

Status Quo Mapping of Hydrogen Production and Consumption in India



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Executive Summary

Anthropogenic activities, with emissions from fossil fuels at the core, contribute to a variety of climate change impacts (Barros et al., 2015; Harley et al., 2006; Pearson & Dawson, 2003). We, as a result, are living in a world that needs to prepare for the impact of at least 1.50 C. warming of the planet while reducing emissions (IPCC 2018).

We, unfortunately, are still heavily dependent on fossil fuels. In 2018-19, the import of oil and natural gas accounted for almost 24% of the India's overall imports (MoPNG 2020). To decarbonize our economy, we have to substitute it with an environmentally benign solution that is available, acceptable, accessible and affordable. Hydrocarbons, apart from being environmentally benign, tick all the other boxes. They are also extremely versatile. They provide us a variety of solutions including energy in form of fuel or electricity, heat for residential and industrial processes and as a feedstock for production of a variety of chemicals, polymers and inputs like cement and steel.

Hydrogen, a viable substitute, is being recognized worldwide as an energy vector, fuel and feedstock. Its role is also being acknowledged in its ability to decarbonize many sectors of the economy, especially those sectors which are hard-to-abate or where electrification is an improper substitute.

India's engagement with hydrogen as a fuel and an energy carrier has also been long. It published its first National Hydrogen Energy Road Map (NHERM) in 2006, which was reviewed in 2016. More recently, the Finance Minister in the Union budget for 2021-22 formally announced the National Hydrogen Mission which aims at production and consumption of hydrogen from renewable energy sources with a focus on industrial decarbonization instead of transport which was at the heart of the earlier NHERM.

In this context, this report aims to capture the status-quo of hydrogen production and consumption in India including stocktaking of various interventions by the Government, its utilities and other players to leverage on the work that has been done so far in India. The report also captures the various pathways for hydrogen production that can be deployed by various sectors in the short-long term.

Domestic hydrogen consumption in India currently amounts to approximately 6 Mt, primarily based on the demand from Indian industry – chemical and refining. Material production processes such as production of basic chemicals (ammonia for fertilizers, methanol, etc.) account for almost two-third of all consumption. Petrochemicals sector, on the other hand account for the bulk of the remainder consumption for production of conventional fuels. Hydrogen being used in these processes, however, is 'grey' hydrogen with only about 1.5% of demand (0.083 Mt) being met via electrolysis (chloralkali) processes.

In order to achieve our common future goals for climate, especially as a part of India's Nationally Determined Contributions (NDC), efforts are required to increasingly substitute Hydrogen produced from renewable sources in the industries where hydrogen is already used as a feedstock. This, however, depends on its availability, affordability and accessibility. Subsequently, the consumption of Hydrogen, based on ongoing research and development, needs to be expanded to include other sectors which have a high emission intensity such as long haul transport, steelmaking, cement production, energy storage etc. This would not only allow these sectors to decarbonise but would also help India in reducing energy imports, increase the penetration of renewable energy and in decreasing harmful emissions and pollution.



Table of contents

Executive Summary	i
Introduction	1
Colours of Hydrogen	2
Hydrogen production in India	3
Hydrocarbon reforming	4
Gasification	5
Steam reforming	6
Partial oxidation	7
Autothermal reforming	7
Waste and coupled stream	7
Electrolytic process	8
Alkaline Electrolysis	8
PEM Electrolysis	9
High temperature electrolysis	10
Biological processes for production of Hydrogen	11
Direct bio-photolysis	11
Photo-fermentation	11
Dark Fermentation	12
Hydrogen as a coupled stream in the electrolytic production of chlorine	12
Cost associated with hydrogen production in India	12
Utilization of hydrogen in the industry	15
Oil Refining	15
Ammonia	16
Methanol	17
Other uses and applications of hydrogen in chemical industry	18
Stationary power	18
Telecom Sector	20
Hydrogen in Transport	20
Demand outlook in transport	21
Hydrogen in transport in India	21
Hydrogen in Energy Intensive industry	24
Iron and Steel	24
Hydrogen in steelmaking in India	26
Annexure 1: Methodology for calculation of hydrogen consumption in oil refineries	27
Annexure 2: Important stakeholders in India	28
Bibliography	36

Abbreviations

ATR	Auto-Thermal Reforming
BF-BOF	Blast-Furnace – Basic Oxygen Furnace
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Use and Storage
CF	Complex Fertilizer
CO₂	Carbon Dioxide
CNR	Catalytic Naphtha Reformer
CUF	Capacity Utilization Factor
DAP	Di-Ammonium Phosphate
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EV	Electric Vehicle
H₂	Hydrogen
KM	Kilometres
Ktpa	Kilo tonnes per annum
LCOE	Levelized Cost of Electricity
LNG	Liquified Natural Gas
Mt	Million tonnes
Mtpa	Million tonnes per annum
NG	Natural Gas
PEM	Proton Exchange Membrane
RE	Renewable Energy
SMR	Steam Methane Reformation
SOE	Solid Oxide Electrolysis
SR-BOF	Smelting Reduction – Basic Oxygen Furnace
TCO	Total Cost of Ownership
VRE	Variable Renewable Energy



Introduction

India's industry – chemical and refining, are the largest producer and consumer of hydrogen in India. Hydrogen, either in its molecular form or in a form where it is bound within a molecule, fulfills multiple roles along the industrial value chain – both in case of organic and inorganic outputs (Ausfelder and Bazzanella 2016). For example, hydrogen produced from feedstocks such as natural gas, naphtha and heavy oil forms the basis of production of nitrogen-based fertilizers, which is an integral part of the agricultural value chain in India and possibly one of the most important process, within the current setting, involving hydrogen. India produced 36 million tons of nitrogen-based fertilizers in 2018–19 (Dept. of Chemicals and Petrochemicals 2020) and imported an additional 9 million tons to fulfill the demand gap.

Hydrogen is also a by-product in some industries. For example, Chlor-alkali units in India produced 2.9 million tons of caustic soda, along with which 83,000 tons of hydrogen was produced as a by-product in 2018–19 (BEE 2018) (Dept. of Chemicals and Petrochemicals 2020). Due to a lack of trading infrastructure, however, hydrogen currently produced in chlor-alkali units is utilized for captive requirements such as process heat, with a portion of the gas also being flared.

Molecular hydrogen, apart from its role in production of useful hydrocarbons, is also used as a reduction agent, both within the chemical industry and other industrial sectors, such as metallurgy, to reduce the precursor molecule, alloy or ore into the desired product. This reducing function also serves to remove undesired compounds from the mixtures, for example in the removal of sulfur containing compounds or in the cleaning of semi-conductor surfaces. Within the chemical industry, hydrogen is also widely used for catalyst regeneration (Ausfelder and Bazzanella 2016).

Currently limited by appropriate regulations¹ and a lack of trading ecosystem, it is not uncommon to see the entire value chain of hydrogen – from production to consumption, in the same industrial unit. This makes it difficult to estimate the overall production numbers

associated with hydrogen, as there is limited availability of data from industrial units which produce or consume the gas.

Table 1 Hydrogen consumption in India (in major sectors) in 2018-19

Industry	Consumption (in Thousand Metric Tons)	Production method	Typology
Oil Refining	2600.00	Hydrocarbon reforming	Grey Hydrogen
Ammonia	2850.21	Hydrocarbon reforming	Grey Hydrogen
Ammonia (imported as fertilizers)	752.15	Hydrocarbon reforming	Grey Hydrogen
Methanol (domestic)	51.67	Hydrocarbon reforming	Grey Hydrogen
Methanol (imported)	361.00	Hydrocarbon reforming	Grey Hydrogen
Chlor-alkali	34.37	Electrolysis	Green hydrogen ^{2*}
Chemical industry	29.25	Electrolysis	Green hydrogen*
Other industries (glass, electronics etc.)	9.51	Electrolysis	Green hydrogen*
Total consumption of hydrogen	6688.16 Thousand Metric Tons (TMT)		

Source: Compiled by author from (MoPNG 2020) (Dept. of Chemicals and Petrochemicals 2020) (BEE 2018)

1 In order to create a conducive environment for the use of hydrogen at scale in India appropriate regulations and standards would have to be created, and in some cases existing regulations would require amendment. For example, in case of mobility, central motor vehicle rules (1989) and gas cylinder rules (2004) would require amendment for usage of the gas as an automotive fuel and for its storage and transportation respectively (DST 2020).

2 * Depending on the source of electricity.

Due to scarcity of hydrogen production data, the data presented above (table 1) has been modelled on stoichiometric calculations based on the data released by Government of India and other related statistics. These estimates, though based on the end uses of hydrogen, may vary slightly from the actual production values. The data perused for India also does not show any significant role of hydrogen in the energy sector. This, based on the upcoming policies of the government, is assumed to change given the role that hydrogen can play in decarbonization of the economy.

Colours of Hydrogen

Hydrogen, though abundant in nature is not readily available for consumption. It is an extremely reactive atom and bonds with most other elements to form compounds such as water (H₂O) or hydrocarbons such as methane (CH₄), coal (C₁₃₇H₉₇O₉NS) etc. To retrieve hydrogen and make it useful, we have to derive it from the aforementioned sources. The derivation of hydrogen from water is through electrolysis, while its derivation from hydrocarbons is through hydrocarbon reforming. Based on the production method deployed to isolate hydrogen and level of associated emissions, the gas has been categorized by the industry in to different colours – grey, blue, green and turquoise.

Grey Hydrogen: Grey hydrogen is based on the use of fossil hydrocarbons. Grey hydrogen is mainly produced via the steam reforming of natural gas. Depending on the fossil feedstock, its production entails considerable carbon emissions.

Blue Hydrogen: Blue hydrogen is hydrogen which is produced using a carbon capture and storage (CCS) system. This means that the CO₂ produced in the process of making hydrogen does not enter the atmosphere, and so the hydrogen production can be regarded on balance as carbon-neutral.

Green Hydrogen: Green hydrogen is produced via the electrolysis of water; the electricity used for the electrolysis must derive from renewable sources. Irrespective of the electrolysis technology used, the production of the hydrogen is zero-carbon since all the electricity used derives from renewable sources and is thus zero-carbon.

Turquoise Hydrogen: Turquoise hydrogen is hydrogen produced via the thermal splitting of methane (methane pyrolysis). This produces solid carbon rather than CO₂. The preconditions for the carbon neutrality of the process are that the heat for the high-temperature reactor is produced from renewable or carbon-neutral energy sources, and the permanent binding of the carbon.

Hydrogen production in India

Majority of hydrogen production in India, is currently based on fossil fuels. This is in accordance to long-established industrial processes optimized for least cost of production notwithstanding associated environmental externalities. For example, oil refineries in India cover main part of their hydrogen requirements via internal refinery processes, especially catalytic reforming. Additional hydrogen requirements are met by gasification of heavy residues. Likewise, hydrogen rich off-gases are also produced as a result of the coking process in the steel industry, but due to their low purity levels are generally flared or utilized as fuel for process heat.

The chemical industry, on the other hand, requires significant amounts of on-purpose generated hydrogen, largely for the production of ammonia and methanol. Hydrogen in the chemical industry is produced through

synthesis gas based processes that in definition can be applied to any carbon containing compound. Usage of green hydrogen, produced from electrolysis utilizing renewable energy, still has to mount several barriers before it becomes ubiquitous. The biggest of these barriers, apart from regulation and process design, is the cost of production.

A choice for the technology (figure 1) utilized depends on the availability of the feedstock and the nature of downstream processes. In India, the feedstocks available to the chemical industry are Naphtha from oil refineries, natural gas or coal. Among these, only coal is available domestically³, while both crude oil (required for production of naphtha, heavy oils etc.) and natural gas are largely imported and account for a significant share of India's trade deficit. In 2018-19, the import of oil and natural gas accounted for almost 24% of the country's

Figure 1 Hydrogen production methods



Source: Adapted from (Kumar and Himabindu 2019)

3 India has significant coal resources (5th largest globally), to the tune of 360 billion metric tons, of which 150 billion metric tons are reserves, which are economically extractable. Indian coal quality, however, is low grade with low heat content along with high ash and moisture content. (USISPF 2019)

overall imports⁴ (MoPNG 2020).

The following section, starting with the basics of synthesis gas production, details out the various technologies utilized, in general, for the production of hydrogen in the industry today.

Hydrocarbon reforming

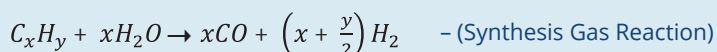
The process design and implementation at industrial scale is driven by [a] composition of the feedstock and, [b] subsequent utilization of the generated synthesis gas – a combination of hydrogen (H₂) and carbon monoxide (CO) with carbon dioxide (CO₂) as a byproduct. As a first step, the feedstock is treated with heated steam (steam reforming) and subsequently the ratio of generated hydrogen and carbon monoxide is adjusted utilizing a water-gas shift reaction. The combination of the aforementioned processes yields synthesis gas. It is the subsequent use of this gas, which is defined by required H₂:CO:CO₂ ratio, that plays a dominant role in the design and implementation of any given synthesis gas-based

process. For example, in the production of urea, the design prefers generation of carbon dioxide (in place of carbon monoxide), while the production of methanol requires a H₂:CO ratio of 2:1.

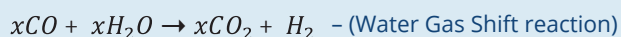
Carbon dioxide, in most cases, is a by-product of this process. In general parlance, if the described process is applied without carbon capture and utilization/sequestration (CCUS) it produces grey hydrogen. If, on the other hand, the process is coupled with CCUS, the process generates turquoise/blue hydrogen. Natural gas, if available, is the preferred feedstock for synthesis gas generation through steam reforming. Other feedstocks such as solid feedstocks, refinery off gases, LPG and naphtha are also utilized by the industry.

Depending on the specific requirements of the process and the availability of feedstock multiple process variations have been developed by the industry. These are [a] Gasification; [b] steam reforming; [c] Partial oxidation; and [d] steam thermal reforming. All of these processes have been discussed in subsequent sections.

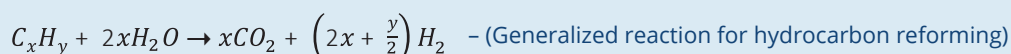
Box 1 Reactions involved in hydrocarbon reforming



Depending on the feedstock's H:C ratio, synthesis gas reaction converts the reactants into a certain H₂:CO product ratio, which may or may not match the requirements of the downstream process. This, however, may be adjusted by incorporating a water-gas shift reaction.

