemical energy in the form of hydrogen, with oxygen as a useful by-product. Cell is core of the electrolyser, where electrochemical process takes place. It comprises of two electrodes separated by an electrolyte. Multiple cells are connected in series to produce a stack to have desired output of hydrogen. The other sub-systems of the electrolyser include equipment for cooling, hydrogen purification and compression, rectifier, DM water supply etc. All these put together are called balance of plant. Commercial low temperature electrolysers have system efficiencies of 56–73%. The most used electrolysis technology is alkaline based, but developmental efforts for proton exchange membrane (PEM) electrolysis and solid oxide electrolysis cells (SOEC) units are also being aggressively pursued.

Electrolysers are not only capable of producing high purity hydrogen, but recently, high-pressure units (pressures > 70 bar) are also being developed. The advantage of high-pressure operation is the elimination of expensive hydrogen compressors, which is needed to raise hydrogen pressure from storage considerations. Currently, it is more expensive to produce hydrogen through electrolysis in comparison to using large-scale fossil fuel reforming techniques. Moreover, if conventional power generated using fossil fuels is used for electrolysis, it results in higher emissions compared to SMR. However, in case SMR produced hydrogen is to be shipped in cylinders or tankers over long distances, then on site production via electrolysis may be less expensive. Several different approaches have been proposed to address these shortcomings. These include using renewable sources of energy such as solar, wind, and hydro to produce electricity or excess power from existing generators to produce hydrogen during off-peak times, and high temperature electrolysis. There have been several studies on the cost of using renewable energy for electrolysis, all reaching the conclusion that as the cost of natural gas increases renewable energy will become economically competitive at central production facilities as well as at distributed generation points especially if the costs of sequestrating carbon dioxide and other pollutants are included in the analysis. The three electrolyser technologies are described in brief in the following sections.

2.2.1.1. Alkaline electrolyser

Alkaline electrolysers are typically composed of two electrodes, a microporous separator, and aqueous alkaline electrolyte of approximately 30 wt% KOH or NaOH. In alkaline electrolysers nickel with a catalytic coating, such as platinum, is the most commonly used cathode material. For the anode, nickel or copper metals coated with metal oxides, such as manganese, tungsten, or ruthenium are used. Alkali such as, KOH/NaOH added to the liquid electrolyte is not consumed in the reaction but must be replenished over time because of other system losses primarily during hydrogen recovery. In an alkaline cell the water is introduced in the cathode where it is decomposed into hydrogen and OH^- ion. The OH^- ion travels through the electrolytic material to the anode where O_2 is formed. The generated hydrogen is then separated from the water in a gas liquid separations unit outside of the electrolyser. The typical current density is 100–300 mA cm^{-2} and alkaline electrolysers

typically achieve efficiencies of 63–70% based on the lower heating value of hydrogen. The overall reactions at the anode and cathode are:

Anode: $4OH^- \rightarrow O_2 + 2\,H_2O + 4\,e^-$ (6)

Cathode: $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$ (7)

Overall: $2H_2O \rightarrow 2H_2 + O_2$ (8)

2.2.1.2. Proton exchange membrane (PEM) electrolyser

PEM electrolysers build upon understanding of the recent advances in PEM fuel cell technology. PEM-based electrolysers typically use Pt black, iridium, ruthenium, and rhodium for electrode catalysts and a Nafion membrane which separates the electrodes and also acts as a gas separator. In PEM electrolyser, water is introduced at the anode where it is split into protons (H^+) and oxygen (O_2). The protons travel through the membrane to the cathode, where they recombine to form hydrogen gas. The O_2 gas remains behind with the unreacted water. There is no need for a separation unit. Depending on the purity requirements a drier may be used to remove residual water after a gas/liquid separations unit. PEM electrolysers have low ionic resistances and therefore high currents of >1600 mA/cm^2 can be achieved while maintaining high efficiencies of 56–60%. Efforts are underway to improve efficiency up to 68% in the coming years. The reactions at the anode and cathode are:

Anode: $2H_2O \rightarrow O_2 + 4\,H^+ + 4e^-$ (9)

Cathode: $4\,H^+ + 4e^- \rightarrow 2H_2$ (10)

Overall: $2H_2O \rightarrow 2H_2 + O_2$ (11)

2.2.1.3. Solid oxide electrolysis cell (SOEC)

SOEC are essentially solid oxide fuel cells (SOFC) operating in reverse. These systems replace part of the electrical energy required to split water with thermal energy. The higher temperatures increase the electrolyser's efficiency by decreasing the anode and cathode over potentials which cause power loss in electrolysis. For example, an increase in temperature from 375 to 1050 K reduces the combined thermal and electrical energy requirements by close to 35%. A SOEC operates similar to the alkaline system in the sense that oxygen ions travel through the electrolyte leaving the hydrogen in unreacted steam stream. The reactions are shown in Eq. 12 – 14. Other advantages for high temperature

electrolysis with a solid oxide-based electrolyser include: the use of a solid electrolyte which, unlike KOH for alkaline systems, is non-corrosive and it does not experience any liquid and flow distribution problems. Of course, the high temperature operation requires the use of costly materials and fabrication methods in addition to a heat source. The materials are similar to those being developed for SOFC, yttria stabilized zirconia (YSZ) electrolyte, nickel containing YSZ anode, and metal doped lanthanum metal oxides as cathode. High temperature electrolysis efficiency is dependent on the temperature and the thermal source. The efficiency as a function of electrical input alone can be very high with efficiencies of the order of 74–81% being reported. However, when the thermal source is included, the efficiencies can drop significantly. Solar energy based SOEC technologies are under development and may result in higher efficiencies.

Anode: $O^{2-} \rightarrow ½\ O_2 + 2e^-$ (12)

Cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$ (13)

Overall: $H_2O \rightarrow H_2 + ½\ O_2$ (14)

Combining SOEC with a SOFC for co-generation of hydrogen and electricity has been proposed. In this hybrid system a SOFC and SOEC are manifolded into the same stack and fed the same fuel, such as natural gas. Hydrogen is produced by the SOEC and electricity is produced by the SOFC. Proof-of-concept stacks have been demonstrated with efficiencies of up to 69%. However, the fuel utilisation is still relatively low at approximately 40% and coking is a serious issue in addition to the other challenges faced by SOEC.

While SOEC electrolysers are the most electrically efficient, yet they are the least developed of the three electrolyser technologies. SOEC technology has challenges such as corrosion, seals, and thermal cycling etc. PEM electrolysers do not have the corrosion and seals issues that SOEC have. PEM electrolysers have relatively lower footprint in comparison to alkaline electrolyser and have better load response. Alkaline systems are the most developed and have the lowest capital cost.

Comparative properties of these three technologies are shown in Table 2 and these processes are discussed in brief in the following section.

Table 2: Comparison of electrolyser technologies

Property	Alkaline Electrolyser		PEM Electrolyser		SOEC	
	Presently	2030*	Presently	2030*	Presently	2030*
Electrical efficiency (%, LHV)	63 – 70	65 – 71	56 – 60	63 – 68	74 – 81	77 – 84
Operating pressure (bar)	1 – 30	-	30 – 80	-	1	-
Operating temperature (°C)	60 – 80		50 – 80		650 – 1000	
Useful life of stack (jn thousand hours)	60 – 90	90-100	30-90	60-90	10-30	40-60
Load range (%, relative to nominal load)	10-110		0-160		20-100	
Plant footprint (m^2/kW_e)	0.095		0.048			
Startup time (minutes)	>30		<30		>30	
CAPEX (US$/$kW_e$)	500-1400	400-850	1100-1800	650-1500	2800-5600	800-2800

*expected value in 2030

2.2.2. Photoelectrolysis

Photoelectrolysis uses sunlight (photon) to directly decompose water into hydrogen and oxygen and uses semiconductor materials similar to those used in photovoltaic cells. In a photovoltaic cell, two doped semiconductor materials, a p-type, and an n-type, are brought together forming a p–n junction. At the junction, a permanent electric field is formed when the charges in the p- and n-type of materials rearrange. When a photon with energy greater than the semiconductor material's bandgap is absorbed at the junction, an electron is released, and a hole is formed. Since an electric field is present, the hole and electron are forced to move in opposite directions which, if an external load is also connected, will create an electric current. Similar situation occurs in photoelectrolysis when a photocathode, p-type material with excess holes, or a photoanode, n-type of material with excess electrons, is immersed in an aqueous electrolyte, but instead of generating an electric current, water is split to form hydrogen and oxygen.

The process can be summarised for a photoanode-based system as follows: (a) a photon with greater energy than the bandgap strikes the anode creating an electron–hole pair; (b) the holes decompose water at the anode's front surface to form hydrogen ions and gaseous oxygen, while the electrons flow through the back of the anode which is electrically connected to the cathode; (c) the hydrogen ions pass through the electrolyte and react with the electrons at the cathode to form hydrogen gas; and (d) the oxygen and hydrogen gasses are separated, for example by the use of a semi-permeable membrane, for processing and storage. This process is currently in advance R&D stage and major improvements are needed in terms of efficiency, material cost etc. To achieve these goals, photo-catalysts used should be based on inexpensive and readily available materials that can utilise the visible part of the solar spectrum and are stable.

2.2.3. Thermochemical water splitting/Thermolysis

Thermochemical water splitting or thermolysis is the processes when only heat is used to decompose water to hydrogen and oxygen. The required heat for this process can be obtained from solar energy using concentrating solar thermal technologies. In this process an overall efficiency of close to 50% is achievable. In general, the decomposition temperature of water is close to 2500°C; however, suitable materials that are stable at this temperature and sustainable heat sources are not easily available presently. To find solutions to these issues, chemical reagents have been proposed to lower down the temperatures. Research in this area has been focused on lowering the operating temperature. Currently, this technology is under R&D stage and it is believed that scaling up the processes may lead to improved thermal efficiency as well as lowering down the hydrogen production cost. Here are the few examples on thermochemical hydrogen generation processes:

Sulphuric acid decomposition:

$$H_2SO_4 \rightarrow H_2O + SO_2 + \frac{1}{2} O_2 \quad (15)$$

$$SO_2 + 2H_2O \rightarrow H_2SO_4 + H_2 \quad (16)$$

Zinc/Zinc Oxide cycle:

$$ZnO \rightarrow Zn + ½ O_2 \text{ [T = 1800°C]} \quad (17)$$

$$Zn + H_2O \rightarrow ZnO + H_2 \quad (18)$$

R&D on various thermo-chemical cycles, prominent being Sulphur-Iodine and Copper-Chlorine are being pursued.

2.3. Hydrogen production from biomass

Biomass is considered as the most likely renewable organic substitute to fossil fuels. Biomass can be obtained from a wide range of sources such as animal wastes, municipal solid wastes, crop residues, agricultural wastes, sawdust, wastepaper etc. For hydrogen generation, the current biomass technologies include (a) thermochemical processes such as gasification, pyrolysis, combustion, liquefaction, and (b) biological hydrogen production processes. Gasification of biomass is the most efficient and developed technologies amongst all thermochemical processes. Pyrolysis process for biomass is same as described in hydrocarbon section. A brief description of biomass gasification and biological hydrogen production processes is given below.