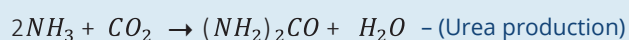
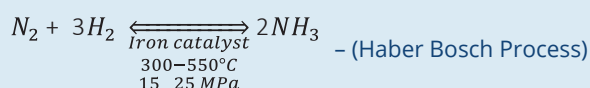


Partial application of water gas shift reaction adjusts the overall H₂:CO ratio by conversion of CO and steam (H₂O) into CO₂ and additional H₂



Both the aforementioned reactions, namely synthesis gas reaction and water gas shift reaction, can be combined to provide a generalized reaction for the entire process.

Synthesis gas generation may be followed by a variety of downstream processes such as production of Urea which combines ammonia synthesis (Haber-Bosch Process) with CO₂ generated from hydrocarbon reforming. Urea production, represented below, due to its preference for CO₂, as opposed to CO, is a unique case of downstream processing of synthesis gas.



Urea production, as described above, seems to (apparently) utilize/sequester carbon dioxide. It, however, may be noted that once urea is applied at the agricultural field (its defined end use), carbon dioxide, approximately equivalent to the amount fixed during the course of its industrial production process, is emitted to the atmosphere. The above described process, therefore, does not permanently store or sequester carbon (Kim, et al. 2016).

⁴ The individual share of oil and natural gas in overall country's import was 22% and 2% respectively (MoPNG 2020).

Gasification

Gasification can be applied to all liquid and solid carbon containing feedstocks, including biomass and waste. The dominant feedstock used by the industry for gasification is coal. This is especially the case in China and is to an extent being promoted by India as well (Saraswat and Bansal 2016).

Solid feedstocks such as coal have a higher Carbon to Hydrogen ratio, when compared to natural gas. In case of biomass, the composition of the feedstock also has significant amounts of oxygen and water. The gasification of feedstock produces synthesis gas, which can be adjusted to the required H₂:CO ratio utilizing a water gas shift reaction. Coal gasification, if not coupled with CCUS has a high emission intensity. For example, well-to-wheel emissions for coal to methanol production is 0.68 tonnes of CO₂eq/MWh, whereas the same number for gasoline production ranges between 0.34 – 0.36 tonnes of CO₂eq/MWh (Saraswat and Bansal

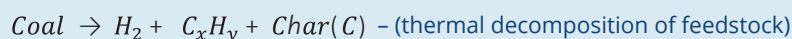
2016). The process, as a result, needs to be approached with caution.

(Ramakumar 2020). The produced hydrogen can subsequently be combined with other components to produce a variety of products such as Synthetic Natural Gas, methanol, diesel/naphtha inter alia. India's Coal India Limited (CIL) is planning to set up a coal-based methanol plant at Dankuni Coal Complex (DCC) of South Eastern Coalfields Ltd (SECL), a subsidiary of CIL (Economic Times 2018). In 2014, a coal to polygeneration project was also proposed by Adani Synenergy Limited (Adani Synenergy Ltd. 2014).

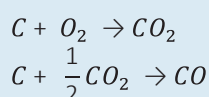
India has large coal reserves, and as a result, coal gasification as a source for production of syngas may see substantial investment from both the public sector (as aforementioned) and private sector⁵. This can be attributed to a

Box 2 Reactions involved in gasification

The most common feedstock utilized for gasification is coal, the main products of which are carbon monoxide and hydrogen. It is largely used for production of hydrogen, methanol, synthetic natural gas and power generation inter alia. The generalized chemical reactions have been summarized below:

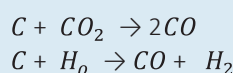


The aforementioned reaction represents the thermal decomposition of coal into volatile matter such as hydrogen, hydrocarbon gas and char – residual solid content consisting of fixed carbon and ash.

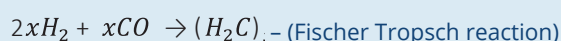


Thermal decomposition of feedstock is followed by combustion and partial combustion. The reaction is endothermic and requires heat and a steady supply of oxygen.

Combustion of volatile matter is followed by main gasification reactions as represented above. These reactions are also endothermic, and also require heat (Miranda 2019).



The gasification reactions are followed by conversion reactions to produce hydrogen, carbon-di-oxide, methane etc. These reactions can be subsequently combined with other downstream processes to produce Synthetic Natural Gas (SNG), Methanol, Diesel, Naphtha inter alia. Some of these downstream processes, as represented below, are for the production of methanol (H₃COH) and higher hydrocarbons [(H₂C)_x] via Fischer-Tropsch reactions.



⁵ US-based industrial gases major Air Products and Chemicals is planning to invest USD 5 – 10 billion over the next five years in coal gasification projects in India (Business Today 2020)

Steam reforming

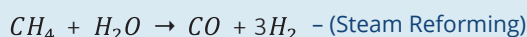
Steam reforming, an inherent part of synthesis gas production, is the dominant process employed by the industry for conversion of feedstock to useful compounds. The incoming feedstock, either natural gas, naphtha or heavy oil, is conditioned, such as by removal of sulfur, which is converted to Hydrogen Sulphide (H₂S) and absorbed. Subsequently, steam reforming takes place in heated tubes, where the gas mix of high temperature steam and desulfurized feed is exposed to a catalyst at high pressures. The amount of steam is adjusted to produce the required H₂:CO ratio. The catalysts used in the process are nickel based and typical process temperature ranges are in 750 – 900°C with pressure ranges between 3 – 25 bar, depending on the individual process design. This, as mentioned earlier, is followed by a water-gas shift reaction with additional steam to adjust the H₂:CO ratio.

These reactions are equilibrium driven and resulting gas mixture depends on the operational conditions of the plant. The syn gas is subjected to separation process steps, depending on its subsequent use. Hydrogen, when required, is separated and purified from remaining gases by pressure swing adsorption (PSA), membrane process and/or methanation of left over CO.

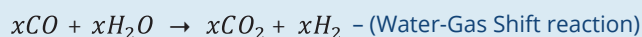
In India, from an economic perspective, steam reforming is the most optimized for costs. Assuming the usage of natural gas available at ~ INR 4,000 per mmbtu, with an efficiency of 75%, hydrogen as an end product can be produced within the range of INR 160 – 200 per Kg. If, however, CCUS is being undertaken then an additional cost of INR 20 – 30 per kg is assumed (Ramakumar 2020) (Hall, Spencer and Dayal, et al. 2020).

Box 3 Reactions involved in Steam Reforming

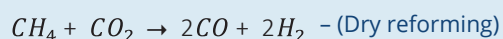
Steam Reforming is undertaken for a variety of feedstocks. The reactions provided in the section consider natural gas (methane) as a feedstock for simplicity. The process consists of four sub-processes – [a] desulfurization, for removal of sulfur from the feed as it can poison the catalyst; [b] steam reforming; [c] water-gas shift reaction; and, [d] hydrogen separation and purification. The first step – desulfurization utilizes either an activated carbon bed or a zinc oxide tank, with the latter having distinct advantages such as removal of carbonyl sulfide (if present), no air emissions and retention of higher molecular weight hydrocarbons. The subsequent processes involved in steam reforming are represented through reactions below.



The reforming reaction converts hydrocarbon (methane in the aforementioned reaction) and steam into a synthesis gas consisting of carbon monoxide and hydrogen. The reaction is endothermic and requires significant amounts of heat supplied via high temperature steam as well as external burning of natural gas and off gases from the process post hydrogen separation. Due to the requirements of external heat, efficient heat recovery in the overall process is critical for economics of the process.



The synthesis gas produced in the reforming reaction is subjected to a shift conversion reaction (water-gas shift) with additional steam to adjust the H₂:CO ratio



The carbon-di-oxide produced as a result of shift conversion reaction also reacts with methane, in a manner similar to steam, resulting in syn-gas with a H₂:CO ratio of 1. This process is also termed as dry reforming.

Partial oxidation

Partial oxidation is a process variation of the steam reforming process, where the feedstock reacts with an under-stoichiometric amount of oxygen, resulting in the partial combustion of the feedstock. This variation compacts the overall process as it reduces the requirement of an external heat source. Partial oxidation can be carried out non-catalytically via combustion through a burner, or catalytically via a catalytic bed without the requirement of a flame.

Autothermal reforming

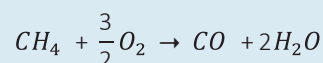
This process is a combination of partial oxidation and classical steam reforming, thereby combining the benefits of both the technologies. In the process a combination of oxygen and steam (and sometimes carbon dioxide) is introduced to the feed. The overall reaction is exothermic and further compacts the

industrial setup. The process, apart from advantages of compact design, low investment and flexible operation, is utilized in producing varying H₂:CO ratios as may be required for subsequent downstream operations. For example, if carbon dioxide recycle is tweaked in autothermal reformer then H₂:CO in ratio of 1:1 is produced, which is conducive for the production of methanol. If, however, the autothermal reformer largely utilizes steam in its input stream then H₂:CO in ratio of 2.5:1 can be achieved which is conducive for ammonia synthesis.

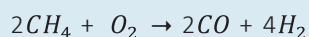
Waste and coupled stream

Industrial processes such as by coking process often produce hydrogen rich off-gases. These gases are often made up of complex mixtures and require additional processing for separation and purification. As a result, in an industrial set-up which is optimized for maximum cost effectiveness, these gases are used thermally

Box 4 Reactions involved in partial oxidation



The aforementioned reaction shows the partial combustion of the feedstock utilizing an under-stoichiometric amount of oxygen. This process is exothermic and provides the process heat required for the subsequent reforming reaction.



The reaction requires pure oxygen, which may be provided from an air separation unit. The traditional reaction involving partial oxidation is carried out at high temperatures beyond 1200°C, which may be lowered to 800 – 900°C through the use of a catalyst, as represented in the aforementioned reaction which produces carbon free synthesis gas with a H₂:CO ratio of 2:1.

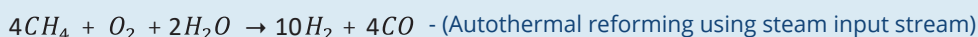
Box 5 Reactions involved in autothermal reforming

Autothermal reforming (ATR) utilizes a reactor which consists of three zones – [a] burner zone, where feed streams are mixed in a turbulent diffusion flame; [b] combustion zone, where partial oxidation reactions produce a mixture of carbon monoxide and hydrogen; and, [c] catalytic zone, where the gases exiting the combustion zone achieve thermodynamic equilibrium. The reformer, depending on the requirement of downstream reaction, can be tuned based on whether it utilizes a higher proportion of steam or carbon dioxide in its input stream. The output H₂:CO ratios, based on input streams, are 2.5:1 and 1:1 respectively.

The reaction in case carbon dioxide is used in the reforming process is provided below



The reaction in case steam is used in the reforming process is provided below



to produce process heat. In some cases, such as in dehydrogenation reactions in refineries and chemical plants, pure stream hydrogen rich off-gases can be produced. This pure hydrogen can easily be traded, if a market exists.

Electrolytic process

Electrolytic production of hydrogen, the mainstay of decarbonization of hard to abate industrial sectors, currently is responsible for a very small fraction of overall production of Hydrogen. The two mature technologies available to industry are alkaline and Proton Exchange Membrane (PEM) electrolyzers, while, high temperature electrolysis based on an inverted solid-oxide fuel cell (SOFC), currently in development stage, shows great promise.

The aforementioned methods of hydrogen production currently contribute to processes where relatively small amounts of pure hydrogen is required. The low production volumes are correlated to prevailing renewable electricity prices, related capex of electrolyzers and infrastructural costs related to storage and distribution (Hydrogen council 2017). Forecasts, driven by growing need of decarbonization in a world experiencing a rapidly changing climate, suggest that with the right policy levers and adoption levels the costs of green hydrogen, which utilizes renewable energy to drive the electrolytic process, may reduce substantially in the next decade (Hydrogen Council 2020).

Costs of electricity generated from renewable sources as well as electrolyzers have been falling. The former has already achieved grid parity levels while the latter, in western economies, has experienced a 40% – 50% fall in costs in the last five years from 2014-19 to now being available at USD 1200/kW and USD 14,00/kW for alkaline and PEM electrolyzers respectively (BNEF 2020). In china, on the other hand, driven by availability of relatively cheaper raw materials and labour, and, higher factory utilization rates (in turn correlated to robust demand) the alkaline electrolyzers are available at rates of USD 200/kW, which are further 83% cheaper as compared to the west (BNEF 2020).

Alkaline Electrolysis

A small fraction of the chemical industry in India utilizes alkaline electrolysis to generate hydrogen. It is an established production method when relative high purity is required. Hydrogen is cogenerated with oxygen by the electrolysis of a concentrated (approximately 30% by weight) potassium hydroxide in water solution at elevated temperatures of 60 – 90 C. the overall efficiency of the process is 70-80%, and is carried out in stacks which can be built up to reach the required capacity. In a variation to the process which normally operates at atmospheric pressure conditions, high-pressure electrolysis plants have been developed, which can further facilitate hydrogen usage in subsequent downstream operations.

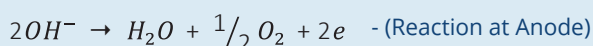
Box 6 Reactions involved in alkaline electrolysis

The overall reaction consists of two half-cell reactions at cathode and anode respectively.

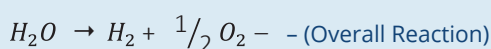
At cathode: The reaction initiates at the cathode, where two molecules of alkaline solution are reduced to one molecule of hydrogen and two hydroxyl ions (OH⁻). The preferred alkaline solution commonly constitutes either Potassium Hydroxide (KOH) or Sodium Hydroxide (NaOH). The hydrogen is expelled from the cathode surface, while the hydroxyl ions travel under the influence of an external electricity current through a porous diaphragm or an anion exchange membrane (AEM) to the anode.



At anode: The hydroxyl ion is discharged to formulate ½ molecule of oxygen and one molecule of water. The oxygen, which is recombined at the surface escapes from the electrode as a gas.



Overall cell: the process of alkaline water electrolysis, if using a porous diaphragm such as asbestos, is characterized by limited current densities, low operating pressure and low energy efficiency. The overall reaction of the cell is represented below.



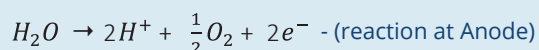
PEM Electrolysis

This method was developed to overcome the issues associated with alkaline electrolysis such as low purity of gases and low dynamics. In this process, water is electrochemically split into hydrogen and oxygen at cathode and anode respectively. Water is pumped into the anode, where it is split into oxygen gas (O₂), proton (H⁺) and electrons (e⁻). The proton travels via the proton conducting membrane to cathode, while the electrons exit via the external power circuit, which provides the driving force (cell voltage) for the reaction. At the cathode end, the protons and electrons recombine to produce hydrogen gas. The membranes most commonly used are Perfluorosulfonic acid polymer membranes

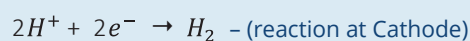
which are available under multiple tradenames. PEM based water electrolysis has the advantages of being extremely compact, sustaining high current densities, high efficiency, providing a fast response, and producing ultrapure hydrogen. Additionally, balancing a PEM electrolysis plant is simple, thus making it attractive for industries. They, however, are more expensive than an alkaline electrolysis setup. A substantial part of the ongoing research is in improving the PEM water electrolysis components such as electrolysis separator plates and current collectors which are responsible for almost 48% of the overall cell cost (Kumar and Himabindu 2019).