2.3.1. Biomass gasification

Gasification of biomass is very mature and commercially used technology. This process is based upon partial oxidation of the biomass to generate a gas mixture of hydrogen, methane, carbon monoxide, carbon dioxide, and nitrogen known as a producer gas. The presence of nitrogen in the producer gas could be eliminated if oxygen is used instead of air for partial oxidation process. The main challenge of the biomass gasification process is the low thermal efficiency due to the presence of moisture content in the biomass which is needed to be vaporised.

Gasification process is accomplished in a fixed bed or fluidised bed reactor in the presence or absence of a catalyst. It is reported that fluidised bed reactor gives better performance and improves efficiency of the process.

Introduction of steam and/or oxygen to the gasification process results in steam reforming and produces a syngas stream (H_2 to CO ratio = 2:1). The generated syngas can further be processed via WGS reaction for hydrogen production. A suitable catalyst (e.g., nickel) has to be deployed in this process to minimise the tar production. Typically, gasification reactors are built on a large scale and massive amount of materials to be continuously fed to them.

Biomass gasification process can achieve efficiencies of the order of 35–50% based on the lower heating value.

2.3.2. Bio-hydrogen production

Biological hydrogen production processes are in R&D stage and research in this area has substantially grown over the last several years. The feeds for biological hydrogen are water for photolysis processes and biomass for fermentative processes. The main bio-process technologies used for bio-hydrogen production are direct photolysis (photolytic hydrogen production from water by green algae or cyanobacteria), dark fermentation (hydrogen production during the acidogenic phase of anaerobic digestion of organic material), photo-fermentative processes, two stage dark/fermentative, and bio water-gas- shift reaction. Brief descriptions with their advantages and limitations are discussed below. Hydrogen production rates from biomass using various technologies are compared in Table 3.

Table 3: Comparison of hydrogen production rates for different bio-hydrogen production processes

Bio-hydrogen production methods	**H_2 generation rate (µmol H_2/h)**	**Reactor volume (m^3)**
Direct Photolysis	0.07	1707
Dark-fermentation	8.2 – 121	1 – 14.75
Photo-fermentation	0.16	747
MEC	5.8	21
Multistage integrated process	NA	

2.3.3. Direct photolysis

In general, photosynthesis process uses solar energy to convert carbon dioxide and water to carbohydrates and oxygen. In some organisms, it has been observed that small amount of hydrogen is produced along with carbohydrates during the photosynthesis process. The major challenges are to maximise the production rate by engineering the algae and bacteria, so most of the solar energy is diverted to hydrogen production. Since oxygen and hydrogen are co-produced during this process, significant safety and separation issues are also present. Photosynthetic hydrogen production process has efficiency of about 1%. As of now, this technology has significant promise, but also tremendous challenges.

2.3.4. Dark fermentation

Dark fermentation uses primarily anaerobic bacteria and some algae on carbohydrate rich substrates grown in absence of the light (dark). For this process, the suitable biomass used are the ones that are biodegradable, readily available in large quantities, inexpensive and must have high carbohydrate content. Major biomass wastes which can be readily utilised for bio-hydrogen production are: (a) starch-based and cellulose-based agricultural and food waste; (b) carbohydrate rich industrial waste; (c) waste sludge from waste treatment plant. Pre-treatment such as purification, hydrolysis etc. of the biomass is needed prior to the fermentation process. The fermentation pathways depend on the type of bacteria used and gas mixture of hydrogen, carbon dioxide, methane, carbon monoxide, and some hydrogen sulphide is produced. Therefore, separation and purification steps are needed to produce high purity hydrogen. Another issue related to dark fermentation process is the production of acids such as acetic, butyric and other organic acids. These acids can suppress hydrogen yield by diverting the metabolic pathway toward organic chemical production.

2.3.5. Photo-fermentation

Photo-fermentation process uses the light harvesting pigments (e.g., chlorophylls, carotenoids, and phycobilins) to collect the photons and transfer it to photolytic organisms (such as algae) where photons break the water molecules into protons, electrons, and O_2 gas. A catalyst, nitrogenase, is used to facilitate reaction of the protons and electrons with nitrogen and ATP (Adenosine Triphosphate) to make ammonia, hydrogen, and ADP (Adenosine Diphosphate). The advantages of this process are that oxygen does not inhibit the process and production of ammonia can be suppressed if the reaction is performed in zero nitrogen environment. However, the rate of the hydrogen production is quite low, and efficiency of the process is approximately 1.9%.

2.3.6. Microbial electrolysis cells

Microbial electrolysis cell (MEC) is a modified microbial fuel cell which uses electro-hydrogenesis to directly convert biodegradable material into hydrogen. A MEC operates in anaerobic state (no oxygen at the cathode) and an external voltage is applied to the cell to generate hydrogen at the cathode.

2.3.7. Multi-stage integrated process

To improve the hydrogen production rate, sometimes more than one process is used, and it is known as multi-stage integrated process. In general, the process comprises of two stages, such as dark fermentation followed by photo fermentation. However, more than two stages have also been proposed in different configurations. In this process, the biomass material is first fed to a dark fermentation reactor where the bacteria decompose the feedstock to hydrogen and an organic acid rich effluent which is then used as feedstock for photo-fermentative process. Integration of multiple processes produces significant challenges for the reactor engineering, system design, process control, and operation and maintenance.

2.4. Comparison of different hydrogen production methods

A comparison of the different hydrogen production processes in terms of their advantages, disadvantages, efficiency and cost of hydrogen production discussed above is presented in Table-4.

Table 4: Comparison of different hydrogen production methods

Hydrogen production Method	**Advantages**	**Disadvantages**	**Efficiency**	**Cost of hydrogen [$/kg]**
Steam Reforming	Well developed technology & widely used in the industry	CO and CO_2 are produced	74‑85	2.27
Partial Oxidation	Established technology	Along with H_2 production, heavy oils and petroleum coke are also produced	60‑75	1.48
Auto thermal Reforming	Well established technology in the existing infrastructure	CO_2 is produced as a by-product	60‑75	1.48
Bio photolysis	Consumes CO_2, O_2 is produced as a byproduct, and operates under mild conditions.	Low yields of H2, sunlight needed, large reactor required, O_2 sensitivity, and high cost of material.	10‑11	2.13
Dark	Simple method, H_2	Fatty acids elimination,	60‑80	2.57

Fermentation	produced without light, no limitation of O_2, CO_2-neutral, and helps in waste recycling	low yields of H_2, low efficiency, and requires huge sized reactor		
Photo Fermentation	Helps in wastewater recycling, uses different organic waste waters, and CO_2-neutral.	Low H_2 production rate, low efficiency, sunlight required, requires huge sized reactor, and O_2-sensitivity	0.1	2.83
Gasification	Availability of abundant cheap feedstock and CO_2 neutral.	Fluctuating H_2 yields because of feedstock impurities, seasonal availability and formation of tar.	30‑40	1.77‑2.05
Pyrolysis	Availability of abundant cheap feedstock and CO_2 neutral.	Tar formation, fluctuating H_2 amount because of feedstock impurities and seasonal availability	35‑50	1.59‑1.70
Thermolysis	Clean and sustainable, O_2-byproduct, copious feedstock	High capital costs, Element's toxicity, and corrosion problems.	20‑45	7.98‑8.40
Photolysis	O_2 as byproduct, abundant feedstock, and no emissions.	Low efficiency, non-effective photocatalytic material, and requires sunlight.	0.06	8‑10
Electrolysis	Established technology, zero emission, existing infrastructure, and O_2 as byproduct.	Storage and transportation problem.	60‑80	10.30

3. Overview on use of hydrogen in industrial applications

The first reported use of hydrogen was in a hydrogen balloon by Jaques Charles (1783) which was used to carry him and a colleague over a distance of 36 km at a height of up to 550 m. The extensive use of hydrogen started from the early 20th century after three major discoveries based on chemical potential of hydrogen were made and these included - (a) hydrogenation (in 1897, the French chemist Paul Sabatier discovered that addition of hydrogen to carbon molecule in the presence of nickel is possible); (b) the Haber process also called the Haber–Bosch process (in 1910, the two scientists discovered that it is possible to synthesise ammonia at high temperature and pressure using nitrogen and hydrogen); and (c) hydrocracking (in 1920s, it was discovered that lighter liquid fossil fuels can be produced by adding hydrogen to heavier liquid fossil fuels). Presently, hydrogen is considered as an essential element in petrochemical, fertiliser, and some other industries. Global demand for hydrogen gas has grown by almost three-fold since 1980 and was around 120 million tonnes during 2018, of which two-thirds was pure hydrogen and one-third was in mixture form with other gases. Growth of global hydrogen demand over a period of about four decades (1980 to 2018) is shown in Fig. 4. It has been estimated that hydrogen demand in refineries will grow by 7% and reach 41 MMT by 2030. In chemical industry, most of the hydrogen gas is used as feedstock for ammonia and methanol production. Around 31 MMT of hydrogen was consumed in 2018 for ammonia synthesis. Most of the synthesised ammonia (80%) is used to produce fertilisers (urea, ammonium nitrate/phosphate etc.).

Hydrogen market in India was valued at US$ 50 million in 2017, and is expected to reach US$81 million by 2025, growing at a CAGR of 6.3% from 2018 to 2025. The data for hydrogen demand and production for India is not available in a consolidated form as of now. In this study, based on information received from various sources, an attempt has been made for estimating hydrogen production capacity in the petroleum refineries, fertiliser plants, chlor-alkali industries and other industries as well as merchant suppliers to get an overall understanding on the hydrogen production and demand in the country as on 31st March 2020. The vast majority of hydrogen is presently produced for on-site consumption by the industry as transporting hydrogen from a centralised facility is uneconomical. The following sections give a brief account of major applications of hydrogen by the different industries.