Box 7 Reactions involved in PEM Electrolysis

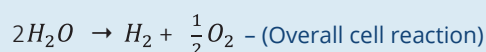
At Anode: The water electrolysis is initiated at the anode where water is pumped, which in the presence of an electric current splits water into oxygen (O₂), protons (H⁺), and electrons (e⁻). The protons travel via the proton conducting membrane to cathode, while the electrons travel through the external power circuit, which provides the requisite potential difference to drive the reaction. Oxygen, a byproduct of the process which is in form of a gas is released from the anode.



At Cathode: The protons split at the anode, which travel through permeable polysulfonated membranes, recombine at cathode to produce hydrogen gas. The gas, as opposed to the process in alkaline electrolysis, can be pressurized to be utilized in a variety of downstream processes.



Overall Cell: The overall reaction generates both hydrogen and oxygen at cathode and anode respectively. The feed water, which is pumped in to initiate the process, decomposes once it reaches the electrode surface into oxygen gas, protons and electrons. Oxygen, as aforementioned, is collected from the electrode surface while the proton travel to the cathode, where they recombine with electrons to produce hydrogen. The major components of a PEM cell are [a] Membrane Electrode Assemblies (MEA) which in turn consist of the membrane, ionomer solution and anode & cathode electrocatalysts; [b] current collectors (gas diffusion layers); and, [c] separator plates. The overall reaction in the cell is represented below.



High temperature electrolysis

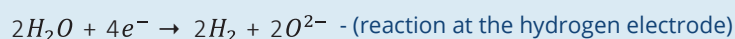
This process uses the principle of an inverted Solid Oxide Fuel Cell (SOFC) to produce hydrogen, where it supplies a portion of the energy required to formally break chemical bonds in form of heat. It usually operates at high temperature and pressure utilizing water in the form of steam. The membranes conventionally are O₂ - conductors which are derived from nickel/yttria stabilized zirconia. Solid oxide electrolysis of water is versatile and can be used to co-electrolyze carbon dioxide to produce a synthesis gas of desired composition. The electricity requirement in this process

is relatively lower as compared to earlier process, as part of the energy is being supplied as high temperature heat. The stacks can be operated at high pressure and can be easily expanded to accommodate downstream methanol or methanization reactions. As a result, this technology offers advantages in reduced electricity requirement, high efficiencies and in the easy combination with follow-up processes. It, however, requires an external heat source which provides high temperatures. From the point of view of chemical industry, which is biased towards the production of synthesis gas as opposed to hydrogen alone, this technology looks promising.

Box 8 Reactions involved in a Solid Oxide Electrolysis Cell (SOEC)

A SOEC consists of three components in solid state, namely [a] cathode, which is also called the hydrogen electrode; [b] anode, which is also called the air electrode; and, [c] electrolyte (Pandiyar, et al. 2019). Steam (H₂O) reduces at the hydrogen electrode to form oxygen ion and hydrogen (in its gaseous form). The oxygen ion migrates through the solid electrolyte to the anode (air electrode) where it oxidizes to form oxygen gas by releasing its electrons. The reactions involved in an SOEC are summarized below:

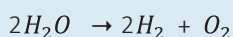
At Cathode:



At Anode:



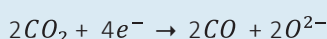
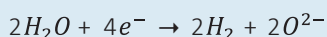
Overall reaction:



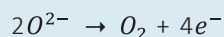
SOEC, like other electrolysis cells has piles of single cells, together called a stack, and has interconnects that carry electric current and ensure gas collection. SOEC, though still not available commercially at scale, has several advantages – [a] it can achieve an efficiency of up to 100%; [b] doesn't require noble metal catalysts, and as a result can be made inexpensive; and, [c] it can operate at high pressures, thus providing support to the downstream processes, which often require hydrogen in a pressurized format. Currently, this process is subject of mainstream R&D, where work is being undertaken to improve its mechanical stability and bulky system design (Voitic, et al. 2018).

Co-electrolysis of steam (H₂O) and Carbon dioxide (CO₂) in an SOEC, on the other hand, yields synthesis gas (Ebbesen and Mogensen 2009). The half-cell reactions for this process are represented below:

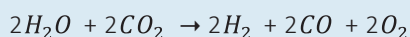
At Cathode:



At Anode:



Overall reaction:



Synthetic Gas, an important constituent of multiple downstream processes is produced at the cathode, while oxygen, in its gaseous form, is produced at the anode.

Biological processes for production of Hydrogen

An alternative approach for hydrogen production, though not currently utilized at an industrial scale, is through the biological route. The approach deploys the use of renewable resources such as nutrient rich wastewater, food and agricultural wastes inter alia under ambient conditions.

In this process microorganisms convert water molecules and organic substrates into hydrogen by catalytic activity of two key enzymes, namely hydrogenase and nitrogenase. Bio-hydrogen, or hydrogen that is synthesized biologically, can be produced through different processes including bio-photolysis, photo-fermentation and dark-fermentation amongst others. In bio-photolysis, microalgae and cyanobacteria have the ability to capture solar energy and generate hydrogen from water and CO₂. Photo-fermentation hydrogen production is carried out by purple non-sulfur (PNS) bacteria from various carbon sources using light energy. In dark-fermentation, anaerobic bacteria generate hydrogen from organic matter using food or agricultural wastes and wastewater. Hydrogen is also produced through CO gas-fermentation from water gas shift reaction via bioconversion of carbon monoxide and water molecule by means of photosynthetic bacteria under anaerobic condition.

Direct bio-photolysis

In the process of direct bio-photolysis, unicellular organisms that produce their own energy utilizing sunlight and CO₂ through photosynthesis (also referred to as photoautotrophic organisms) convert water molecules into hydrogen. Two group of organisms that facilitate the process of direct bio-photolysis hydrogen production are green algae and cyanobacteria⁶. They undertake this process utilizing the catalytic activity of hydrogenase and nitrogenase enzymes. The former enzyme is produced by both cyanobacteria as well as green algae, while the latter is only produced by cyanobacteria which are nitrogen fixing.

The enzyme hydrogenase is categorised into either [a] uptake hydrogenase (Hup), which consumes H₂ by oxidising hydrogen molecule into electrons and protons; and, [b] reversible hydrogenase (Hox), which has the ability to both produce and consume H₂ through catalysing the reversible oxidation of a hydrogen molecule based on the prevalent operating conditions. On the other hand, nitrogenase is an enzyme responsible

for catalysing nitrogen fixation, which is reduction of nitrogen (N₂) to ammonia (NH₃) – a process vital to sustaining life on earth.

The process utilizes energy from sunlight in anaerobic conditions i.e., without the presence of oxygen. Both cyanobacteria and green algae, in anaerobic conditions, produce hydrogen in the presence of light. Green algae, however, in absence of illumination or sunlight uptakes hydrogen through CO₂-fixation process producing carbon compounds that store energy. Nitrogen fixer cyanobacteria, which has both bi-directional hydrogenase (Hox) and uptake hydrogenase (Hup) also consumes the produced hydrogen through nitrogen fixation. The basic difference between the two organisms is that the process in case of green algae is extremely oxygen sensitive (the production of hydrogen drops significantly if there is a presence of oxygen in the bioreactor) while cyanobacteria can be more resistive to oxygen. Also, it is possible to genetically modify a cyanobacteria to delete the process of hydrogen uptake.

This method of hydrogen production is attractive as it only requires the use of water as primary feed along with sunlight which in turn acts as the motivating agent for the biocatalyst. For even spread of sunlight, however, bioreactors with large surface areas are required which poses a limitation in case of large industrial set-up. Also, simultaneous production of oxygen and hydrogen poses a significant drawback for the process, as the presence of oxygen in the bio-reactor significantly hampers the rate of hydrogen production. This oxygen can be removed by continuous sparging (by introducing a noble gas such as argon), but it is not extremely cost-effective, especially in a commercial set-up. Use of genetically engineered strains is an advanced technique which can improve oxygen tolerance. The process has a light conversion efficiency in the range of 6% - 42%. It has been reported that utilizing direct bio-photolysis, hydrogen can be produced at approximately USD 3.15 per Kg H₂ (Nikolaidis and Poullikkas 2017).

Photo-fermentation

Hydrogen production in photo-fermentation process is mediated by Purple Non-Sulfur (PNS) bacteria. These bacteria possess versatile metabolism. Depending on the operating conditions such as available carbon sources, light intensity, oxygen presence etc. the bacteria can grow either as photoautotrophs (organisms that create their own food), heterotrophs (organisms which depends on other organisms/nutrients present in the environment) or as chemoheterotrophs⁷ (organisms that

6 Cyanobacteria, based on scientific enquiries, are responsible for the Great Oxidation Event – a time period when the Earth's atmosphere and the shallow ocean first experienced a rise in oxygen approximately 2.5 billion years ago.

7 Chemoheterotrophic bacteria is a sub-type called lithotrophic bacteria, also known as "rock eaters" or "stone eaters". They are unable to make their own food (like autotrophs do) so they get their energy from the oxidation of inorganic minerals in their environment. Also, these bacteria cannot make organic

obtain energy by the oxidation of electron donors in their environments). Amongst these, photoheterotrophs who use light and organic compounds for sources of energy and carbon are preferred for hydrogen production.

Photo-fermentation, like bio-photolysis, is also carried out by hydrogenase and nitrogenase through the citric acid cycle (TCA cycle) and is strongly dependent on the nitrogenase activity. As a first step, the organic substrate is oxidised to CO₂, protons and electrons through the TCA cycle. The generated electrons are transferred to nitrogenase. In parallel, Adenosine triphosphate (ATP), which provides energy to drive the biological processes, is synthesised in the photosynthetic membrane apparatus of the bacteria and is supplied. This facilitates the reduction of protons to hydrogen. The overall reaction requires high amount of intracellular energy (ATP) and a nitrogen deficient condition for high hydrogen production. The production is dependent on the type of substrate (such as pre-treated waste water from various industrial processes), nitrogen source, amount of trace metals and minerals present in the substrate and level of illumination. The major drawbacks of this process are low efficiency of solar energy conversion because of the high energy demand of the reactions, requirement for maintaining anaerobic conditions and photobioreactors with large surface areas. In the long run, photo-fermentation is not considered a viable method for hydrogen production (Abdalla, et al. 2018).

Dark Fermentation

Dark fermentation is the most studied method for hydrogen production through biological processes. The method uses a wide range of waste materials such as food and agricultural waste, waste water inter alia in conjunction with anaerobic organisms. The reaction is carried out via an acetate mediated pathway. Anaerobic bacteria as well as microalgae such as green algae under anoxic and dark conditions within operating temperature range of 30 – 80°C are utilized for the process.

This differs from the bio-photolysis process as it does not require light and produces a variety of gases including H₂, CO₂, CH₄ or H₂S, depending on the reaction conditions and organic substrate used. The quantum of hydrogen production is affected by pH value of the substrate, time of hydraulic retention and gas partial pressure. The best results have been obtained by regulating the partial pressure of H₂, maintaining a pH value within the range of 5 – 6, and maintaining an optimised hydraulic retention time (HRT) of 0.5 days. This process has several merits over the other biological

processes as [a] it does not need a steady source of light energy and as a result is relatively economical; [b] generates a higher amount of H₂, for example, it has an efficiency of 60–80% as compared to 6–46% in case of bio-photolysis; [c] it is technically simpler not requiring bio-reactors with high surface areas for even illumination; and [d] uses lower value waste as organic substrate or feedstock. Utilizing this process hydrogen production can be achieved at approximately USD 2.85/kg H₂ (Nikolaidis and Poullikkas 2017).

Hydrogen as a coupled stream in the electrolytic production of chlorine

Chlorine (Cl₂), caustic soda (NaOH) and soda ash (Na₂CO₃) are important chemicals produced by industrial units and are inputs to a variety of downstream units such as textiles, pulp & paper, alumina, soaps & detergents, pharma, etc. In 2018–19, chlor-alkali units in India produced almost 2 million tons of chlorine, and approximately 3 million tons of each – caustic soda and soda ash (Dept. of Chemicals and Petrochemicals 2020). Chlorine and caustic soda are mass produced by electrolytic processes, utilizing saturated brine solution, that produces hydrogen of high purity as a by-product.

Hydrogen, however, is frowned upon in the chlor-alkali units as a waste of energy as well as a safety hazard. The industry utilizes variations of the electrolytic process in [a] Membrane cell process; [b] Mercury cell process, and [c] Diaphragm cell process. Amongst these, the mercury cell process is being phased out around the globe, as it utilizes mercury as an input and also has a high electricity demand. In India, the sector has also upgraded from mercury cell process to membrane cell process and in the transition, has been able to save ~ 800 kWh/MT from an energy intensity of 3200 kWh/MT required in the former process to approximately 2400 – 2500 kWh/Mt in the latter (BEE 2018). The primary product of the chlor alkali industry is caustic soda, with chlorine and hydrogen generated as by products in the ratio of 1.00:0.89:0.025 (BEE 2018).

Cost associated with hydrogen production in India

The various hydrogen production methods along with their advantages, disadvantages, efficiencies inter alia are represented in table 2. Currently, as also aforementioned, a lion share of the hydrogen production is from non-renewable fossil fuels, in particular, steam reforming of natural gas, naphtha or heavy oils. The usage of fossil fuel as a feedstock produces 'grey hydrogen' of low purity with a high concentration of greenhouse gases. Growing energy needs of the country,

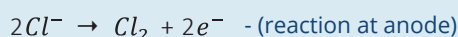
molecules from inorganic sources (they cannot "fix" carbon) so they eat other organisms to get the carbon they need. The common food and energy sources for them are dead organic material and elemental sulfur and iron and gases having these elements such as hydrogen sulfide.

Box 9 Reactions involved in hydrogen production as a coupled stream (chlor-alkali)

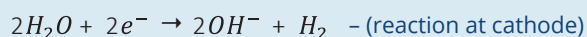
Hydrogen is produced as a by-product in a chlor-alkali setup which utilizes chlorine-alkaline electrolysis through three processes, as mentioned above.

Membrane Cell process:

The process is based on a saturated brine solution (NaCl) that is oxidized at anode, such that the chloride ions from the brine solution are converted into chlorine gas, which is subsequently captured.

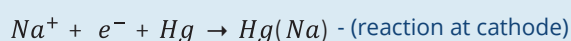


Sodium ions, left over at anode, pass through a non-permeable ion exchange membrane to the cathode which is enclosed in a concentrated caustic soda solution (30%). At cathode, water is broken down to directly produce hydrogen and hydroxyl ions. The subsequent combination of sodium ions and hydroxyl ions further concentrates the caustic soda solution, which needs to be refreshed periodically. The overall reaction produces chlorine at the anode, along with, hydrogen and concentrated caustic soda solution at the cathode.



Mercury Cell process:

This process categorized by its mercury emissions, equivalent to 0.81g per ton of chlorine production, poses an environmental hazard and as a result is gradually being phased out. It also has a relatively higher electricity demand. The procedure consists of introducing a saturated solution of brine over the cathode, which under the influence of an external electric current reduces into sodium and chlorine ions. The sodium ion, at the cathode reacts with mercury to form an amalgam, whereas the chlorine ions, at the anode, recombine to form chlorine gas.



Leftover mercury and amalgam are transported to a graphite decomposer, where pure mercury is recovered and recycled along with hydrogen and concentrated caustic soda solution, which are coproduced.



Diaphragm Cell Process:

This process is a variant of the membrane cell process. It utilizes a permeable diaphragm to separate the cathode and anode of the cell. The diaphragm, while it separates the gases, allows the brine solution to pass from anode to cathode part of the cell. The formal reactions, in this process, are identical to the membrane cell process. The resulting mixture of brine and caustic soda at the cathode, however, require separation, which often requires significant amounts of steam.

coupled with the import burden of natural gas or crude oil, along with the imperative of lowering emission intensity of various sectors, should urge policy-makers and industry alike to look at processes that decarbonize.

Table 2 Hydrogen production methods in India

Technology	CAPEX (in INR/KW)	OPEX	Efficiency	LCOH ⁸ (in INR/Kg)
Electrolysis PEM/Grid	81,400	3% of CAPEX Electricity – INR 6290/MWh	Equipment - 58% Electricity CUF – 95%	400
Electrolysis PEM ⁹ /Solar	81,400	3% of CAPEX Electricity – INR 2146/MWh	Equipment - 58% Electricity CUF – 19%	325
Electrolysis Alkaline/Grid	66,600	2% of CAPEX Electricity – INR 6290/MWh	Equipment - 67% Electricity CUF – 95%	350

⁸ The costs of hydrogen represented in the table are approximate and may vary by 10 – 15% on the higher side based on changes in cost of fuel

⁹ PEM – Proton Exchange Membrane based Electrolyser

Technology	CAPEX (in INR/KW)	OPEX	Efficiency	LCOH ⁸ (in INR/Kg)
Electrolysis Alkaline/Solar	66,600	2% of CAPEX Electricity – INR 2146/MWh	Equipment – 67% Electricity CUF – 19%	300
SMR ¹⁰ without CCS ¹¹	45,510	5% of CAPEX NG – INR 592 – 888/mmbtu	Equipment – 74% Carbon capture rate – NA	160
SMR with CCS	63,714	7% of CAPEX NG – INR 592 – 888/mmbtu	Equipment – 74% Carbon capture rate – 70%	180
ATR ¹² Without CCS	55,870	2% of CAPEX NG – INR 592 – 888/mmbtu	Equipment – 81% Carbon capture rate – NA	140
ATR With CCS	78,218	3.5% of CAPEX NG – INR 592 – 888/mmbtu	Equipment – 81% Carbon capture rate – 97%	170
Coal Gasification Without CCS	1,85,000	10% of CAPEX Coal – INR 3700 – 6660/ton	Equipment – 55% Carbon capture rate – NA	290
Coal Gasification With CCS	1,94,250	12.5% of CAPEX Coal – INR 3700 – 6660/ton	Equipment – 55% Carbon capture rate – NA	400
UCG ¹³ Without CCS	1,18,400	10% of CAPEX Coal – INR 3700 – 6660/ton	Equipment – 55% Carbon capture rate – NA	180
UCG With CCS	1,24,320	12.5% of CAPEX Coal – INR 3700 – 6660/ton	Equipment – 55% Carbon capture rate – NA	230

Source: (Ramakumar 2020) (Hall, Spencer and Dayal, et al. 2020)

Green hydrogen produced from electrolysis is a possible solution for decarbonization. The total cost of ownership of this environmentally benign method, however, is comparatively higher, currently. A just transition, which doesn't overlook the environmental externalities, requires policy alignment which would level the playing field and accelerate scale-up of hydrogen usage not only as an industry feedstock but also in other sectors which require decarbonization. The indicative (but not limiting) policy requirements are [a] formulation of a national

strategy, which India is undertaking and is likely to establish targets for hydrogen production and consumption (Economic Times 2020); [b] co-ordination on potential investment opportunities and competitive business models with industry stakeholders; [c] regulation to remove barriers to adoption of hydrogen through an environmentally benign process; [d] standardization; [e] creation of infrastructure for usage of hydrogen; [f] incentives to promote acceleration of green hydrogen production.

10 UCG – Underground Coal Gasification

11 SMR – Steam Methane Reformation

12 CCS – Carbon Capture and Storage

13 CCS – Carbon Capture and Storage

Utilization of hydrogen in the industry

Hydrogen as an energy vector or a chemical agent can be utilized [a] for transportation; [b] as a feedstock; or, [c] for heat and power for building and industry. Current uses of hydrogen in India are primarily in the form of industry feedstock and in some cases to provide process heat. Most of these processes depend on fossil fuels as a feedstock and as a result produce accompanying greenhouse gases. In 2018–19, India domestically produced and consumed ~ 5.6 million tons of hydrogen in a wide range of industrial processes. Some details of consumption are provided in sections below:

Oil Refining

The Indian refining sector has seen tremendous growth, from a single refinery with a capacity of 0.25 MMTPA in 1901 to 23 refineries with a cumulative capacity of 249.37 MMTPA as on April 2019 (MoPNG 2020). Given the evolution in demand for middle distillates¹⁴, which are expected to peak by 2030 (CRISIL 2018), a focus in the industry has also been to improve petrochemical yields, making the operations within the refinery more complex.

The production and recovery of hydrogen, in context of refining operations, is essential to processes that convert crude oils to light, high quality products (Aitani 1996). The product slate of a refinery, therefore, is closely correlated with the availability and consumption of hydrogen (Ozcelik and Karamandal 2019). Recent years have been seeing a higher demand for hydrogen from the oil refineries (Matijasevic and Petric 2016). This is a resultant of several factors such as decreasing quality of crude which are now heavier (have a high C:H ratio) and sourer (have a high sulfuric content) on one end, and, stricter emission norms which require that oil products used by end user have lower levels of impurities. Further, the use of heavier crude oils and more bottom-of-the-barrel processing has increased the hydrogen demand in hydrocracking and heavy oil hydrotreating units, while, new specifications for low-sulphur fuels signal increased hydrogen consumption in hydrotreaters (Rabiei 2012). At the same time, limits on the aromatics content of gasoline and requirements

for oxygenates have led to lower severity in the catalytic reformer and as a result hydrogen production in this unit has decreased over time.

Hydrogen, therefore, constitutes a significant portion of refinery processing and operational cost and is usually regarded as a utility within the industry (Ratan 2014). The supply and use of hydrogen, as a result, is to the extent possible maintained internally, to avoid constraints on the refinery operations. If the demand for hydrogen, however, exceeds the available supply from within the internal refining processes¹⁵, then the incremental demand is met by either increasing hydrogen plant production or through an external source. Thus, in order to optimise costs, complex mathematical models have been developed for hydrogen network optimization (Linnhoff 1993) (Kumar, Gautami and Khanam 2010) (Hallale and Liu 2001) (Alves and Towler 2002), which attempts at balancing the production and consumption of the gas within the complex.

As a result, the numbers associated with production and consumption of hydrogen in refineries, though accessible to refinery operators are not easily available in the public domain, at least in the Indian context. The data, however, can be modelled/estimated for a particular refinery based on [a] quality of crude benchmarked as the specific gravity and proportion of sulfur content; [b] the gas to distillate ratio of the refinery which can be derived from the distillate yield of the refinery; and, [c] the throughput of LPG as an end product of the refining operation (Elgowainy, et al. 2019) (A. Elgowainy 2020) (Pivovar 2018).

These data inputs have been modelled for approximately 40 refineries in the US, which has resulted in the development of a regression model that can predict hydrogen usage within the refineries in the US (Elgowainy, et al. 2019). The resultant model, however, cannot be directly adopted for Indian refineries as there is a substantial difference in the product slates, with US refineries producing refining products with a much higher G/D ratio as compared to their Indian

14 The distillate yield of Indian refineries has, as a result, increased from 74 to 80 from 2008-09 to 2018-19

15 The primary source of hydrogen within the refinery has been the catalytic naphtha reforming unit. If the hydrogen from catalytic reforming is insufficient, Additional hydrogen requirements, may be supplied by building a hydrogen plant that produces the gas by steam reforming of natural gas, LPG or naphtha and partial oxidation.

counterparts. Based on the predictions for US refineries, however, it may be estimated that the refining industry in India consumed approximately 2600 thousand metric tons (TMT) of hydrogen in 2018-19 (Details of methodology employed to calculate consumption is provided in Annexure). The crude characteristics, in the estimation, are represented by the Indian crude basket, which is the weighted average of Oman & Dubai for sour grades and Brent sweet grade (MoPNG 2020) (S&P Global Platts 2020).

Ammonia

Ammonia is amongst the largest consumer of hydrogen in India, as it is the precursor compound of nitrogen-based fertilizers. Apart from fertilizers, nitric acid is also an important derivative generated by oxidation of ammonia with air over a platinum catalyst¹⁶ (Ausfelder and Bazzanella 2016). In 2018-19, India produced 36.9 million tons of nitrogen-based fertilizers including urea, DAP and various NPK complex fertilizers (Dept. of Fertilizers 2019). Almost all hydrogen production utilized in the fertilizer sector in India is from hydrocarbon processing, which utilizes naphtha, natural gas or coal as feedstock. The steam reforming process is in fact the preferred option in case of urea, which subsequently utilizes the CO₂ co-produced in the synthesis gas stream. The alternative to steam reforming is electrolysis, which generates hydrogen thereby producing 'green ammonia'. This method, however, is not the favored choice of the industry, limited by cost constraints. In India, Nangal fertilizer plant was the only plant based

on a carbon-neutral electrolysis process which operated for almost three decades – from 1961 to 1990. The plant produced ammonia and calcium ammonium nitrate. The electrolysis plant, however, was systematically decommissioned, since 1974, to eventually be replaced by reforming process utilizing feedstocks such as naphtha and heavy oil, which, as mentioned above, coproduce CO₂ (World Bank 1981), an important input for the production of Urea. The electrolysis setup for the plant, which successfully operated over a period of 30 years was supplied by German firm Linde in 1962 (NTI n.d.).

Ammonia, in India, almost exclusively is produced by the Haber-Bosch process, a catalytic process where hydrogen and nitrogen are passed over an iron catalyst at elevated temperature and pressure. Air is directly or indirectly used as the source of nitrogen. In the latter case nitrogen is utilized in its pure form fed through an associated air separation facility. Hydrogen, on the other hand is supplied as synthesis gas through a steam reforming unit which forms an integral part of the ammonia plant.

The ammonia production usually involves the following three processes – [a] The gasification/reforming of the feedstock to produce a stream of synthesis gas to feed the ammonia synthesis plant. In 2018-19, India used 460.4 TMT of furnace oil, 351.6 TMT of Naphtha and 14,987 MMSCM of natural gas as feedstock for fertilizers (MoPNG 2020); [b] The purification of gases and adjustment of hydrogen-nitrogen ratio prior to ammonia production. The purification includes removal of sulfur, carbon-di-oxide and traces of carbon oxides

Table 3 Hydrogen consumption in fertilizer sector in India (2018-19)

Particulars	N component	P component (P2O5)	K component (K2O)	Production in India (2018-19)	H2 Consumption (2018-19)
	% age	% age	% age	Lakh Metric Ton (LMT)	Thousand Metric Ton (TMT)
Urea	46%			240.23	2375.40
DAP	18%			46.5	177.91
NPK1 Complex fertilizer	20%	20%	0%	34.67	149.05
NPK2 Complex fertilizer	15%	15%	15%	4.78	15.41
NPK3 Complex fertilizer	17%	17%	17%	0.83	3.03
NPK4 Complex fertilizer	10%	26%	26%	18.86	40.54
NPK5 Complex fertilizer	12%	32%	16%	10.52	27.14
NPK6 Complex fertilizer	14%	35%	14%	3.07	9.24
NPK7 Complex fertilizer	19%	19%	19%	0.66	2.70
NPK8 Complex fertilizer	28%	28%		5.58	33.58
NPK9 Complex fertilizer	16%	20%		1.32	4.54
NPK10 Complex fertilizer	14%	28%	14%	0.02	0.06
NPK11 Complex fertilizer	24%	24%		2.25	11.61
Total H2 Consumption in the fertilizer sector in India in 2018-19					2850.21

Source: estimated from (Dept. of Fertilizers 2019)

using a scrubber, absorber and methanator respectively; and, [c] the ammonia synthesis process which produces ammonia from the ammonia synthesis gases.

The process is an exothermic equilibrium reaction involving volume reduction and is favored by high pressures and low temperatures. Further, only partial conversion is achieved in a single pass, hence, the produced ammonia is condensed by refrigeration, leaving liquid ammonia and remaining gas mixture (hydrogen and nitrogen in the gas phase) which is fed back into the reactor. The separated liquid ammonia is expanded and stored or processed further, for example in a urea plant (Pattabathula and Richardson 2016). For economic reasons ammonia plants are usually large-scale plants (BEE 2018).

Table 4 estimates the consumption of hydrogen within the fertilizer industry in India in 2018-19. The estimates are based on stoichiometric calculation, primarily by estimating the N component of various fertilizers which is usually in the form of ammonia, and subsequently by estimating the hydrogen requirement for production of ammonia. One metric ton (MT) of ammonia production requires approximately 0.18 MT of hydrogen (Ausfelder and Bazzanella 2016) which may be derived from various feedstocks. In essence, 1 MT of ammonia can be produced from either [a] 32-38 mmBtu of natural gas; or, [b] 0.9 MT of Naphtha; or, [a] 1.05 MT of furnace oil; or, [d] 1.9 MT of coal; or, [e] 8,000-12,000 kWh of electricity needed for electrolysis of water (Nutrien 2019).