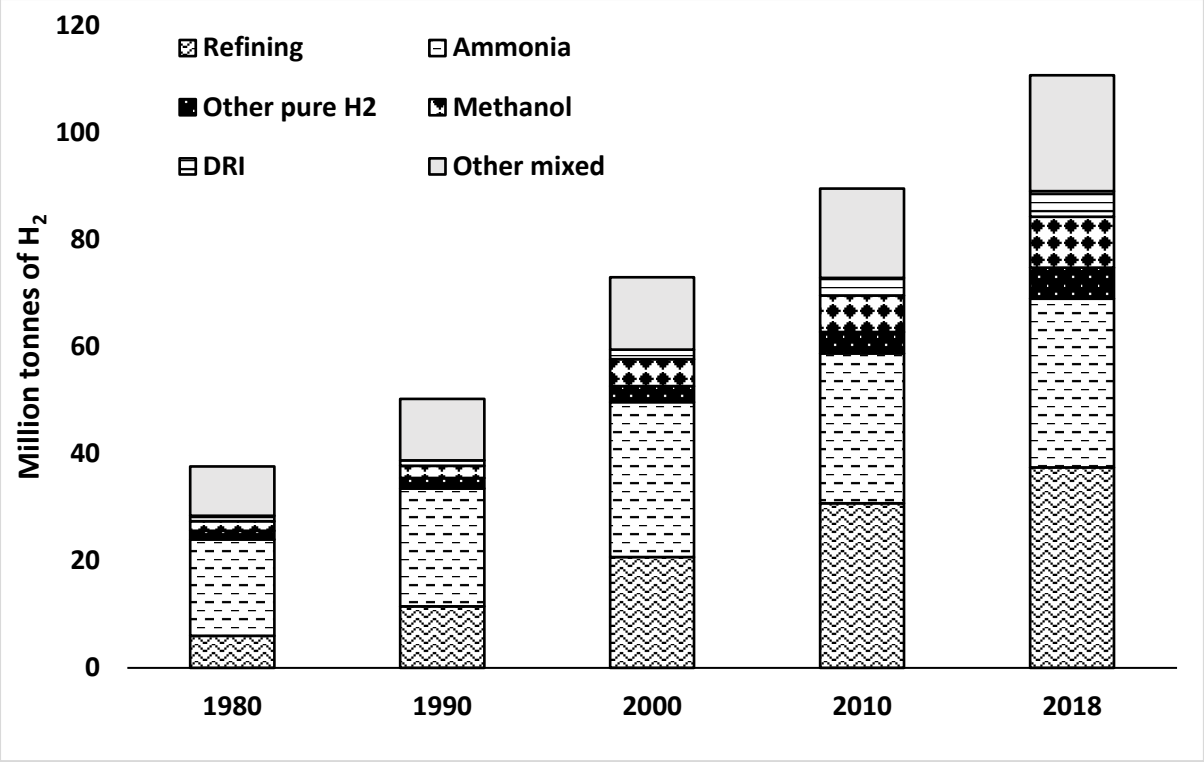

Fig. 4: Trends of hydrogen consumption in the world during 1980 – 2018

3.1. Petroleum refinery and petrochemical industry

Petroleum refineries carry out many industrial processes that transform crude oils into valuable products such as gasoline, jet fuel, diesel, kerosene, liquified petroleum gas, naphtha etc. The petroleum refineries also carry out various processes that need hydrogen and a term 'hydro-processing' is used for such processes. In hydro-processing, hydrogen is catalytically reacted with hydrocarbons in many ways and these processes are further categorised as hydrocracking and hydrotreating. In the hydrocracking process, cracking and hydrogenation of hydrocarbons (generally heavy gas oils) takes place simultaneously to produce refined fuels with smaller molecules and higher H/C ratios. Hydrocracking yields high volumes of diesel and kerosene. In the hydrotreating, hydrogen is used to hydrogenate sulphur and nitrogen compounds and to finally remove them as H_2S and NH_3. The sulphur removal process is known as hydro-desulphurisation (HDS). The hydrogen demand in the petroleum refineries for hydro-processing has been steadily increasing. The primary reason for this is the tightening of regulations associated with unit emissions and as well as product specifications; the growing demand for lighter, hydrogen rich products, such as gasoline;

and the need for refiners to improve profitability margins by processing poorer quality crudes.

The primary source of hydrogen within the refinery is known as hydrogen generation unit (HGU) where hydrogen is produced from steam reforming of naphtha, natural gas, LPG or by partial oxidation process. Some hydrogen is produced in the refineries as by-product of other processes. Alternatively, hydrogen can also be brought to the refinery via a pipeline. The amount of hydrogen required for a particular process in the refinery depends on crude quality and the amount of heteroatoms (sulphur, nitrogen, etc.) to be removed.

Hydrogen is extensively used in petrochemical industry for production of many chemicals such as: acetic acid, butanediol, tetrahydrofuran, butyraldehyde, hexamethylene diamine, cyclohexane etc. Hydrogen is also used in polymer synthesis such as polypropylene where hydrogen is used to control the molecular weight of the polymer. Recently hydrogen is also used in polymer recycling where molten plastic is hydrogenated to produce lighter molecules.

3.2. Fertiliser industry

Fertiliser industry is heavily dependent on ammonia which is produced by reaction between nitrogen and hydrogen. The industrial process used for ammonia production is known as Haber – Bosch process. In this process, hydrogen and nitrogen (3:1 ratio) are introduced in a reaction vessel containing a specific catalyst under high pressure (150 – 250 bar) and temperature (400 – 500°C). The most widely used catalyst for this process is iron (Fe) promoted K_2O (potassium oxide), CaO (calcium oxide), SiO_2 (silica) and Al_2O_3 (alumina). In general, to improve the conversion efficiency, the mixed gases are passed through several catalyst beds with cooling in between. An overall conversion efficiency of 95 – 97% is achievable in the current ammonia production plants. The required hydrogen for ammonia production is generally obtained from fossil fuels (NG or naphtha) by reforming process and nitrogen is obtained from the air by its purification. The generated ammonia by this process is used to produce nitrogen based single nutrient fertilisers such as ammonium nitrate (NH_4NO_3), urea [$CO(NH_2)_2$] and other ammonium nitrate salts. These fertilisers are further mixed with phosphorus (P) and/or potassium (K) based fertilisers to obtain binary (NP/NK) and ternary (NPK) fertilisers.

3.3. Hydrogenation process in vanaspati production

Hydrogen has been used extensively to decrease the degree of unsaturation in fats and oils and to turn unsaturated fats to fully or partially saturated oils and fats. Hydrogenated vegetable oils such as vanaspati ghee are produced using this process.

The hydrogenation process is performed in a heated tank under vacuum at around 140 – 250°C. A process diagram used for this purpose is shown in Fig. 5. In general, palm oil, sunflower seed or olive oil is used as oil feed for this process. Mechanical stirring is often applied to maintain uniform temperature throughout the reaction chamber. A catalyst (mostly nickel based solid catalyst) and the hydrogen gas (at 2.7 – 4 bar pressure) are introduced in the reaction chamber as the temperature stabilises. The hydrogenation reaction is an exothermic process, so the external heating is not needed. As soon as the reaction starts, cooling is applied. Mechanical stirring process is continued till the end of the reaction. At the end, hydrogenated oil mixture is taken out and the catalyst solids are removed using filters. Hydrogen is often used to improve the activity of the nickel catalyst as it may from surface oxide layers.

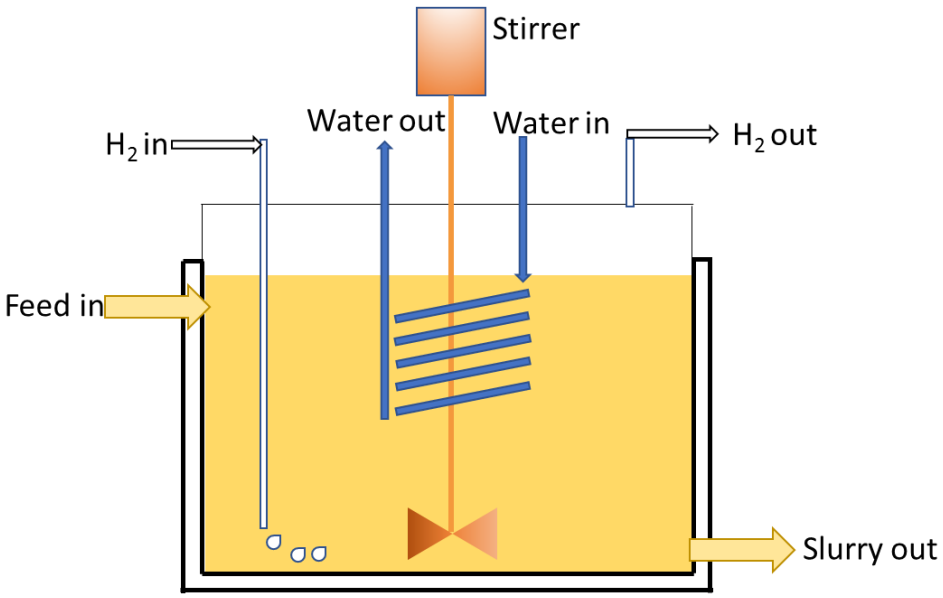

Fig. 5: Hydrogenation process during vanaspati production

3.4. Metal industry

Industrially, tungsten is extracted from its ore (WO_3) using hydrogen reduction method. Carbon is not used for reduction of WO_3 as it can form stable tungsten carbide. In this

process, an excess amount of hydrogen feed is passed through the powdered tungsten ore at high temperature (550 – 850°C) as shown in Eq. 19. The generated steam is carried out with the excess hydrogen gas.

$$WO_3 + 3H_2 = W + 3H_2O \quad (19)$$

It has been envisaged that direct reduction of iron and other metals such as copper is possible using hydrogen as reducing agent instead of carbon. A Swedish steel plant (Luleå Steel) intends to implement hydrogen reduction method for iron production. Trials of the pilot plant are on and are likely to be completed by 2024. Iron and steel industry contributes 5% of global CO_2 emissions and use of hydrogen in place of carbon will provide avenues for decarbonisation of this sector, which is considered to be very hard to decarbonise.

3.5. Thermal power plant's generator cooling

In thermal power plants, modern large electrical generators are cooled using hydrogen gas. Hydrogen as coolant has several advantages such as, low density; high thermal conductivity; high specific heat capacity; and cleaner than the air. In general, hydrogen used for power plant cooling is at a pressure of around 4 bar. Hydrogen absorbs heat from power generating winding enclosure. The amount of hydrogen used per day is a function of capacity of the power generator and condition of hydrogen seals. The higher capacity power generators require hydrogen to be maintained at high pressure for effective cooling. Higher pressure results in higher leakage rate and thereby requiring replenishment of more hydrogen to maintain the pressure for optimal heat transfer. Another issue that is important is maintaining purity of hydrogen above a particular level from safety consideration. Hydrogen required for cooling of generators could either be brought in cylinders or it could be produced on-site using electrolysers.

3.6. Float glass industry

Hydrogen is extensively used as reducing agent in the manufacturing process of float or plate glass. Float glass is a specialised type of glass with an extremely smooth and uniform structure with excellent optical properties. This makes it suitable for a wide variety of applications including windows, solar panels, LCD displays and automotive windscreens. Float glass is produced via a process which involves floating the molten glass on a bed of

molten metal and then allowing the glass to set. The method facilitates production of large panes without much difficulty and also controlling the thickness very effectively. Molten glass at a temperature of about 1540°C is poured onto a 'tin bath' consisting of molten tin, which acts as a level template for the glass to distribute over and then harden. The molten tin is prone to oxidising and it is prevented by keeping the tin bath in an atmosphere of 90% nitrogen and 10% hydrogen. The oxidation of tin introduces flaws in the surface of glass. Presence of hydrogen ensures removal of oxygen that is responsible for oxidation of tin by reacting with any oxygen. To ensure that oxidation of tin does not occur, huge volumes of nitrogen and hydrogen gases are required.

3.7. Hydrogen peroxide production

Hydrogen peroxide (H_2O_2) is used in many applications such as (a) sterilising agent in clinics and hospitals; (b) strong oxidising agent in chemical synthesis; (c) bleaching agent for hair, cloths and teeth; and (d) antiseptic to clean wounds, cuts and other damaged tissue portions.

Industrially, hydrogen peroxide is manufactured using a cyclic process known as anthraquinone process (Fig 6). Anthraquinone mainly acts as a hydrogen carrier and reacts with oxygen to produce hydrogen peroxide. This process consists of three steps: hydrogenation, filtration, and oxidation.