Methanol

Methanol, a clear liquid chemical that is water soluble and is readily biodegradable, comprising of four parts hydrogen, one part carbon and one part oxygen, is another large consumer of hydrogen in the chemical industry. Globally, with a production of 98.9 million MT (Methanol Institute 2020), its hydrogen consumption is only second to ammonia. By comparison, its production is relatively low in the case of India, which produced 271.93 TMT in 2018-19 utilizing 57% of its installed capacity of 474.30 TMT (Dept. of Chemicals and Petrochemicals 2020). Conventionally, methanol is produced from synthesis gas generated by reforming process or coal gasification. The production model in the conventional sense, therefore, is biased towards large production facilities (Bergins, et al. 2015). In India

there are five major producers of methanol, of which Gujarat Narmada Fertilizer Company (GNFC) has the largest installed capacity. India's domestic production, however, does not meet its demand for methanol, which is substituted by import. In 2018-19, India imported 1.9 million MT of methanol (Dept. of Chemicals and Petrochemicals 2020).

Methanol, though suggested to play a central role as a replacement for transportation fuel¹⁷ in a proposed methanol economy (NITI Aayog 2018), currently, is utilized in the production of several high-volume chemicals¹⁸ such as formaldehyde, acetic acid, methyl tert-butyl ether (MTBE), methyl methacrylate, dimethyl terephthalate (DMT), inter alia. Formaldehyde, which is utilized to produce paints laminates and plywood generates almost 40% of India's methanol demand (S&P Global 2020).

Traditionally, methanol can be produced by either using light feedstock such as natural gas or heavier feedstock such as coal or biomass. In case of the former, the feedstock is desulfurized and reformed with steam and oxygen at elevated temperature and pressures. The resulting syngas is compressed and transferred to methanol-synthesis unit. Additional hydrogen, required by the process in form of a stream into the synthesis unit, is largely supplied by recycling the gas after separation of methanol from remaining gases. For heavier feedstocks, however, an external hydrogen supply is required as they are unable to meet the stoichiometric ratio (of hydrogen to carbon) for optimum synthesis conditions.

The most economic process followed by the industry is a combination of steam reforming and autothermal reforming. In this combined process, a fraction of desulfurized feed gas is steam reformed at high pressure and temperatures in order to provide the necessary hydrogen. This gas stream is then combined with the non-reformed feed gas – produced from gasification of solid feedstock, and together subjected to autothermal reforming. In both the above cases, the reactions of syngas to methanol are highly exothermic and the overall economics of a methanol plant is critically dependent on efficient heat recovery and management.

The stoichiometric ratio favored by the process is two parts of hydrogen and carbon-di-oxide gas stream with one-part carbon monoxide and carbon-di-oxide gas stream. In gravimetric terms, approximately one ton of methanol requires 0.19 tons of hydrogen for synthesis

17 For comparison, [a] a 61 L compressed hydrogen at 700 bar, with a weight of 43 kgs, combined with a fuel cell with an overall efficiency of 62% provides 52.8 MJ; [b] 16 pieces of 840 Wh lead acid batteries, with a combined weight of 461 Kg, with a conversion efficiency of 90% produces 48 MJ; [c] a 7 L methanol tank with a weight of 5.5 Kg, combined with a methanol reformer and fuel cell with an overall conversion efficiency of 40% provides 45 MJ; [d] 1628 pieces of 10 Wh 18650 Li-ion cells, with a combined weight of 73 kgs with an overall efficiency of 77% provides 45 MJ (DTI 2018).

18 Methanol, apart from the aforementioned chemicals is also used to produce Methanethiol (Methyl Mercaptan), Methylamines, Methyl Chloride (Chloromethane), alternative fuels such as in gasoline blending, biodiesel and DME. It is also utilized for energy generation in fuel cells and for its conversion into olefins.

(Dolan 2019). In 2018–19, therefore, India consumed 51.67 TMT of hydrogen domestically for the production of methanol and imported 361 TMT of hydrogen in the form of methanol for consumption by its various chemical industries.

Apart from its use in the chemical industry, methanol in India is receiving considerable attention (Saraswat and Bansal 2016) for the role it can play [a] as a substitute for transportation fuel in automotive and marine sectors; [b] its use in the derivative DME which is most commonly used as a replacement for propane in liquid petroleum gas (LPG) and can also be used as a replacement for diesel fuel in transportation; [c] as a key component in the process of making biodiesel, where it is used to convert the triglycerides in different types of oils into usable biodiesel fuel; [d] as a key component in the development of different types of fuel cells – which are quickly expanding and are expected to play a larger role in our energy economy. They range from large-scale fuel cells to power vehicles or to provide back-up power to remote equipment, to portable fuel cells for electronics and personal use (Sonde 2020) (RIL 2020); [e] as an attractive emerging fuel for electricity generation. In fact, conversion of power to methanol provides renewable energy operators flexibility where surplus power can be used to produce green methanol which can be stored and transported for its reconversion to electricity (Dolan 2019); [f] its use in industrial boilers to provide industrial process heat and its use at the household scale where methanol can be used in cookstoves to replace LPG and solid biomass based fuels (Methanol Institute 2020).

Other uses and applications of hydrogen in chemical industry

In India, currently, hydrogen is largely consumed in oil refining, production of ammonia and nitrogen-based fertilizers. Hydrogen is, however, used as feed in many other smaller chemical processes (Ausfelder and Bazzanella 2016). Production of synthetic fuels from gasification of coal followed by Fischer-Tropsch synthesis is another large-scale process, which may become a major consumer of hydrogen in the near future, considering the large availability of coal resources¹⁹ in India (Padmanabhan 2019) (IHS Markit 2019). Other processes which require hydrogen are hydrogenation reactions that are commonly used and enter the chemical value chain at various positions, for example in the production of MDI and TDI (precursors for subsequent polyurethane production), saturation of animal/vegetable fats in the food processing industry etc.

Stationary power

Hydrogen, at a very small scale is being used by industry to generate power in India, especially in the remote areas which do not have access to 24/7 electricity from the grid. Within this sector, the telecom industry has been, in the past, regarded as a possible consumer.

Table 4 Sustainability initiatives in energy consumption by major tower companies in India.

Service Provider	Description	Market Share	Initiatives
Indus Tower	Incorporated in 2007, Indus Towers is a joint venture towerco founded by Bharti Infratel, Vodafone India, Aditya Birla Telecom (Idea). In 2018, the towerco announced plans to merge with Bharti Infratel, which was approved by the latter's board on 1st September 2020. The merger would create the largest towerco in India and one of the largest in the world. ²¹	130416 towers	<ul style="list-style-type: none"> Renewable energy sources consisting of solar and biomass have been deployed at over 1100 sites across India. The company plans to scale up its deployment to cover 50% of all telecom sites by 2021 Since 2011, the company has converted 71,191 sites to green sites by removing diesel generators and deploying battery banks in their stead The company does not mention any sites being currently served by fuel cells

¹⁹ India is the world's second largest consumer of coal and has significant coal resources of 360 billion metric tons, as of 2017.

Service Provider	Description	Market Share	Initiatives
Reliance Jio Infratel	Reliance Jio Infratel utilized the base built by Reliance communications. It has one of the largest market shares. Reliance has signed a binding agreement with Brookfield Infrastructure partners LP and its institutional partners for investment in the units to be issued by the Tower Infrastructure Investment Trust (InvIT).	175,000 towers	<ul style="list-style-type: none"> The company has developed first fully indigenous prototype of a High Temperature-Polymer Electrolyte Membrane (HT-PEM) fuel cell system comprising fuel cell stack, methanol reformer, balance of plant and control system that has been built and is presently being tested on simulated Jio towers. In the long-term fuel cells will be supplied by renewable hydrogen and replace current methanol reforming to produce in-situ hydrogen. Reliance Jio has considerably reduced the use of diesel generators and has installed Lithium-Ion batteries on 80% of its sites. The operator is also working on utilising either solar based solutions (with batteries) or methanol fuel cell systems for the remainder (20%) of its sites with long power outages or which are completely off-grid.
American Tower	American Tower, headquartered in the US, is to date the largest independent towerco in the world, operating a global portfolio of over 170,000 sites. It has a growing presence in India, where through its M&A activity, began with the acquisition of 1,730 towers from XCEL Telecom in 2009, continued with the acquisition of 4,450 towers from Essar Telecom in 2010, and culminated in the acquisition of Viom Networks and their 42,200 towers, announced in October 2015. In 2018, American Tower added 20,100 towers to its growing portfolio from Vodafone and Idea.	75,113 Towers	<ul style="list-style-type: none"> 23,000 sites of ATC are diesel free sites as per industry standards The company is generating 13 GWh of energy from solar resources, with 10 MW of installed capacity in Bihar, Uttar Pradesh, Odisha and West Bengal. Through the use of battery banks, the company has converted approximately 2200 sites to green sites. The company does not mention the use of hydrogen based fuel cells for energy generation.
Bharti Infratel	Bharti Infratel is one of the pioneers of shared telecoms infrastructure, Bharti Infratel was created in 2007 as an independent tower company to provide compelling capex saving opportunities to telecom service providers, while optimally utilising Bharti Airtel's large tower base in India. As of September 2020, its merger with Indus Towers has been approved by the company's board	95,372 Towers	<ul style="list-style-type: none"> The company has 45,752 tower sites as green sites using high-end VRLA batteries and Li-Ion batteries. The company has had successful trials of Piped Natural Gas (PNG) Generator in the Uttar Pradesh West Circle where a gas pipeline was available in contrast to the conventional diesel based energy The company has installed 4 fuel cell based sites, as a pilot project, in the north-eastern states of India
GTL Infrastructure	GTL Infrastructure, a publicly-listed tower company in India, was founded in 2004 and listed in 2006, the company began expanding its portfolio in 2008 and acquired 17,500 towers from Aircel. However, the cancellation of 122 operator licenses by the government, slow uptake of 3G and price wars between service providers have left GTL Infrastructure with a heavy debt burden.	27,209 Towers	<ul style="list-style-type: none"> As of March 31, 2020, the total number of operational diesel free sites were 2,869. In 2015, UK Based Intelligent energy deployed fuel cells in partnership that claimed to have delivered 10 MWh of clean and efficient power to the company's telecom towers. Post 2015, the company has deployed li-ion based battery banks to power the telecom towers, though it is still exploring avenues utilizing fuel cells

Source: (Indus Towers 2020) (Tower Xchange 2019) (RIL 2020) (ATC India 2019) (Bharti Infratel Ltd. 2020) (GTL Infrastructure 2020) (Intelligent Energy 2016)

Telecom Sector

The sector has experienced phenomenal growth in the past decades, growing from a subscriber base of 36.3 million and a tele-density of 3.58% in 2001 to 1.18 billion with a tele density of 90.1% as of 2019 (Department of Telecommunications 2020). The growth has also seen a transition from a voice-centric to a data heavy consumption pattern, with a non-existent internet base in early 2000's to 636 million internet subscribers in 2019. This large subscriber base is served by a network of 5,96,000 telecom towers²⁰ (COAI 2020). These towers, which have played a pivotal role in the unhindered growth of India's telecom sector, consume 3.2 billion litres of diesel per annum, emitting around 8.6 million tons of CO₂ (Energy Management, telefocus 2019).

The financial cost of energy (notwithstanding the environmental costs), which includes the high consumption of diesel, constitutes 35% of the total revenue of the tower industry (Kapoor, et al. 2019). The industry, thus, with a goal of improving economics and reducing carbon emissions by 40% by 2022-23 (with 2011-12 as the base), has been working towards implementing solutions (table 5) that are reliable, cost effective and environmentally benign (GOI 2019).

A review of documents available in the public domain suggest that within the current settings, battery banks based on valve regulated lead acid (VRLA) and lithium-ion (Li-ion) batteries are the preferred solution adopted by tower companies (towerco) in India. These battery banks are coupled with either available grid electricity or with renewable based power generation. For example, Ascend Telecom – a towerco with around 6355 telecom towers in India, optimises the use of electricity from the grid by storing it in VRLA batteries while using Li-ion batteries only for auto-changeover between grid and genset/VRLA based battery bank (Tower Xchange 2019). A combined use of the aforementioned solution allows the company to provide the lowest TCO to mobile network operators (MNO).

Fuel cells, based directly on hydrogen or on methanol, have advantages in terms of being lightweight and noise free. It is also proven as a complete low footprint solution which has no requirements of any ancillary units such as a backup generator and thus can operate as a stand-alone system. These advantages, however, are outweighed by its higher costs, especially in an over-competitive market such as the telecom sector in India. Fuel cells have a comparatively higher TCO as compared

to utilizing battery banks for energy storage. This is largely due to [a] comparatively higher upfront capital expenditure required for a fuel cell solution; [b] low availability of fuel in the form of hydrogen/methanol; and [c] complex distribution ecosystem of the fuel due to lack of an established market. These barriers to adoption of hydrogen as a clean energy vector are reflected in the solution's inability to scale-up within India even after several promising starts such as Tata Teleservices efforts for installing and maintaining fuel cell systems as back-up power supply for telecom towers along with US based M/s Plug power culminating in 200 sites in India with HPCL as the fuel supplier (Plug Power 2009) (TTML 2020), ACME Telepower Group's tie-up with Canada based M/s Ballard Power systems and M/S Dantherm for fuel cell installation in telecom sector which resulted in 30 installations across India in 2012 (US DoE 2014), UK based Intelligent Energy's tie up with GTL Infrastructure to install several PEMFC in telecom sector (Intelligent Energy 2016), and initiatives of Alteryg (Alteryg 2012) and ReliOn which were also targeting India for fuel cell application in telecommunication towers (GoI 2016).

With a focus on decarbonization of the sector, further permeation of hydrogen-based energy systems would require policy levers such as [a] reduction of supply uncertainty, especially of fuel which makes most investors wary of funding new hydrogen projects. This can be overcome, on the other hand, in case of integrated companies such as Reliance (table 5) which can assure supply of fuel from its petrochemical units and thus drive investments in the domain; [b] creation of ecosystem which allows the deployment of complementary solutions with positive spill-over effects. This can be undertaken for the telecom sector, which is already evaluating its potential in adjacent business segments such as providing power as a service in underserved areas (Rockefeller Foundation 2012), create space for warehousing, cold storages and collection points for goods, and, provide charging infrastructure for electric vehicles (Kapoor, et al. 2019); and, [c] incentivization of utilizing a hydrogen backed energy system that would scale applications in the telecom sector to reach critical tipping points, post which the cost of deployment and ownership would see a sharp decline, as has the case been with solar deployment in India (Hydrogen Council 2020) (TERI 2020).