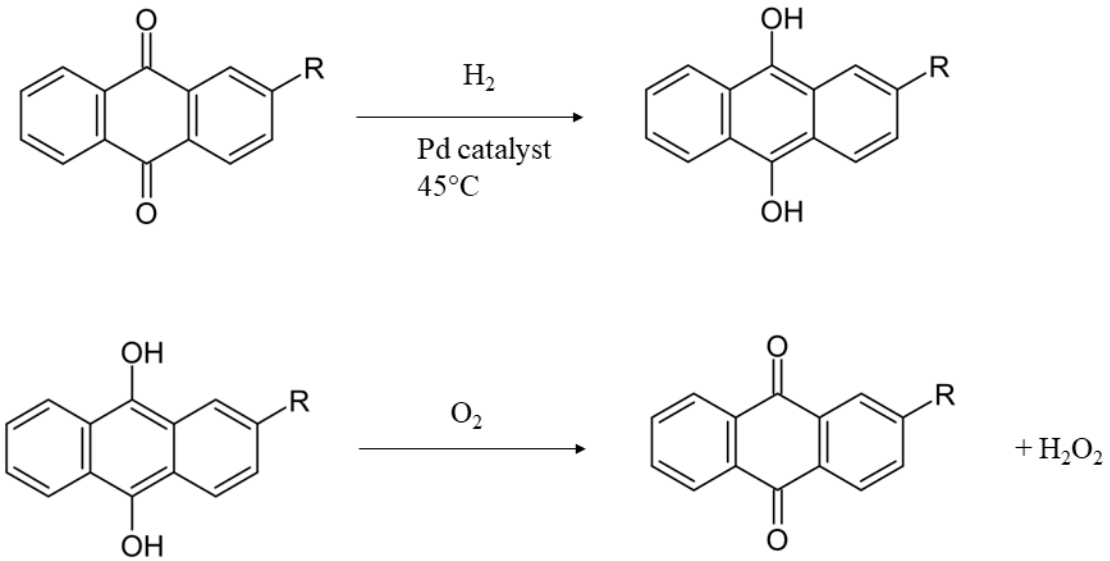

Fig. 6: Anthraquinone process for industrial hydrogen peroxide production

In the first step, hydrogen and anthraquinone reacts in presence of palladium (Pd) catalyst at 45°C to form anthrahydroquinone. The hydrogenation stage is needed to be carefully controlled to avoid formation of by-products due to the over-hydrogenation of the anthraquinone rings.

In the second step, the catalyst is removed from the solution. If any trace of Pd catalyst is present in the solution, it will decompose the produced H_2O_2 in later stages and consequently yields will be reduced. At last, anthrahydroquinone is oxidised using air/oxygen, forming H_2O_2, and releasing the anthraquinone. The produced H_2O_2 is isolated from the solution using a liquid-liquid extraction column. Demineralised water is used for the extraction process. The generated crude H_2O_2 is then purified and distilled to increase the concentrations. Proper stabilisers are used to avoid the unwanted decomposition.

Recent studies are focused on synthesis of H_2O_2 directly from hydrogen and oxygen. Bimetallic materials consisting of palladium are found to be effective towards the direct synthesis of H_2O_2 from hydrogen and oxygen.

3.8. Methanol production

Industrially, methanol is produced from syngas using a fixed bed reactor in presence of catalysts (copper on alumina and zinc oxide support). Feedstocks used for syngas production are generally natural gas, coal, oil, or biomass.

In recent years, research is focused on production of methanol by the direct reaction of hydrogen and carbon dioxide. This is mainly attractive as it offers removal of atmospheric CO_2 and turns it into a useful product. However, the major challenge is to discover a suitable catalyst which can make the reaction thermodynamically favourable so that the energy required for this reaction could be reduced. Palladium and copper-based catalysts are found to be highly active towards this reaction and methanol could be produced at 180–250°C with a conversion efficiency of about 24%.

3.9. Space applications

NASA has relied upon hydrogen gas as a rocket fuel to deliver crew and cargo into space. With the Centaur, Apollo and space shuttle vehicles, NASA has developed extensive experience for safe and effective handling of hydrogen. For example, the rocket engines of

each shuttle flight consume about 500,000 gallons (~1900 m^3) of cold liquid hydrogen with another 239,000 gallons (~900 m^3) depleted by storage boil off and transfer operations.

Indian Space Research Organisation (ISRO) is a premier national space agency and is one of the six government space agencies in the world which possess full launch capabilities, deploy cryogenic engines, launch extra-terrestrial missions and operate large fleets of artificial satellites. In the beginning, ISRO used solid fuels for space applications. However, after gaining experience in handling cryogenic hydrogen fuel, ISRO has been using it for their space applications.

3.10. Other uses of hydrogen

Hydrogen is used in semiconductor industry. It is also used in atomic hydrogen welding (AHW) process to weld tungsten and refractory metals. This is an arc welding process where two metal tungsten electrodes are kept in a shielding atmosphere of hydrogen. Various chemical analysis methods such as atomic absorption spectroscopy, gas chromatography etc. use hydrogen.

4. Hydrogen production and demand in India

4.1. On-site hydrogen production and consumption in India

4.1.1. Petroleum refineries

India had 23 operational refineries located throughout the country with installed refining capacity of about 249.9 MTPA as on 01.4.2020 (Fig. 7). Eighteen of these refineries are owned and operated by Public Sector Undertakings (PSU) and two refineries are in joint sector. Other 3 refineries are owned and operated by the private sector.

Indian Oil Corporation Limited (IOCL) is the largest oil sector PSU in India having a total of 9 refineries at different locations in the country. It has overall installed production capacity of about 69.7 MTPA. IOCL refineries are located in (a) Barauni, Bihar (b) Koyali, Gujarat, (c) Haldia, West Bengal, (d) Mathura, Uttar Pradesh, (e) Panipat, Haryana, (f) Guwahati, Assam, (g) Digboi, Assam, (h) Bongaigaon, Assam, and (h) Paradip, Odisha. Other PSU based refineries are operated by Bharat Petroleum Corporation Limited (BPCL) – 2 numbers, Hindustan Petroleum Corporation Limited (HPCL) – 2 numbers, Oil and Natural Gas Corporation (ONGC) – 1 number and Numaligarh Refinery Limited – 1 number. Five of the PSU refineries are operated with either state government or other agencies in Joint Venture mode.

Fig. 7: Location of petroleum refineries in India

Reliance Industries Limited (RIL) and Nayara Energy Limited (NEL) are the two private sector companies that are currently operating three refineries in the country. RIL owns two oil refineries at Jamnagar in Gujarat with an aggregate capacity of 68.2 MMTPA, which make RIL as the owner of the world's largest oil refinery. The refinery complex is spread across 7,500 acres and has more than 50 process units which refine the basic feedstock, crude oil to obtain various finished products. NEL has a refinery at Vadinar in Gujarat having installed capacity of 20 MMTPA.

Table 4: List of petroleum refineries along with installed refining and hydrogen production capacities as on 1.4.2020

Organisation	Refinery Location	Installed capacity (MTPA) as on 01.04.2020
IOCL	Barauni, Bihar	6.0
	Koyali, Gujarat	13.7
	Haldia, West Bengal	8.0
	Mathura, Uttar Pradesh	8.0
	Panipat, Haryana	15.0
	Guwahati, Assam	1.0
	Digboi, Assam	0.65
	Bongaigaon, Assam	2.35
	Paradip, Odisha	15.0
HPCL	Mumbai, Maharashtra	7.5
	Visakh, Andhra Pradesh	8.33
HPCL- HMEL	Bhatinda, Punjab	11.3
BPCL	Mumbai, Maharashtra	12.0
	Kochi, Kerala	15.5
BPCL- BORL	Bina, Madhya Pradesh	7.8
CPCL	Manali, Tamil Nadu	10.5
	Cauvery Basin, Tamil Nadu	1.0
NRL	Numaligarh, Assam	3.0
ONGC	Tatipaka, Andhra Pradesh	0.07
ONGC- MRPL	Mangalore, Karnataka	15.0
RIL	Jamnagar (DTA), Gujarat	33.0
	Jamnagar (SEZ), Gujarat	35.2
NEL	Vadinar, Gujarat	20.0
	TOTAL	249.9

All these 23 refineries have their own on-site hydrogen generation unit (HGU) for hydrogen production. The HGUs are directly connected with the refinery plant via pipeline for various

hydro-processing purposes. Most of the hydrogen in these HGUs is generated by SMR process using Naphtha as feedstock. Few of the refineries are using NG or Regasified Liquefied Natural Gas (RLNG) for hydrogen generation and only one refinery (HPCL, Mumbai) uses heavy naphtha as feedstock for hydrogen production via Continuous Catalytic Reformed (CCR) process. The purity of the hydrogen produced in these refineries varies in the range of 97.54 – 99.99%. In most of the SMR generated hydrogen plants, purity is found to be 4N and in other process (i.e., CCR) purity is comparatively poorer. The estimated hydrogen production capacity of all 23 petroleum refineries as on 01.04.2020 was in excess of 2.845 MTPA.

4.1.2. Fertiliser industry

Indian soils are generally deficient in nitrogen (N), phosphorus (P), and potassium (K) and consequently do not provide high agricultural yields. Hence, the need for fertilisers is necessary for obtaining high yields of agricultural produces. Green revolution in India has made a significant impact on Indian agriculture sector by implementing use of chemical fertilisers. During this time, several PSUs (National Fertilizers Limited, Rashtriya Chemicals & Fertilizers Limited etc.), Cooperatives (IFFCO, KRIBHCO etc.), and decision-making bodies (Department of Fertilisers, Ministry of Chemicals & Fertilisers etc.) were established for development and growth of the fertiliser industry. As of now, India is occupying the 3rd position in terms of production of fertiliser and 2nd in terms of consumption of fertiliser in the World.

There are 39 ammonia-based fertiliser production units located in various part of India (Fig. 8). Ammonia production capacity and location of these plants are listed in Table 5. Total installed hydrogen production capacity of the 39 fertiliser production units as on 1.4.2020 was 3.38 MTPA. Almost all of these plants are producing hydrogen by steam methane reforming of natural gas except MCFL, Mangalore and SPIC, Tuticorin plants where hydrogen is produced using naphtha reforming process. It has been learnt from Fertiliser Association of India (FAI) that these two plants will also be switched to natural gas shortly, thus entire ammonia synthesis process will be based on natural gas reforming. However, as the renewable electricity generation has increased in the country in the last few year, it is

envisaged that this is the best time India should generate green hydrogen for production of fertilisers in the country.

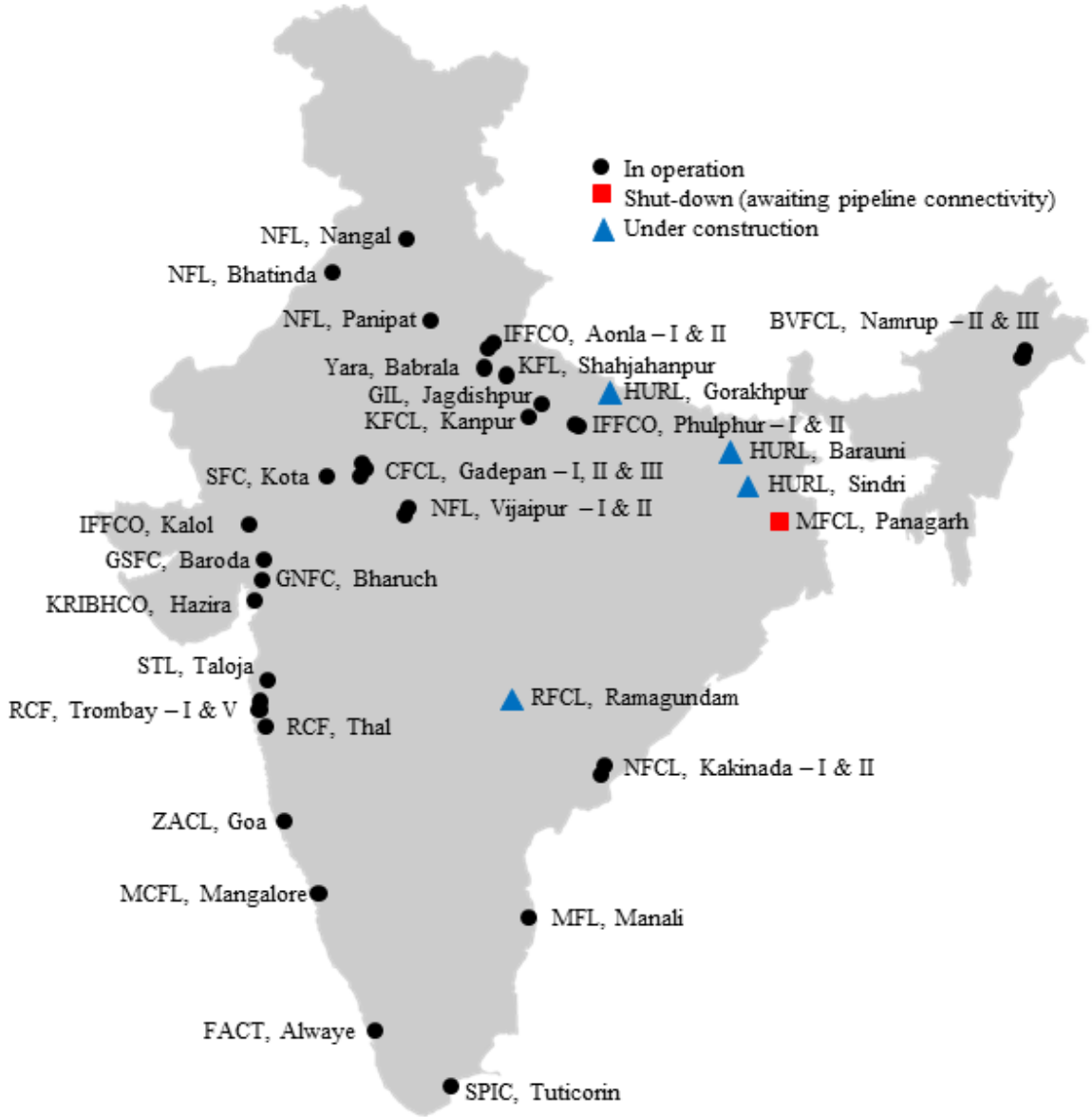

Fig. 8: Location of the ammonia-based fertiliser production plant in India

It is worth mentioning that earlier coal gasification and water electrolysis processes were also used in India for production of hydrogen for ammonia synthesis. The Fertiliser Corporation of India Ltd. (FCIL) owned and operated five fertiliser plants at Gorakhpur, Korba, Ramagundam Sindri, and Talcher. Three of these fertiliser plants at Ramagundam, Sindri and Talcher were utilising coal gasification technology for ammonia synthesis and

went out of operation in late 1990s to early 2000s as fertiliser production from these plants was becoming economically unviable. However, Talcher plant is likely to be made operational again by 2023 using coal gasification technology as India has large reserves of coal and import dependence on NG/LNG is continuously increasing. The urea production plant at Nangal, Punjab was equipped with alkaline electrolyser during 1960s for hydrogen production where comparatively inexpensive and surplus hydroelectricity was used from nearby Bhakra multipurpose project. Later, it was replaced by fuel oil-based system when demand for electricity increased.

Table 5: Location and ammonia production capacity of various fertiliser plants in India as on 01.04.2020

Sr. No	Ammonia production plant (Company)	Location	Installed NH_3 production capacity as on 01.04.2020 (1000 T)
1	STL, Taloja	Maharashtra	125.4
2	GSFC, Baroda-IV	Gujarat	445.5
3	BVFCL, Namrup II	Assam	144.0
4	BVFCL, Namrup III	Assam	167.4
5	IFFCO, Kalol	Gujarat	363.0
6	IFFCO, Aonla-I	Uttar Pradesh	574.2
7	IFFCO, Aonla-II	Uttar Pradesh	574.2
8	GIL, Jagdishpur	Uttar Pradesh	630.3
9	KRIBHCO, Hazira	Gujarat	1247.4
10	NFL, Vijaipur-I	Madhya Pradesh	577.5
11	NFL, Vijaipur-II	Madhya Pradesh	615.1
12	RCF, Trombay -I	Maharashtra	115.5
13	RCF, Trombay -V	Maharashtra	297.0
14	RCF, Thal	Maharashtra	1155.0
15	NFCL, Kakinada -I	Andhra Pradesh	437.3
16	NFCL, Kakinada -II	Andhra Pradesh	429.0
17	CFCL, Gadepan -I	Rajasthan	583.1
18	CFCL,Gadepan-II	Rajasthan	564.3
19	CFCL,Gadepan-III	Rajasthan	726.0
20	Yara Fertilisers ,Babrala	Uttar Pradesh	660.0
21	KFL,Shahjahanpur	Uttar Pradesh	501.6
22	IFFCO, Phulpur-I	Uttar Pradesh	401.0
23	IFFCO, Phulpur-II	Uttar Pradesh	574.0
24	SFC, Kota	Rajasthan	223.5
25	ZACL , Goa	Goa	264.0
26	KFCL, Kanpur	Uttar Pradesh	418.8
27	FACT, Alwaye	Kerala	326.7
28	GNFC, Bharuch	Gujarat	445.5
29	NFL, Bathinda	Punjab	297.0
30	NFL, Nangal	Punjab	313.5
31	MFL, Manali	Tamil Nadu	346.5

32	NFL, Panipat	Haryana	297.0
33	MCFL, Mangalore	Karnataka	217.8
34	SPIC , Tuticorin	Tamil Nadu	420.0
35	MFCL, Panagarh	West Bengal	726.0
36	RFCL, Ramagundam	Telengana	726.0
37	HURL, Gorakhpur	Uttar Pradesh	726.0
38	HURL, Barauni	Bihar	726.0
39	HURL, Sindri	Jharkhand	726.0
TOTAL			19108.1

4.2. Production in chlor-alkali industries as by product

Chlor Alkali is considered to be one of the oldest industrial sectors, which plays a key role in supplying chemicals to other manufacturing sectors such as textiles, pulp & paper, alumina, soaps and detergents, pharma, etc.

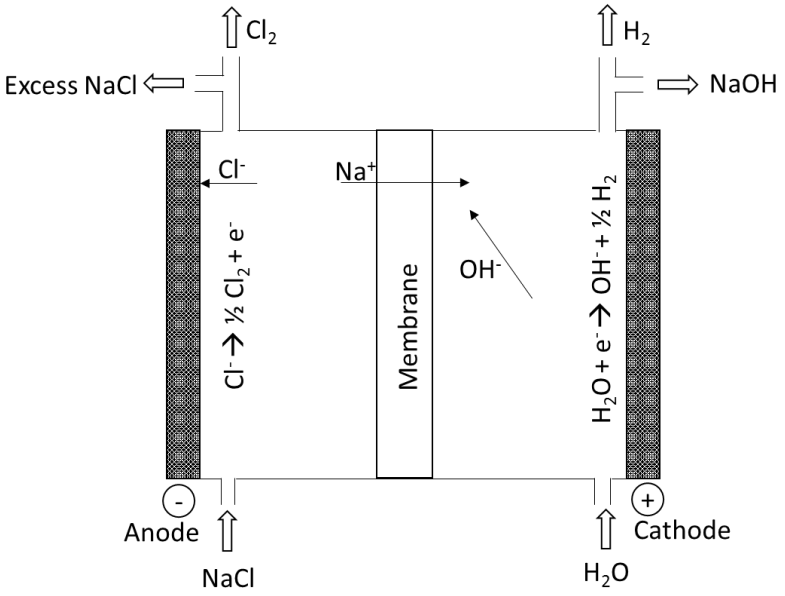

Fig. 9: Schematic diagram of membrane cell used in chlor-alkali industry

The primary product of the chlor alkali industry is caustic soda, with chlorine and hydrogen being by-products in the ratio of 1.00: 0.89: 0.025. Caustic soda can be produced using any one of the three electrochemical cell technologies: (a) Diaphragm cell, (b) Mercury cell, and (c) Membrane cell. The mercury cell technology has been phased out owing to its high electricity consumption and environmental pollution. The membrane cell technology is the

latest development of clean and energy efficient method of production of caustic soda. In a membrane cell, brine solution is fed into the anode half of the system and chlorine is separated from the brine, when the electric current is passed through the anode (Fig. 9). The caustic solution is dispersed along the cathode through the permeable membrane, and 30-35% caustic soda and hydrogen is obtained at the cathode shell.

India contributes to 4.7% of global chlor-alkali capacity (about 95 MTPA), with installed capacity of 4.5 MTPA. There are a total of 33 chlor-alkali units installed in the country (Table 6 and Fig. 10).