Hydrogen in Transport

In 2015, transport accounted for 17% of the total energy demand in India and emitted 251 Mt of CO₂ equivalent emissions (Mohan, et al. 2019) (DST 2020). Almost all²³

20 As of December 2019, DoT reported 5,86,379 telecom towers (DoT 2020).

21 The data represented, here forth in the table, is for Indus Towers, as consolidated data is currently unavailable

22 Data as of Q2 of 2019

23 98.5% of the entire energy demand was met by either diesel or petrol. The sector consumed 99.6% of all petrol and 70% of all diesel refined in the country. The production of petrol and diesel are inexorably linked to crude imports.

energy demand for transportation in India is currently met by petroleum products. The sector, as a result, was responsible for 39% and 30% of all NO_x and PM 2.5 emissions, respectively, as well (DST 2020) (Guttikunda, Goel and Pant 2014).

The demand for transportation services, either passenger or freight, are intricately linked with the ongoing levels of economic activity and changing demographics in any country (Gupta and Garg 2020). As growth is envisaged, in the case of India, in both of these parameters, the emission levels from the sector are also projected to increase, almost three-folds by 2050 (Gupta and Garg 2020), if effective measures to decarbonize mobility are not put in place.

Meeting the growing demands and regulating emissions may not, however, be mutually exclusive. Multiple technological pathways exist within the contemporary settings that should be explored and implemented. A large repository of research suggests that a combination of electrification and use of hydrogen as fuel for short distances and long-distance travel, respectively can facilitate this decarbonization (Hydrogen Council 2020) (Hydrogen council 2017) (IEA 2019).

Demand outlook in transport

The movement of goods and people in India is dominated by road transportation, where two/three wheelers, cars, buses and trucks utilizing internal combustion engines accounted for 90% of the passenger movement (17,832 billion passenger km) and 59% of freight (2,260.2 billion tons km) (MORTH 2019). Movement by road, as a result, was responsible for 88.4% of all CO₂ equivalent emissions in the sector, with other modes, namely aviation, rail and navigation contributing 7.3%, 3.9% and 0.4% respectively (Mohan, et al. 2019).

India also has one of the largest rail networks, spread over 68,400 route km, and ninth largest waterway globally with 14,500 km of navigable inland waterways consisting of canals, rivers, backwaters and creeks (Indian Railways 2019) (NITI Aayog and Rocy Mountain Institute 2018). Though, as indicated by modal shares of freight transport, only 35% of the freight demand is met by rail, and of the remainder, 6% is met by waterways. Similarly, in passenger movement rail and air together accounted for only one-tenth of the total demand.

The modal split, especially in case of freight movement, is contrary and unlike other countries which share similar geographies and freight compositions, such as China and US, where the share of road in freight load is much lower at 30 – 40% (NITI Aayog and Rocy Mountain Institute 2018). Rail and waterway transport, both, are

considered energy efficient and less emission intensive, with the potential of cutting pollution by 77.4% and emissions by 43.8% (Kumar and Anbanandam 2020), when compared to a scenario which is road dominated. Government of India, with this in mind, launched its draft national logistics policy in Feb 2019 which aims to align freight movement with international benchmarks of 25–35% share of road, 50–55% share of railways and 20–25% share of waterways (WRI India 2020).

Hydrogen in transport in India

India is heavily dependent on crude oil imports, which forms the basis of all transport services today. In 2018–19, India had an outlay of USD 112 billion for import of crude. The country, on the other hand faces large developmental challenges and spent USD 75 billion, during the same period, on national social and developmental programmes. Reducing dependence on petroleum products, a majority (approximately 47%) of which is consumed by transportation and mobility, would therefore ease up capital which may then be apportioned to programmes/schemes which facilitate development. Taking this into account, several forward-looking policies have been introduced, such as Faster Adoption and Manufacturing of (Hybrid) and Electric Vehicles (FAME), Corporate Average Fuel Economy (CAFÉ) standards, inter alia in the past to improve energy efficiency, curb emissions and promote energy security. The aforementioned schemes and standards encourage the adoption of efficient mobility solutions such as electric vehicles by way of offering incentives and also by way of establishing necessary infrastructure.

India, along with pushing for electric mobility, has also initiated steps which aim at adopting hydrogen as a fuel, but still has a long way to go to achieve satiety in regulations, efficacious technology and cost efficiencies (Cheema 2019). This is evident from the poor performance against targets set towards Green Initiatives for Future Transport (GIFT) under National Hydrogen Energy Roadmap. The targets set for 2020 aimed at [a] One million hydrogen powered vehicles on road, against which less than 100 are currently on road, most of which are still in demonstration phase; [b] 750,000 hydrogen powered two/three wheelers on road, of which less than 50 are currently operational; [c] 100,000 buses/vans that are powered by hydrogen of which less than 10 exist (MNRE 2016). Most of the progress, summarized in the table below, has been a direct result of public finance with private initiatives being limited to industry participation as knowledge partners. This may be attributed to low levels of national ambition, absence of requisite regulations and a lack of appropriate signaling mechanisms that are necessary to catalyze demand.

Table 5 Initiatives in India that promote hydrogen as a fuel in Transport

SL. No.	Institution(s)	Remarks
1	Indian Oil Corporation Limited Setting up of Hydrogen dispensing station	The demonstration project, commissioned in 2008-09, has an electrolyser with 5 Nm ³ /hr hydrogen production capacity (about 11 kg/day). Hydrogen produced from the electrolyser is being blended with CNG for use in demonstration and test vehicles. The project aims to acquire experience and knowledge in handling hydrogen for use in vehicles and also provide field performance feedback on hydrogen-CNG blends as a fuel in automobiles.
2	Society of Indian Automobile Manufacturers (SIAM), Tata Motors, Ashok Leyland, Eicher Motors, Mahindra and Mahindra and Bajaj Auto Field trials of automobiles with H-CNG	Three buses, two cars and two three wheelers were part of the project and were used for field trials based on 18% hydrogen (by volume) blended with CNG. The project involved modifications in engine and fuel injection system. Existing hydrogen-CNG dispensing station set up by India Oil Corporation at Faridabad is currently being used for filling hydrogen-CNG blends in the test vehicles. The project helped in optimization of engine performance and blend ratio of hydrogen with CNG. The criteria for optimization was high efficiency and lowest NO _x emissions. The project demonstrated that hydrogen up to 20% (by volume) can be blended with compressed natural gas (CNG) for use as an automotive fuel
3	IIT Delhi, Mahindra & Mahindra, Air Products Development of Hydrogen fuelled three wheeler	Hydrogen powered three-wheeler 'HyAlfa' was developed by the consortium and launched in 2012. The project was funded by United Nations Industrial Development Organization (UNIDO). Exhaustive lab tests were carried out on the vehicular engine in the Engines and Unconventional Fuels Lab of Centre for Energy Studies under varying operating conditions. The test results provided the technical guidelines and thus the existing designs of engines were converted to run on hydrogen. Based on IIT Delhi recommendations, Mahindra had developed hydrogen operated three wheelers for passenger and cargo version vehicles. Limited field trials demonstrate that the hydrogen fuelled three wheelers provide a mileage of 85 km per kg of hydrogen consumption
4	IIT BHU, Varanasi Development of Hydrogen fuelled two wheeler	The project was funded by MNRE and DST. It demonstrated the successful operation of hydrogen powered motorcycle through combustion of hydrogen aimed at 100 – 175 CC, 4 stroke vehicles. The project employed timed manifold hydrogen injection in the internal combustion chamber. Hydrogen was stored in in-house fabricated AB5 type (Mn:Ni:Fe) hydride with ~ 2 wt% storage capacity mounted in vehicle exhaust coupled heat exchanger tank. The range of the vehicle was tested for 60-80 km.
5	IIT Guwahati Metal hydride-based hydrogen storage system at STP	Under the project, IITG designed, fabricated several pre-industrial scale prototypes of hydrogen storage reactors of about 1000 – 22000 L capacity for automobile and industrial applications, and their performances were tested at different operating conditions. Metal hydrides were utilized for storage. They are compounds formed by the reversible chemical reaction of hydrogen and metallic atom. The reaction can be summarised as when specific metallic atoms are exposed to hydrogen near ambient conditions, the metal atoms absorb enormous amount of hydrogen by releasing heat (Exothermic reaction) spontaneously, called absorption process. When the heat is supplied to the metal hydride molecules, the hydrogen gets separated from the metal hydride and becomes free hydrogen (Endothermic reaction), through a process called desorption.
6	International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) Development of PEMFC for automotive application	ARCI's Centre for Fuel Cell Technology, since 2007, with the objective of developing Polymer Electrolyte Membrane fuel cells (PEMFC) in its entirety and demonstrate its application in Decentralised power generation systems and transportation applications, has developed process know-how for the various components used in the fuel cell stacks, built fuel cell stacks of capacity up to 10 kW, demonstrated fuel cell based power packs with the required Balance of systems in Decentralised power generation and demonstrated fuel cells in electric vehicle for use as range extenders. The R&D activities are aimed at performance improvement and cost reduction
7	Mahindra & Mahindra (M&M) Development and Demonstration of Diesel Hydrogen Dual Fuel SUV	Dual fuel system, retrofitted in existing vehicles, feeds the internal combustion engine with combination of two fuels, hydrogen and diesel in this case. It is aimed at reducing the consumption of diesel. The innovations consisted of [a] developing an electronic control design system which controls the compression ignition engine electronically thereby providing the needed flexibility for an alternative fuel – hydrogen; [b] dual fuel control module which is an auxiliary electronic control unit which interfaces with the engine control module and controls the fuel injected into the engine. The demonstration vehicle utilizes hydrogen at 200 bar pressure and can operate on either just diesel or on a combination of fuels with little input from the operator. The project demonstrated that a substitution of 45% diesel with renewable hydrogen is possible with benefits of reduction in CO ₂ , CO, HC, PM by 25%, 68%, 68% and 30% respectively. The energy efficiency is also enhanced in the process by 5-10%.

SL. No.	Institution(s)	Remarks
8	IIT Delhi, M&M Development and demonstration of hydrogen powered mini bus with multicylinder Spark Ignition (SI) engine	Hydrogen as fuel performs well in Spark Ignition (SI) engine as it has multiple benefits including a wide range of ignition limits, good mixing characteristics with other fuels, inter alia. The project aims at developing a well optimised hydrogen ICE that would improve energy efficiency and control emissions. The project has been tested on a H2 mustang engine and required the development of several components including turbochargers, piston, injectors, regulators etc. The demonstration vehicle is proposed to include six hydrogen cylinders of 70L water capacity which utilizes hydrogen compressed at 200 bar. The developed IC engine has been introduced into Mahindra's tourist/model minibus. Two vehicles have already been built and calibrated which are currently undergoing field trials of 100,000 km.
9	CSIR, KPIT, NMITLI, and M&M Development of indigenous Fuel Cell Electric Vehicle (FCEV)	The consortium has converted an Mahindra eVerito into an FCEV. The prototype runs on a hydrogen fuel cell stack developed in-house at CSIR's National Chemical Laboratory in Pune, Maharashtra. This hydrogen fuel cell stack is a 10 kWe Low-Temperature Proton Exchange Membrane Fuel Cell (LT-PEMFC). The membrane electrode assembly of the PEM fuel cell technology was contributed by CSIR. KPIT brought its expertise in stack engineering, which included light-weight metal bipolar plate and gasket design, development of the balance of plant, system integration, control software and electric powertrain. CSIR and KPIT retrofitted the 72-volt battery-electric platform of the Mahindra eVerito with a hydrogen fuel cell stack. The Mahindra eVerito hydrogen fuel cell prototype features a Type III commercial hydrogen tank that can store around 1.75 kg of H2 at about 350 bar pressure. It has a range of approximately 250 km when driven at 60-65 km/h speeds.

Source: (DST 2020) (MNRE 2016) (Electricvehicleweb 2020) (ARCI 2020) (IITG 2018)

As India develops and moves towards a low carbon economy it would necessarily have to take into account the critical role of transport sector in mitigating climate change and informing future Nationally Determined Contributions (NDC). This would, however, require [a] structural changes, such as introducing a modal shift towards more efficient transportation modes such as railways or waterways for both freight and passenger movement; [b] generating public awareness towards promoting sustainable behavioral changes, originally ushered in response to the COVID 19 pandemic, such as increasing share of work from home, use of teleconferencing wherever possible, and a deliberate shift to public transport; [c] creation of infrastructure such as Mass Rapid Transit System (MRTS), Dedicated Freight Corridors (DFC), sidings/freight terminals, charging stations, hydrogen refueling stations etc.; [d] encouraging trends which allow Mobility as a Service (MaaS); [e] introducing regulatory and policy changes that promote an aggressive switch to green vehicles – a combination of Battery Electric Vehicles, FCEV and vehicles that operate on blended fuel, increase fuel and vehicle efficiency etc. (Gupta and Garg 2020) (Kumar and Anbanandam 2020) (Hydrogen Council 2020) (NITI Aayog and Rocy Mountain Institute 2018).

Evidence based on envisaged technological improvements, cost effectiveness and user acceptance reiterate a combination of electrons²⁴ and protons²⁵ to deliver deep decarbonization needs of the transport

sector (BNEF 2020). Electricity, with assumptions of grid being available and stable, may be relatively efficient and cost effective in certain use cases such as urban mobility, sub-urban rail, dedicated freight corridors etc. Hydrogen, on the other hand, becomes feasible in use cases where electrification is either not possible or is limited due to weight restrictions imposed by an electric solution. These use cases may include heavy road transport, aviation and waterway navigation (Turner, et al. 2020). Energy-economy models, based on Indian data and realities, suggest a penetration of 10–18% by share of hydrogen-based vehicles, by 2050 which may in turn represent modal shares of up to 4000 BPKM and 2400 BTKM (Gupta and Garg 2020), which are substantial compared to current use. Both electrification and use of hydrogen for mobility would, however, assume a considerable reduction in the carbon intensity of the grid.

Based on the aforementioned results, if hydrogen is to be utilized at scale, India would have to move beyond demonstration and pilot projects. It would, apart from the structural changes mentioned above, require improving the pace of technological improvements along with providing political-administrative support by way of public finance, investment and regulation (Singh, et al. 2015) (Gupta and Garg 2020). In addition, interventions in form of issuing appropriate code and standards are required, such that the marketplace perceives a sense of consistency which in turn would encourage private participation and deployment.