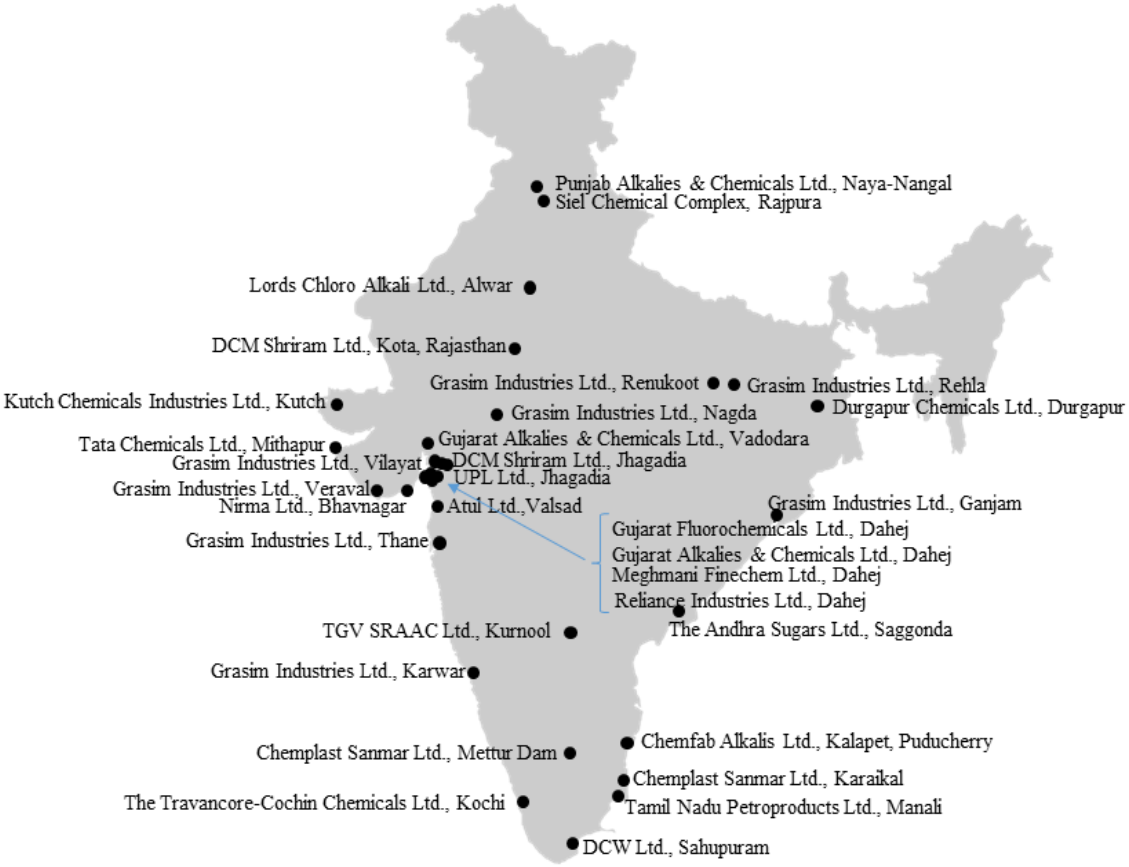

Fig. 10: Location of chlor-alkali plants in India

Emphasizing upon the utility of chlorine and hydrogen, both of these gases find applications in diverse industries. In India chlorine has plenty of industrial uses that include making bulk materials like bleached paper products, plastics such as PVC and solvents like as tetra-chloromethane, chloroform and dichloromethane. Its applications include in industries like - dyes, textiles, medicines, antiseptics, insecticides and paints. Driven by the various

consuming industries, PVC is one of the chlorine derivatives that has seen a rapid growth in the country with an annual growth rate of 7.25% in the past decade. Expecting a double-digit growth in the coming fiscal years, a higher demand of PVC will add to issues related to chlorine utilisation in the country.

India consumes chlorine mainly in the production of hydrochloric acid, chlorinated paraffin wax, organic and inorganic compounds, chloromethane, vinyls (PVC) and paper industry in the descending order. The market scenario of India is quite different when compared in the global perspective and one example being – while global consumption of chlorine in vinyls (PVC) is 40% it is only 6.64% in India. When it comes to hydrogen, 27.8% of hydrogen produced in chlor-alkali units is used for HCl production, 39.5% is used as fuel in boiler and 13.5% is used for other downstream products synthesis (Fig 11). Total installed hydrogen production capacity in the chlor-alkali units as on 01.04.2020 was around 0.114 MT.

Table 6: Location, installed production capacity of caustic soda and hydrogen in various chlor-alkali plants in India

Sr. No.	Chlor-alkali units (Company)	Installed caustic soda production capacity as on 01.04.2020 (MT)
1	Atul Ltd.,Valsad, Gujarat	47,450
2	Chemfab Alkalis Ltd., Kalapet, Puducherry	45,625
3	Chemplast Sanmar Ltd., Karaikal, Puducherry	51,000
4	Chemplast Sanmar Ltd., Mettur Dam, Tamil Nadu	61,200
5	DCM Shriram Ltd., Jhagadia, Gujarat	508,000
6	DCM Shriram Ltd., Kota, Rajasthan	190,000
7	DCW Ltd., Sahupuram, Tamil Nadu	100,000
8	Durgapur Chemicals Ltd., Durgapur, West Bengal	33,000
9	Grasim Industries Ltd., Thane, Maharashtra	26,450
10	Grasim Industries Ltd., Rehla, Jharkhand	109,000
11	Grasim Industries Ltd., Ganjam, Odisha	91,250
12	Grasim Industries Ltd., Karwar, Karnataka	100,000
13	Grasim Industries Ltd., Nagda, Madhya Pradesh	270,100
14	Grasim Industries Ltd., Renukoot, Uttar Pradesh	129,000
15	Grasim Industries Ltd., Veraval, Gujarat	91,250
16	Grasim Industries Ltd., Vilayat, Gujarat	365,000
17	Gujarat Alkalies & Chemicals Ltd., Dahej, Gujarat	259,050
18	Gujarat Alkalies & Chemicals Ltd., Vadodara, Gujarat	169,950

19	Gujarat Fluorochemicals Ltd., Dahej, Gujarat	140,400
20	Kutch Chemicals Industries Ltd., Kutch, Gujarat	176,750
21	Lords Chloro Alkali Ltd., Alwar, Rajasthan	90,729
22	Meghmani Finechem Ltd., Dahej, Gujarat	180,000
23	Nirma Ltd., Bhavnagar, Gujarat	273,750
24	Orient Paper Mills-CS Unit, Amlai, Madhya Pradesh	44,250
25	Punjab Alkalies & Chemicals Ltd., Naya-Nangal, Punjab	99,000
26	Reliance Industries Ltd., Dahej, Gujarat	178,850
27	Siel Chemical Complex, Rajpura, Punjab	82,500
28	Tamilnadu Petroproducts Ltd., Manali, Tamil Nadu	56,100
29	Tata Chemicals Ltd., Mithapur, Gujarat	36,000
30	TGV SRAAC Ltd., Kurnool, Andhra Pradesh	259,150
31	The Andhra Sugars Ltd., Saggonda, Andhra Pradesh	165,000
32	The Travancore-Cochin Chemicals Ltd., Kochi, Kerala	57,750
33	UPL Ltd., Jhagadia, Gujarat	56,940
TOTAL		**4,544,494**

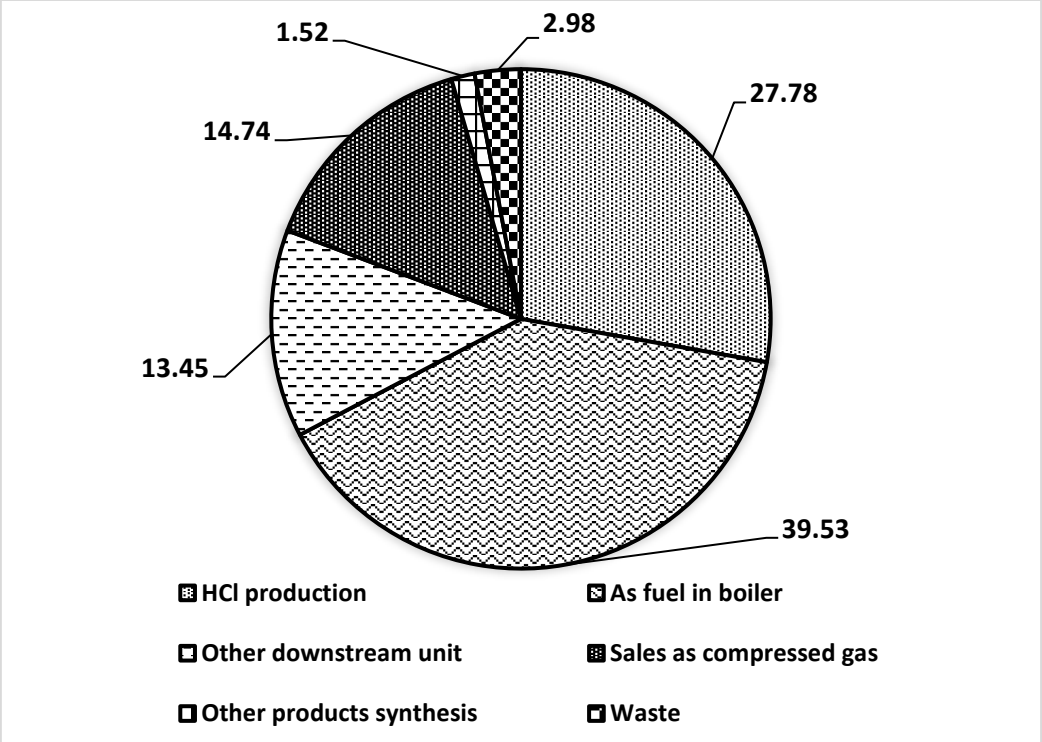

Fig. 11: Use pattern of hydrogen from Chlor-Alkali Units

4.3. Production for selling (merchants)

Major merchants who sell hydrogen in Indian market are Linde, Inox Air Products, Bhuruka gases and Air liquide India. Linde does not have any hydrogen production plant for commercial sale of hydrogen, and it provides hydrogen for captive use to a tin plate plant at Jamshedpur. Linde also manages another hydrogen production plant installed at Paradip refinery, which has already been included in the petroleum refinery section of the report. The plant installed at Jamshedpur is based on electrolysis with hydrogen production capacity of 80 Nm^3/h. Inox Air Products manages a total of five hydrogen generation facilities in India and most of them are catering to meeting bulk hydrogen demand of the identified clients. All of these five hydrogen generation plants are based on SMR of NG and each of them have an installed hydrogen production capacity of 24.06 Lakh Nm^3 /annum. Three of the Inox Air Product hydrogen plants are located at Mangaon, Maharashtra and other two are situated at Bhiwadi, Rajasthan and Sripermebdur, Tamil Nadu. Some of these hydrogen production facilities have surplus hydrogen capacity that is being sold to retail customers. The details of hydrogen production capacities of the facilities managed by two merchant producers of hydrogen as on 01.04.2020 and their actual hydrogen production during 2019-20 are given in Table 7. The other merchant producers of hydrogen did not share information with NISE for this study in spite of the repeated requests made to them.

Table 7: Hydrogen production facilities managed by private sectors and their production capacity as on 01.04.2020

Sr. No.	Company	Location	Installed H_2 capacity as on 01.04.2020 (Tonnes/year)	Total H_2 production during FY 2019 -20 (tonnes)
1	Linde India Pvt. Ltd.	Jamshedpur, Jharkhand	1143.2	629.5
2	Inox Air Products Pvt. Ltd.	Mangaon MIDC plot C1, Maharashtra		
		Mangaon MIDC plot B93, Maharashtra		
		Mangaon MIDC plot B93, Maharashtra		

		Bhiwadi, Rajsthan		
		Sriperumbudur, Tamil Nadu		

4.4. Total hydrogen production capacity in India

NISE approached the petroleum refineries through the Ministry of Petroleum and Natural Gas, Government of India; The Fertiliser Association of India, Alkali Manufacturers Association of India; and merchant producers of hydrogen in India to share information relating to hydrogen production capacity in petroleum refineries, fertiliser plants, chlor-alkali units and merchant producers of hydrogen as on 01.04.2020 and actual hydrogen produced during 2019-20. Some of the petroleum refineries in the public sector and private sector refineries did not share any information for this study. Information with regard to these refineries has been estimated based on the information that is available in the public domain. Based on the information obtained from the above-mentioned organisations for this study, it is estimated that India has total hydrogen production capacity in excess of 6.34 MTA as per details given in Fig. 12. Some organisations like IOCL did not share information with regard to actual production of hydrogen during 2019-20 citing commercial reasons. Only a few public sector petroleum refineries have shared information on actual hydrogen production during 2019-20. The information shared by such public sector petroleum refineries indicate that the production capacity was operated in the range of 65 – 87% capacity factor. It is an indication that the refinery sector had some spare capacity for hydrogen production during 2019-20, which could have been utilised for some other applications such as providing hydrogen to hydrogen fuelled vehicles in the vicinity of petroleum refineries. It is difficult to estimate spare capacity of hydrogen from refineries as actual hydrogen requirement depends on number factors that include quality of the crude, fuel quality standards, range of products of the refinery and any overcapacity keeping in view future plans. Considering spare capacity in the range of 1-10% of the installed hydrogen production capacity, spare hydrogen that may be available for applications other than the captive use by the refineries may be in the range of 28450 – 284500 TPA as per details given in Table 8. Similarly, chlor-alkali units could also divert some hydrogen for new applications in the vicinity of such plants.