24 In the form of electricity

25 In the form of hydrogen utilized in fuel cells

Standards in addition to continuity of policy would provide a pathway to Original Equipment Manufacturers (OEM) and allow technologies which are at laboratory demonstration level to progress towards commercialization. This would include certification guidelines and regulations by Petroleum and Explosives Safety Organization (PESO), Bureau of Indian Standards (BIS) and MORTH respectively, with regard to ensuring quality of hydrogen production and consumption, enabling large scale hydrogen storage for use in vehicles, developing requisite infrastructural facilities such as refuelling systems and providing requisite licenses and certificates to operators (DST 2020). These further need to be developed in line with technical and environmental standards notified by International Organization of Standards and other countries and regions such as EU, Japan and Korea.

Hydrogen in Energy Intensive industry

Hydrogen, though niche and nascent, both as a reducing agent and as an energy carrier, also finds its utility in a socially, economically and environmentally relevant industrial sector - iron and steel. The sector, however, is currently biased towards coal as a feedstock and fuel. It represents a duality. On one hand, a posteriori evidence from industrialized countries suggests that economic growth is concomitant with increasing levels of steel consumption. On the other hand, an increase in consumption, if fulfilled domestically through incumbent technologies, signals a substantial increase in emission intensity. In addition, the sector is also dominated by large industrial set-ups, characterized by long lifetimes and high trade intensity. This introduces a sense of inertia when it comes to adopting new technologies that aim at a long-term transition, as against incremental improvements in energy efficiency, to decarbonize the sector.

Iron and Steel

India, with approximately one-tenth production capacity of China, is the second largest steel producing nation in the world. In 2018-19, the sector employed 2.5 million people, had an energy demand of 72 million tons of oil equivalent (Mtoe) and emitted 242 million tons of carbon-di-oxide. The resultant production of 111.2 Mt of finished steel translated into apparent consumption of 74.3 kg per capita, which is approximately 32% of the world average (World Steel Association 2020) (Hall, Spencer and Kumar 2020). The low per capita consumption of steel illustrates that current levels of access to building and infrastructure, mechanical equipment usage, automotive ownership, inter alia in India is still low relative to that of high-income countries. Further, it also indicates that if India is to

follow the development path adopted by most of the industrialized nations, where determinants of steel demand are the rate of investment and industrialization in the economy, then it would need to raise its steel consumption manifold (Hall, Spencer and Kumar 2020). Taking this into account, the Ministry of Steel has set a target for steel production capacity of 300 Mt for 2030-31, which represents a steel consumption of 158 kg per capita per annum (GOI 2019).

Moving beyond 2030, India in 2050, is predicted to be one of the few world regions where steel demand still wouldn't have peaked. Under Business as Usual (BAU) conditions, TERI estimates that the domestic manufacturing capacity of steel, in order to meet demands for new buildings, roads, bridges, agricultural implements, automobiles etc., would increase five folds to 528 Mt/annum with an apparent steel consumption of 295 kg per capita (Hall, Spencer and Kumar 2020). This, if fulfilled through technologies reliant on coal, would substantially increase emissions from the sector to approximately 840 Mt CO₂, assuming that the industry curtails the specific CO₂ emissions to 1.6 t/tcs from 2.26 t/tcs, currently prevalent in best-in-class manufacturing set-up at TATA Steel, Jamshedpur (GOI 2020).

In order to avoid such a scenario, India, therefore, needs to ensure that steel plants built in the near future anticipate and enable deep decarbonization needs of the sector and that the involved stakeholders do not inadvertently commit themselves to a technology pathway which is inherently polluting. If, however, viewed from another perspective, India, from where it stands now is presented with a unique opportunity. It can prepare the sector for a future where responsible sourcing and carbon border adjustments are already being actively considered, by leading global production of low carbon steel.

This would require formulation of forward-looking policies that go beyond incremental measures to improve energy, resource and carbon efficiency, which already exist in India in the form of the Perform Achieve and Trade (PAT) Scheme, the Steel Scrap Recycling Policy and the Draft National Resource Efficient Policy. These, by virtue of being cost effective and recoverable over short payback periods are preferred by the industry incumbents. For example, 158 iron and steel units participated in the first cycle of PAT that achieved a saving of approximately 8.5% in terms of overall energy demanded per annum by these units (Hall, Spencer and Kumar 2020). It is further estimated that if energy and resource efficiency is aggressively pursued through adoption of Best Available Technologies, the sector would, at best, be able to lower its emissions by a maximum of 35% as compared to BAU in 2050. Thus, these incremental measures are certainly necessary,

but not enough to ensure a trajectory consistent with limiting warming to less than 2°C.

In a changing climate, therefore, and when India is considered to be one of the most at-risk countries due to its perceived impacts, adoption of new low carbon technologies becomes important. This further takes centre stage, given that the Indian iron and steel sector is relatively energy intensive compared to international benchmarks and is expected to expand substantially. The sector, currently, relies heavily on coal for both fuel and feedstock and is responsible for 13% of India's total coal consumption, resulting in large quantities of greenhouse gas emissions (Hall, Spencer and Kumar 2020).

Coal is ubiquitously utilized in both of the two prevalent routes for steel production in India, namely [a] the Oxygen route; and [b] the Electric route. Oxygen route is the conventional integrated route consisting of a Blast Furnace which processes iron ore along with coke and limestone to hot metal²⁶ followed by a Basic Oxygen Furnace (BF-BOF) to produce liquid steel which can be further cast, rolled, finished into various steel products. The hot metal if not utilized within the integrated set-up can also be casted as pig iron²⁷, which is thereby utilized by iron foundries or by smaller steelmaking set-ups. Electric route, on the other hand utilizes Sponge Iron (SI)²⁸ which is produced in a Direct Reduction (DR) furnace in combination with steel scrap. SI is subsequently processed in either an Electric Arc Furnace (EAF) or Electric Induction Furnace (EIF). A DR furnace uses syngas, instead of coke, which is injected along with iron ore (in form of iron ore pellets) at high temperatures. Hydrogen and Carbon monoxide, present in syngas, act as reducing agents thereby stripping the oxygen out of the ore to produce solid Direct Reduced Iron (DRI) or SI (BNEF 2019).

In case of the former route, coal in its processed form of coke, is utilized both as a feedstock and fuel in the blast furnace. India, however, has a limited supply of coking coal and the industry resorts to imports, largely from Australia. The Indian iron and steel sector currently use 60 Mt of coking coal per annum, of which only 20% is supplied domestically. The import of coking coal, pegged at 10.3 billion USD in 2018-19, puts a substantial burden on the Indian economy, and is only slated to increase if the sector expands based on incumbent technologies.

In case of the Electric route, which utilizes sponge iron (SI) or Direct Reduced Iron (DRI), 85% of the Indian units use coal directly in the furnace instead of natural gas as a source of syngas (MoS 2019). This is largely due to the unavailability of Natural Gas in India, as the country has limited supplies and imports are prohibitively expensive. Further, domestic gas is regulated by the central government, being designated for use in certain priority industries, namely, fertilizers, transport and domestic cooking gas supply. Further, the high cost of imported natural gas makes coal-based DR, not taking into account the environmental externalities, far more competitive economically, thus making it unique to India. The use of induction furnaces in conjunction with coal-based DR, however, results in low quality steel²⁹, restricted to use in non-critical or non-load bearing applications. Improving quality of steel from this route requires either an additional refining step or use of higher shares of good quality scrap.

As fuel, coal is either utilized directly in production process to provide process heat or is used to generate electricity in captive power plants – the route preferred by large production units. Coal, in captive power plants, provided almost 40% of all electricity in the sector in 2015-16. The remainder portion of electricity was supplied by the grid that currently has an emission factor of approximately 700 gCO₂/kWh which, however, is envisaged to come down given climate policy has made strides in improving penetration of renewables in the grid. Captive power plants, still, are favoured as they guarantee continuous access to electricity for production units. They, however, are an expensive and emission intensive option for power production. The integration of renewables in the grid not only signals availability of cheaper power but also promises a substantial reduction in emission intensity³⁰. In the long run, therefore, power from thermal captive power plants may affect the viability of production units, especially those operating through electro-intensive steel production routes such as EIF/EAF.

26 It is the hot, liquid, metallic iron product obtained upon reduction of iron ore, normally in Blast Furnace. It contains about 93-94% Iron (Fe) and other elements/impurities like Carbon (4%), Silicon (~1%), Manganese (+1%) Sulphur, Phosphorus etc. Hot metal is the primary input for production of steel in the Integrated Steel Plants.

27 Pig iron is a solid (lumpy) form obtained upon solidification of hot metal in pig casting machines.

28 Sponge iron is a solid metallic iron product obtained upon Direct Reduction of high-grade iron ore in solid state without being converted into liquid form like that in a blast furnace. It is primarily used for production of steel in either an EAF or EIF.

29 Low quality steel is due to traces of residual phosphorous, which is not removed completely in the process.

30 In its NDC the India government has pledged to reduce its overall emissions intensity 33-35% below 2005 levels by 2030. A 35% in the country's 2005 emissions intensity of 901.7 gCO₂/kWh would be 586 gCO₂/kWh.

Hydrogen in steelmaking in India

As the economy develops, it is envisaged that the proportion of steel scrap as an input in overall production cycles, also termed as secondary steel production, would increase, which in turn may reduce the emission/energy intensity as it reduces the primary step of processing iron from iron ore. This, however, requires multiple strategic interventions and a certain level of steel consumption, which may not be possible in India in the short to medium term. Recycling of scrap would also not provide a substitute for high quality steel. Both these drivers/barriers indicate that India, based on its national targets, would still require a considerable quantum of steel through primary steelmaking routes which are both energy and emission intensive. The sector in India, thus, needs to look beyond coke and coal and explore alternatives with dual objectives of reducing emissions and import dependency. The latter objective substantially limits the role of natural gas. They, however, do not theoretically limit the use of hydrogen in the sector. Having said that, the use of the gas may be constrained due to other factors such as hydrogen availability, costs, industry inertia and lack of enabling policies/targets/roadmaps.

In terms of production process, hydrogen with some modification to the original process flow, as a reducing agent and fuel, can partially or completely replace fossil fuel use in the steel industry. It can be utilised in both DR-EAF and BF-BOF processes. In the case of DR-EAF hydrogen can replace 90-100% use of natural gas³¹. The process, proposed to be utilized in hydrogen based integrated steel plant (H₂ DR-EAF), is technically ready but not yet demonstrated at commercial scale. The major barriers to commercial feasibility being unavailability

of hydrogen in large quantities and the process's cost effectiveness relative to the conventional steelmaking process. It is, however, being explored by multiple companies under forward looking projects, namely HYBRIT in Sweden, SALCOS and Hamburg project in Germany, H₂FUTURE in Austria, inter alia (BNEF 2019). In case of the BF-BOF route, the gas can partially replace coke³² in the blast furnace to reduce emissions by 10-21% from the overall process. This has been explored under COURSE50 project in Japan, POSCO CO₂ breakthrough project in South Korea and Duisburg project in Germany (Hall, Spencer and Kumar 2020). India, thus, can benefit substantially from international cooperation, especially with Germany which has gained experience from introducing hydrogen in both routes.

Research undertaken by TERI for the steel sector estimates that for a new H₂ DR-EAF facility to be competitive with a greenfield BF-BOF plant, the delivered cost of hydrogen would need to be within the range of USD 2.5 – 3.5 per kg. The actual competitive cost fluctuates within the range depending on the efficiency of the BF-BOF unit and the delivered cost of coking and non-coking coal. If India were, however, to utilize H₂ DR-EAF facilities for primary steel making, the potential demand for hydrogen can range from approximately 1 Mt of hydrogen per annum to 18 Mt of hydrogen per annum in 2050³³. The lower range assumes that only final 5% of the production capacity is shifted while the higher range is for theoretical maximum where all steel is produced from H₂ DR-EAF units (Hall, Spencer and Kumar 2020) (BNEF 2019).

31 DR technologies have been modified by Midrex, Tenova HYL and Outotech to operate on 90-100% hydrogen which has the potential to reduce emissions to 0.5t/tsteel. Eight plants in India with a cumulative capacity of approximately 10 Mt per annum already utilize Midrex shaft furnace direct reduction modules which may benefit from a changeover to hydrogen (Midrex 2019)

32 Partial replacement of coke by hydrogen has been piloted in Japan under the COURSE50 program.

33 The calculation of hydrogen demand is based on the analysis carried out by BNEF and TERI which assumes global and Indian steel production of 2500 Mt and ~530 Mt, respectively by 2050.

Annexure 1: Methodology for calculation of hydrogen consumption in oil refineries

The level of hydrogen consumption in case of oil refineries is dependent on several factors including [a] specific density of crude oil; [b] sulphur ratio of the crude oil; [c] the complexity of the refining operations and the quantum of bottom-of-the-barrel refining; [d] the product slate of the refinery; and, [e] the emission norms applicable at the end-user level.

To understand the relationship with each of the aforementioned factors and to model the hydrogen consumption levels of refining operations in the US, Elgowainy et al. developed a regression function of hydrogen demand by refineries using EIA's database. The regression function, which takes into account the specific gravity of sourced crude oil, sulphur ratio of crude oil and the product stake of the refining unit has been reproduced for reference as below.

$$H_2 \text{ (mmBtu/mmBtu Crude)} = 0.059 - 0.00175 \times (\text{Crude API}) + 0.02218 \times (\text{Sulfur Ratio}) - 0.00139 \times (\text{G/D Ratio}) - 0.59416 \times (\text{LPG/Total})$$

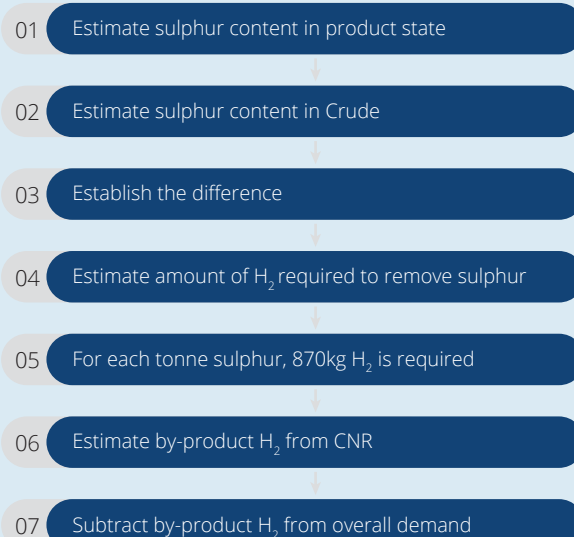
The above regression function is applicable for – [a] Crude API within the range of 28.5 – 34.3; [b] sulphur ratio within a range of 0.65 – 1.6; and, [c] G/D ratio within the range of 0.5 – 5.8.