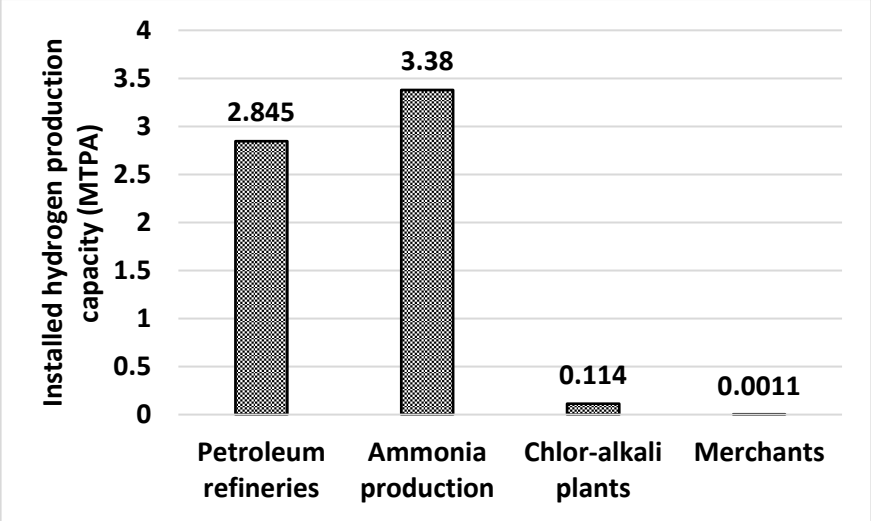

Fig. 12: Installed hydrogen production capacity in India

Table 8: Availability of spare hydrogen in petroleum refineries

Sr. No.	Spare hydrogen in percent (%)	Spare hydrogen available (TPA)
1	1%	28450
2	2%	56900
3	3%	85350
4	4%	113800
5	5%	142250
6	6%	170700
7	7%	199150
8	8%	227600
9	9%	256050
10	10%	284500

4.5. Hydrogen demand in other industries/applications

4.5.1. Space applications

In space applications, hydrogen is being used as fuel for decades. NASA, ISRO and other space agencies are using liquid hydrogen as fuel for their spacecrafts. In the spacecraft mainly liquid hydrogen is used. However, for other applications such as flight acceptance tests, shock tunnel tests, meteorological balloons, sintering processes compressed hydrogen gas (at around 120 – 300 bar pressure) is used.

For this study, information has been received from the Vikram Sarabhai Space Centre (VSSC) about yearly consumption of hydrogen in their organisation and as per information obtained; about 24,183 tonnes of hydrogen was used during FY 2019-20. The amount of hydrogen consumption in space applications is highly dependent on the number of spacecrafts launched in a particular year. Hydrogen consumption during FY 2019-20 was comparatively lower than the other years as only one GSLV was launched during this year. It can be noted that the amount of hydrogen consumption would increase in the coming years and projected to be around 50,000 tonnes of hydrogen per annum.

4.5.2. Float glass industry

There are five major companies that are producing float glass in India with an overall production capacity of about 7000 tonnes/day (Table 9). Total hydrogen needed to run these 10 lines of float glass would be around 670 tonnes per year.

Table 9: Float glass production plants and their production lines as on 01.04.2020

Company	Location	Lines
Saint-Gobain India	Sriperumbudur, Tamil Nadu	4
	Jhagadia, Gujarat	1
	Bhiwadi, Rajasthan	1
Asahi India	Roorkee, Uttarakhand	1
Gujarat Guardian	Ankleshwar, Gujarat	1
HNG Float Glass	Halol	1
Gold Plus Glass	Roorkee, Uttarakhand	1
TOTAL		**10**

4.5.3. Thermal power plant's generator cooling

There are around 135 coal based thermal power plants in India and their capacity could be found in the range of 55 MW to 4760 MW. Each of the power plants is consisting of several small units and their capacity varies between 50 MW to 800 MW. Total number of such thermal power generating units in the country was 531 as on 01.04.2020 and they can be categorised in four ranges as per their hydrogen consumption for generator cooling: (a) <150 MW, (b) 150 – 250 MW, (c) 250 – 400 MW and (d) 400 – 800 MW. A histogram depicting various installed power generation units is shown in Fig. 13. The amount of hydrogen used in the power plants for cooling purposes is shown in Table 10. It can be seen that around 253.46 Tonnes of hydrogen was consumed during 2019-20 for generator cooling purposes.

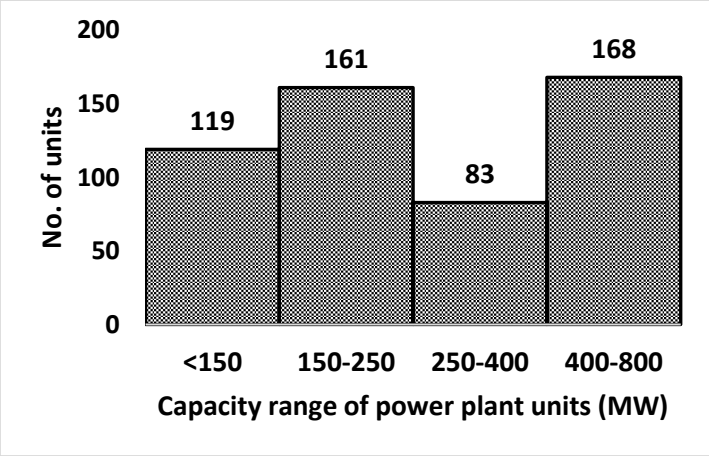

Fig. 13: Histogram on distribution of power plant units w.r.t. their capacity in India

Table 10: Unit capacity of installed thermal power plants in India as on 01.04.2020

Sr. No.	Unit capacity range (MW)	Number of units installed	Hydrogen consumption (TPA)
1	<150	119	19.50
2	150-250	161	52.80
3	250-400	83	43.50
4	400-1200	168	137.60
TOTAL			253.46

4.5.4. Vanaspati production

As discussed earlier, vanaspati is fully or partially hydrogenated vegetable cooking oil often used as a cheaper substitute for ghee (clarified butter). In India the consumption of edible oils and vanaspati is comparatively high as compared to any other country. In India, the main source of trans-fat is Vanaspati, a form of vegetable ghee that is a Partially Hydrogenated Vegetable Oil (PHVO). Vanaspati has an important role in our edible oil economy. Its production is about 1.2 million tonnes annually. It has around 10% share of the edible oil market. Newer oils like soybean, sunflower, rice bran and cottonseed and oils from oilseeds of tree and forest origin had found their way to the edible pool largely through vanaspati route.

In hydrogenation of vegetable oil, high purity (99.8%) hydrogen is required. The purity of the hydrogen used in this process is of great importance. The impurities in the hydrogen flow may act as catalyst poison (e.g., sulphur, chlorine, carbon monoxide, water, oxygen) or they may slow down or even stop the reaction due to an accumulation in the headspace during hydrogenation (inert gases like nitrogen, argon, methane). Based on the reported average hydrogen consumption per tonne of vanaspati, it has been estimated that around 1063 Tonnes of hydrogen was needed to produce 1.2 MT vanaspati during FY 2019-20.

4.5.5. Hydrogen peroxide production

India has installed production capacity of about 165.85 thousand tonnes for H_2O_2, and actual production was about 156.45 thousand tonnes during FY 2019 – 20. Hydrogen peroxide is mainly produced by anthraquinone process. It has been reported that the anthraquinone process has about 95% yield efficiency than that of the theoretical efficiency. Accordingly, hydrogen demand for hydrogen peroxide production during FY 2019 – 20 was estimated to be around 9,804.6 Tonnes.

4.5.6. Methanol

On an industrial scale, methanol is predominantly produced from natural gas by reforming the gas with steam and then converting and distilling the resulting syngas mixture ($CO + CO_2 + H_2$) to create pure methanol. There is an installed methanol production capacity of about 474.30 thousand MT available in India. It has been reported that around 271.93 thousand

MT of methanol was produced during FY 2019 – 20 in India. All of these methanol production plants are based on NG. Apart from NG, Indian high ash coal, stranded gas, and biomass are also envisaged as future feedstock for methanol production. India, with 125 Billion Tonnes of proven coal reserves and 500 million tons of biomass generated every year and the huge quantities of stranded and flared gases has a huge potential for ensuring energy security based on alternate feedstock and fuels. India is also expected to adopt CO_2 capturing technology to make use of coal fully environment friendly and realise its commitments to achieve decarbonisation goals. It has been suggested that use of CO_2 and green hydrogen produced from renewable energy could mitigate the GHG emission to the atmosphere which are likely to minimise the pollution and global warming.

Several aspects of methanol production from pure CO_2 and H_2 are different than the process using syngas. Processes for synthesizing methanol from syngas typically entrain CO and CO_2, as well as many other light and heavy weight co-products along with the methanol product. The co-products are a result of the more complex series of reactions that take place when the three reactant gasses interact with each other and the catalytic surface. Methanol synthesis starting from pure sources and controlled concentrations of CO_2 and H_2, greatly simplifies the chemistry and reaction products and follows these three reactions:

$$CO_2 + 3H_2 = CH_3OH + H_2O \quad \Delta H = -49.16 \text{ kJ/mol } CO_2 \qquad (20)$$

$$CO_2 + H_2 = CO + H_2O \quad \Delta H = 41.22 \text{ kJ/mol } CO_2 \qquad (21)$$

$$CO + 2H_2 = CH_3OH \quad \Delta H = -90.4 \text{ kJ/mol } CO_2 \qquad (22)$$

The overall CO_2 to methanol conversion efficiency is not high and therefore, several sets of reactors are used to improve the conversion efficiency. Hydrogen is also recycled into the reactor for better efficiency. Considering an overall conversion efficiency of about 70%, total hydrogen requirement for producing the current methanol production of 271.93 thousand tonnes would be around 66,283 tonnes. To fulfil the installed production capacity of methanol, it has been estimated that around 1,15,610 tonnes of hydrogen will be needed.

4.5.7. Metal industry

Estimating demand of hydrogen for iron and steel and other metal production industries is being talked a lot as hydrogen has the potential to decarbonise this hard to decarbonise sector. Coke oven gas is used in iron and steel industry and has substantial hydrogen (H_2 - 51%) along with other gases such as methane (CH_4 - 34%), carbon monoxide (CO - 10%), and ethylene (C_2H_4 - 5%). Estimating either production and demand of hydrogen in iron and steel and other metal industry has not been undertaken as a part of this study as the same may be an independent study in itself.

5. Prospects for applications of hydrogen in other sectors

Hydrogen has the potential to be used in the transport, buildings, and power generation, if the costs of production and utilisation processes become favourable relative to the available options.

5.1. Power sector

There is a huge potential for use of hydrogen in power sector for electricity generation using fuel cells, conventional ICE, hydrogen-fired gas turbines and combined-cycle gas turbines. In the current gas turbine technology, gas mixture containing 3-5% hydrogen could be used. A successful demonstration of using maximum of 30% hydrogen gas mixture in a modified gas turbine was performed by Mitsubishi Hitachi Power Systems. The power industry is highly confident that gas turbines entirely run-on hydrogen could be developed by 2030.

Fuel Cells (FC) are versatile and can also be used for power generation. In the last ten years, several stationary FC have been installed for power generation with current global installed capacity of around 1.6 GW. The FC units have been mostly installed in Japan, Germany, Korea and the United States. Japan aims to reach 1 GW of power generating capacity based on hydrogen by 2030. Korea has a goal of 1.5 GW installed FC capacity in the power sector by 2022 and 15 GW by 2040. Hydrogen is an excellent energy storage medium with variable renewable power generation systems based on solar and wind and FC using stored hydrogen could be used for power generation, depending on needs. Just to mention about demand for hydrogen, if it were to be used for power generation too using fuel cell technology having efficiencies of about 50%, an aggregate capacity of 1 MW operating with 70% capacity utilisation would need about 372 tonnes of hydrogen per annum.

5.2. Transport sector

Currently, electric vehicles (EV) and hydrogen fuelled vehicles (HFV) are the only options with no GHG emissions at use point as the energy carriers used for their operation can be generated using renewable sources. HFV offer similar driving range and lower refuelling time as available with fossil fuel-based IC engine vehicles (ICEV). The potential of hydrogen in transport sector is huge and different types of vehicles can be powered by either FC or hydrogen-based ICE technologies. It has been estimated that about 300 MT H_2/year will be

needed, if all current vehicles are completely replaced by hydrogen economy. Nevertheless, high cost of hydrogen and FCs and technical/infrastructure challenges associated with hydrogen production, transportation and storage are inhibiting introduction of HFVs and their rapid market deployment. Hydrogen could also be used in the maritime sector. Around 2.5% of global energy-related CO_2 emissions are caused by the maritime freight. Rail sector is mostly run by electricity and alternative fuels could be used instead of diesel in those portions of the tracks where electrification is difficult. Germany is already using two hydrogen FC trains which can travel 800 km/day on a single refuelling and they intend to run 14 such trains by the end of 2021. Austria, France, Japan, and UK have plans to deploy hydrogen trains by 2022. For operation of material handling equipment like forklifts, hydrogen has already emerged as an attractive option in the USA. Hydrogen could also be used in future for other rail yard and logistics hub machinery. Aviation sector is responsible for around 2.8% of global CO_2 emissions (2017) and it will increase further. Alternative fuels such as biofuels and hydrogen are among the best options to avoid increase in emissions from this sector. Although, feasibility tests and demonstration have been performed for using hydrogen in small planes, significant R&D on refuelling, storage infrastructure and aircraft design are needed to use 100% hydrogen fuelled engine in the aviation sector. Hydrogen-based liquid fuel could be used in the current aircrafts with a little or no modifications.

If we restrict ourselves to road transport and that too for community applications that would make use of FC buses, annual demand of hydrogen for operating 1000 buses (each running for about 60,000 km per annum) would be about 4000 tonnes.

5.3. Household applications

Natural gas is the current source for cooking and heating in buildings and a huge amount of gas is consumed every year. Hydrogen could be blended in existing natural gas networks for use in buildings. Local district energy networks could also use hydrogen for cooling or heating their building networks. In fact, complete use of hydrogen in household applications such as cooking, heating, cooling etc. could significantly reduce environmental impact, caused by current use of fossil fuels. For the sake of simplicity, if we blend 5% of hydrogen in

the city gas network in India that used about 4.27 MT of natural gas during 2018-19, about 0.21 MT of hydrogen would be needed.

6. R&D on hydrogen energy in India

With a view to develop sustainable hydrogen production technologies based on renewable energy sources, GoI has been supporting R&D activities at academic institutions ranging from IITs and Universities, Council of Scientific and Industrial Research (CSIR) laboratories, public and private research organisations for more than two decades. These efforts got momentum after National Hydrogen Energy Roadmap (NHER) was prepared in 2005. Some notable efforts made by the different organisations related to R&D of hydrogen production in the country are mentioned in this section.

In the area of hydrogen production from carbonaceous feed stocks, the Indian Institute of Chemical Technology (IICT), Hyderabad designed and developed a methanol reformer to produce around 10,000 L/h hydrogen for coupling with 10 kW FC. Central Institute of Mining and Fuel Research (CIMFR), Dhanbad developed a novel process to produce hydrogen from renewable and fossil fuel-based liquids (soybean oil, methanol and ethanol) and gaseous hydrocarbons by non-thermal plasma reformation technique. IIT Hyderabad worked for transforming greenhouse gases like methane and CO_2 into syngas/H_2 by low temperature plasma catalysis.

Indian Institute of Science (IISc), Bangalore developed a process for oxy-steam gasification of biomass for hydrogen production with hydrogen yield of about 100 g/kg of biomass. National Institute of Technologies (NITs), Calicut and Rourkela also made efforts in the area of hydrogen production through biomass gasification. It is worth noting that India generates 683 MMT of dry biomass every year, of which only 178 MMT (26%) was found to be surplus. This has estimated potential to produce 15-17 MMT of hydrogen through biomass gasification route.

As mentioned earlier, water electrolysers are going to play an important role for sustainable hydrogen production by utilising renewable energies. In this direction, Bhabha Atomic Research Centre (BARC) has developed water electrolysers up to 30 Nm^3/h capacity with high current density based on indigenously developed advanced electrolytic modules incorporating porous nickel electrodes. It is learnt that the technology has been transferred to an industry for commercialisation. While, Energy Research and Development Association

(ERDA), Vadadora has demonstrated the concept of utilising electricity generated by small wind turbines for hydrogen generation using commercial alkaline water electrolyser (AWE) , NISE, Gwal Pahari, Gurugram has utilised solar photovoltaic systems for production of hydrogen using an AWE. CSIR- CECRI has developed a PEM based water electrolyser system and the know-how has been transferred to an industry. SPIC Science Foundation (SSF), Chennai and Centre for Fuel Cell Technology (CFCT), Chennai developed PEM based water electrolysers for hydrogen generation using water-methanol as a feedstock instead of water. Jawaharlal Nehru Technological University (JNTU), Hyderabad has also developed indigenous PEM based water electrolyser. R&D Centre of IOCL at Faridabad is producing hydrogen by using a PEM based water electrolysis unit.

In India, first dedicated pilot-scale bio-hydrogen production unit using distillery effluent was installed by Shri AMM Murugappa Chettiar Research Centre (MCRC) at Nellikuppam, Tamil Nadu. IIT Kharagpur along with five other organisations explored hydrogen production through dark and photo fermentation routes and installed two pilot bioreactors of 10 Nm^3 capacity each at IIT Kharagpur and IICT, Hyderabad using distillery effluent and kitchen waste respectively for delivering about 30-50 Nm^3/day of hydrogen. IIT Kharagpur has also transferred the technology for industrial application. Indian Association for the Cultivation of Science (IACS), Kolkata undertook basic research for development of bio inspired catalysts that would efficiently catalyse hydrogen evolution reaction in water splitting process.

In the area of thermo-chemical hydrogen production using solar and nuclear heat, a number of cycles have been developed globally. High temperature reactor-based Iodine-Sulphur (I-S) thermo-chemical cycle offers a promising approach to the high efficiency production of large volumes of hydrogen from water. In this direction, BARC has initiated the efforts and made some progress so far. BARC is also engaged on studying various aspects of 3-step Copper Chlorine (Cu-Cl) cycle for hydrogen production. Thermo-chemical hydrogen production using waste heat from nuclear reactors may emerge as an inexpensive method for producing large quantity of hydrogen along with production of drinking water in near future. ONGC Energy Centre (OEC) is also working on some aspects of I-S process along with IIT-Delhi and CSRI-CECRI, Karaikudi. They are also working on Cu-Cl process along with Institute of Chemical Technology (ICT), Mumbai.

A number of research groups are engaged in developing catalysts that are suitable for providing high hydrogen production rate through photo-electro-chemical route by splitting water. Their efforts are focussed on developing low cost and durable catalysts that can work in the visible range of solar spectrum for making the process economically viable.

7. Conclusion

Based on the information collected from different sources, hydrogen production capacity in the country has been estimated as 6.341 MTPA as on 01.04.2020, as per details given below:

-	Petroleum refineries	:	2.845 MTPA
-	Ammonia synthesis for fertiliser production	:	3.380 MTPA
-	Chlor-alkali units	:	0.114 MTPA
-	Merchant hydrogen	:	0.0011 MTPA
	Total	:	6.341 MTPA

Hydrogen demand in petroleum refineries in India during 2019-20 could not be estimated because the petroleum refineries both in public and private sector did not share the information. Some of them from public sector cited this to be confidential and others from private sector did not share any information. Considering hydrogen demand in the petroleum refineries at 90% of the installed capacity, demand for hydrogen during 2019-20 was estimated at 2.5605 MT. For other industries, the demand for hydrogen during 2019-20 was estimated at 5.39943 MTPA, as per details given below:

-	Petroleum refineries	:	2.5605 MT
-	Ammonia synthesis for fertiliser production	:	2.647 MT
-	Chlor-alkali units	:	0.090 MT
-	Merchant hydrogen	:	0.00063 MT
-	Space applications	:	0.0242 MT
-	Float glass	:	0.0007 MT
-	Thermal power plants	:	0.0003 MT
-	Hydrogen peroxide	:	0.0098 MT
-	Methanol production	:	0.0663 MT[#]
	Total	:	5.39943 MT

estimated based on the actual methanol produced in the country during 2019-20

In addition, there would be demand for hydrogen for applications related to (a) stationary power generation; (b) transport sector; and (c) household sector. Presently, there may be hardly demand of hydrogen for these applications. It is difficult to estimate demand for these applications in the immediate future.

Government of India has announced launching of hydrogen mission during 2021-22. Based on information obtained, it emerges that some surplus hydrogen is available from the major hydrogen production units. However, the exact amount would be known, if information relating to actual production is shared by the industry. The surplus hydrogen from the petroleum refineries, chlor-alkali units and merchant producers may be significant for initiating some demonstration projects without investing in creating new infrastructure for hydrogen production.

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