The Indian refining industry meets the boundary conditions for two out of three factors, namely crude API and sulphur ratio. This regression function, however, is not applicable in case of India as the product slate of Indian refineries is very different from the United States with much lower G/D ratios. This implies that further work needs to be undertaken in this domain such that similar regression functions be established for the Indian operating conditions.

Hall et.al., however, followed a different approach where a proxy for hydrogen consumption was established

by estimating the quantum of hydrogen required for removal of sulphur from the crude oil based on the sulphur content of crude oil and the emission norms followed in India such as Bharat Standard VI (BSVI) standards, which limit the amount of sulphur. Assuming that for each tonne of sulphur, 870 kg of hydrogen is required to remove it from the product, they estimated current hydrogen demand at 2.6 Mt (Hall, Spencer and Dayal, et al. 2020). The approach followed by Hall et al. is represented in the figure below. It may however be noted that this approach may provide an underestimation as hydrogen demand of oil refining units, apart from sulphur removal is also required for [a] hydrocracking – conversion of diesel from crude; and, [b] conversion process required for diesel production from Ultra Low Sulphur Diesel hydrotreater.

Figure 2 Approach followed to estimate hydrogen consumption by Indian refining operations.



Source: Adapted from (Kumar and Himabindu 2019)

Annexure 2: Important stakeholders in India

S.No.	Title	Name	Designation	Department	Affiliation	Sector	Typology of work
1	Dr	SSV Ramakumar	Director	R&D	IOCL	Industry	SATAT
2	Dr	Ashish Lele	Senior VP & Head	Advanced Materials & Alternate Energy	Reliance Industries Limited	Industry	
3	Dr	RR Sonde	EVP	Research, Technology & Innovation	Thermax	Industry	
4	Dr	PC Maithani	Advisor	MNRE	GoI	Government	Fuel Cells, methanol
5	Prof	A K Shukla	Emertius Professor	Solid State and Structural Chemistry Unit	IISc	Academia	Fuel Cells, storage batteries and supercapacitors
6	Prof	Aninda J. Bhattacharyya	Professor & Chair	Solid State and Structural Chemistry Unit	IISc	Academia	H2 generation
7	Dr	Narayana Das Janadhanan Pillai	Dr Raja Ramanna DRDO Distinguished Fellow	Fuel Cell Technology	DRDO	Research	Fuel Cell Technology
8	Mr	MV Kotwal	Former Member of the L&T Board & President Heavy Engineering			Industry	
9	Prof	Debabrata Das	Professor	Department of Biotechnology,	IIT Kharagpur	Academia	Biohydrogen production
10	Dr	Suman Roy Chowdhary	Scientist 'G'	Naval Materials Research Laboratory	DRDO	Industry	
11	Prof	Avinash Kumar Agarwal	Professor	Department of Mechanical Engineering	IIT Kanpur	Academia	Engines
12	Prof	S Srinivasa Murthy	Visiting Professor	Interdisciplinary Centre for Energy Research (ICER)	IISc	Academia	Hydrogen storage
13	Mr	William Hall	Associate Fellow	Energy Program	TERI	Research	
14	Mr	Akshay Bhardwaj	Director	Strategic communication	FTI Consulting	Research	
15	Mr	Tirtha Biswas	Programme lead	Industrial Sustainability & Competitiveness	CEEW	Research	
16	Mr	Karthik Ganesan	Research Fellow	Industrial Sustainability & Competitiveness	CEEW	Research	
17	Mr	Ravindra Paygude	Operation head	Fuel Cell division	Thermax	Industry	

S.No.	Title	Name	Designation	Department	Affiliation	Sector	Typology of work
18	Dr	CS Gopinath	Scientist	Hydrogen Generation and storage	CSIR-National Chemical Laboratory	Research	Hydrogen storage
19	Dr.	K Vijaymohan	Scientist	SWCNT for storage	CSIR-National Chemical Laboratory	Research	Hydrogen storage
20	Mr	Siddharth Rastogi	Executive Director	Sales	MVS Engineering	Industry	
21	Mr	R K Malhotra	President		Hydrogen Association of India	Industry	Fuel Cell Technology
22	Dr	Anil Kakodkar	Former Chairman		Atomic Energy Commission of India	Industry	
23	Mr	K K Gandhi	Consultant		TVS Group	Industry	
24	Mr	Vikram Gulati	Country Head & Vice President		Toyota Kirloskar Motor Pvt Ltd	Industry	
25	Mr	E S Ranganathan	Managing Director		Indraprastha Gas Limited	Industry	
26	Mr	Sturle Harald Pedersen	Chairman		Greenstat Hydrogen Asia	Industry	
27	Mr	Jasvant Singh	General Manager	Research & Development	Haldor Topsoe India Pvt. Ltd.	Industry	
28	Mr	Sukhmeet Singh	Founder & CEO		A2P Energy	Industry	
29	Mr	Sandeep Bhasin	Plant manager		Luxfer Uttam (India)	Industry	Hydrogen storage & processing
30	Dr	Swati Neogi	Professor	Chemical Engineering	IIT Kharagpur	Academia	Hydrogen production (SMR)
31	Mr	Rajiv Sikka	CEO		IndianOil-Adani Gas Pvt. Ltd.	Industry	
32	Mr	Ravi Subramaniam	Business Development Manager		Air Products and Chemicals Inc.	Industry	Storage and processing
33	Mr	Jitendra Goyal	General Manager		Toyota Kirloskar Motor Pvt. Ltd.	Industry	
34	Mr	Mahesh Murthy	Head	TATA Group Fuel Cell Initiative	TATA Motors	Industry	
35	Dr	K A Subramanian	Professor & HOD	Centre for Energy Studies	IIT Delhi	Academia	Development of zero emission engines / vehicles fuelled with hydrogen
36	Mr	Siddharth R. Mayur	CEO & Founder		H2e Power	Industry	Solid Oxide Fuel Cell
37	Mr	Neelkanth V. Marathe	Officiating Director	Power Train Engineering	Automotive Research Association of India	Government	
38	Mr	P. Kumar	Joint Chief Controller of Explosives		Petroleum & Explosives Safety Organization	Research	Safety and regulation
39	Mr	Sant Ranjan	Principal Architect, CTO		KPIT Technologies	Industry	

S.No.	Title	Name	Designation	Department	Affiliation	Sector	Typology of work
40	Dr	D Parvatalu	Domain expert	R&D	ONGC Energy Centre	Industry	Hydrogen storage
41	Dr	P K Patro	Scientific officer	Powder Metallurgy Division	Bhabha Atomic Research Centre (BARC)	Industry	Solid Oxide Fuel Cell
42	Prof	Akula Venugopal	Senior Principal Scientist		Indian Institute of Chemical Technology (IICT)	Academia	COx free hydrogen production by CH4 decomposition
43	Prof	N K Singh	Assistant Professor	Physical Chemistry, Electrochemistry, Electrocatalysis, Fuel Cells, Hydrogen Energy	University of Lucknow	Academia	
44	Mr	Sachin Chugh	Senior Research Officer		Indian Oil Corporation Limited (R&D Centre)	Industry	H-CNG
45	Mr	A S Ramadhas	Senior Research Manager	Vehicle Testing Fuels & Emissions Department	Indian Oil Corporation Limited	Industry	Alternative fuels for transportation
46	Mr	Amit Bhosale	Assistant Professor	Department of Hydro and Renewable Energy	IIT Roorkee	Academia	PEM Fuel Cells, Electrolysers, Stack Development, Cylindrical PEM Fuel Cells, contact resistance management
47	Mr	T J Dhilip Kumar	Associate Professor	Department of Chemistry	IIT Ropar	Academia	Hydrogen storage materials (MOF)
48	Dr	Muhammad Shahid Anwar	Principal Scientist		CSIR-Institute of Minerals and Materials Technology Bhubaneswar	Research	Proton conducting-Solid oxide fuel cell
49	Mr	Laxmidhar Besra	Chief Scientist	Materials Chemistry	CSIR-Institute of Minerals and Materials Technology Bhubaneswar	Academia	Solid Oxide Fuel Cells (SOFC)
50	Mr	M K Soni	Assistant Professor	Center for Renewable Energy & Environment Development (CREED)	BITS Pilani	Research	
51	Mr	Sujeesh S		Solar Energy	Indian Oil Corporation Limited	Industry	
52	Mr	Amit Soman	Country BD Lead	Renewable Power Business	Shell Energy	Industry	
53	Mr	SS Mishra	General Manager (HOD)	Renewable Energy - engineering	NTPC	Industry	
54	Mr	Subodhika Vohra	Senior Technical Officer		CDP India	industry	Carbon pricing

S.No.	Title	Name	Designation	Department	Affiliation	Sector	Typology of work
55	Dr	Venkata Ramana Putti	Programme manager		World Bank	Funding	
56	Ms	Surbhi Goyal	Senior Energy Specialist		World Bank	Funding	
57	Ms	Kanika Chawla	Director	Centre for Energy Finance	CEEW	Research	
58	Ms	Tamiksha Singh	Associate Fellow		TERI	Research	
59	Mr	K N Rao	Director	Energy, Environment & Sustainability	ACC Limited	Industry	
60	Mr	Ashwani Pahuja	Chief Sustainability Officer		Dalmia Cement	Industry	
61	Mr	Devesh Singh	Chief Risk Officer		PTC India Financial Services	Industry	
62	Mr	Suvojoy Sengupta	Partner & Lead	Renewables within Electric Power & Natural Gas Practice – India	McKinsey & Company	Industry	
63	Mr	Sunil K Krishna	Vice President	Business Development	ACME Cleantech Solution Private Limited	Industry	Green Ammonia
64	Dr	M. Sterlin Leo Hudson	Professor	Physics	Central University, Tamil Nadu	Academia	
65	Dr	Nasani Narendar	Scientist		Centre for Materials for Electronics Technology	Research	Fuel cell and batteries
66	Mr	TSR Gopalrao	CGM	Technology Promotion and forecasting	Indian Oil Corporation Limited (R&D Centre)	Industry	
67	Dr	K.Bala Subramanian	Director		Nonferrous Materials Technology Development Center (NFTDC)	Research	
68	Prof	O N Srivastava	Professor Emeritus	Centre for hydrogen energy	BHU	Academia	
69	Dr	S. Venkata Mohan	Scientist		CSIR-Indian Institute of Chemical Technology (CSIR-IICT)	Research	
70	Dr	V Himabindu	Professor	Centre for Environment	Institute of Science & Technology, JNTU, Hyderabad	Academia	
71	Dr	Aravind S. Bharadwaj	CTO	Mahindra Research Valley	Mahindra & Mahindra	Industry	

S.No.	Title	Name	Designation	Department	Affiliation	Sector	Typology of work
72	Dr	N Rajalakshmi	Senior Scientist & Team Lead	Centre for Fuel Cell Technology	International Advanced Research Centre for Powder Metallurgy and New Materials - ACRI	Research	PEMFC
73	Dr	Anbarasu Subramanian	Assistant Professor Grade-I	Mechanical Engineering	National Institute of Technology Rourkela	Academia	Fluid and Thermal Engineering - Hydrogen storage and applications
74	Dr	R. P. Badoni	Distinguished Professor	Chemical	University of Petroleum and Energy Studies (UPES), New Delhi	Academia	Green Fuel - Hydrogen
75	Dr	Sadhana Rayalu	Chief Scientist	Environmental Material Division	NEERI	Research	Hydrogen generation and CCS
76	Mr	Damandeep Singh	Director – India		CDP India	Research	Carbon pricing
77	Mr	Tarun Singh	Scientist 'D'	Hydrogen Energy	MNRE	Government	Hydrogen Energy policy
78	Mr	Dipesh Pherwani	Scientist 'C'	Hydrogen Fuel Cell	MNRE	Government	Fuel Cell Technology
79	Dr	N. Rajalakshmi	Senior Scientist & Team Leader		Centre for Fuel Cell Technology (CFCT-ARCI)	Research	PEM Fuel Cells, Hydrogen Storage
80	Dr	R Balaji	Scientist	Fuel Cell division	Centre for Fuel Cell Technology (CFCT-ARCI)	Research	PEMFC
81	Dr	S Ramakrishna	Project Scientist 'C'	Fuel Cell division	Centre for Fuel Cell Technology (CFCT-ARCI)	Research	PEMFC, methanol economy
82	Mr	R R Singh	Scientist 'E'	Transport Engineering	Bureau of Indian Standards	Government	Automotive Industry Standards Committee
83	Dr	Vidya S Batra	Senior Fellow	Resource Efficient Technologies	TERI	Research	Adsorption media
84	Dr	Amitesh Kumar	Assistant Professor	Department of Mechanical Engineering	BHU	Academia	Averera
85	Mr	Milind Deore	Birector		BEE	Government	Regulation
86	Mr	Girish Sethi	Senior Director	Energy	TERI	Research	Green Steel
87	Ms	Nisha Jayaram	Senior Counsellor		CII-Sohrabji Godrej Green Business Centre	Research	Green Steel
88	Mr	Indu Shekar Chaturvedi	Secretary		MNRE	Government	RE - Hydrogen
89	Dr	S Nand	Deputy Director General		Fertilizer Association of India	Industry	Green Ammonia

S.No.	Title	Name	Designation	Department	Affiliation	Sector	Typology of work
90	Mr	Deependra Kashiva	Executive Director		Sponge Iron manufactures association	Industry	Green Steel
91	Dr	Anshu Bhardwaj	CEO		Shakti Sustainable Energy Foundation	Research	Energy transition - hydrogen
92	Mr	Deepak Amitabh	CMD		PTC India Ltd	Government	Hydrogen - energy storage
93	Mr	Rajat Gupta			McKinsey & Company	Research	
94	Mr	Mohit Bhargava	Executive Director	Renewable Energy	NTPC	Industry	H2 generation
95	Mr	Anindya Chowdhury	Country Manager	Energy Transitions	Shell Energy	Industry	H2 generation
96	Lord	Adair Turner	Chair		Energy Transitions Commission	Research	Energy transition - hydrogen
97	Mr	Anil Razdan	Ex Secy - Power		Indian Chamber of Commerce	Industry	
98	Mr	Manoj Mathur	Director	Solar	SECI	Industry	H2 generation
99	Mr	A K Sinha	AGM	Schemes	SECI	Industry	H2 generation
100	Mr	Deepak Gupta	Honorary Director General		National Solar Energy Federation of India (NSEFI)	Industry	Hydrogen Economy - policy
101	Mr	K R Jyoti Lal	Principal Secretary	Revenue, Transport and General Administration	Government of Kerala	Government	Hydrogen Economy - policy
102	Mr	Jayant Parimal	CEO		Adani Renewables	Industry	H2 generation
103	Mr	Subrahmanyam Pulipaka	CEO		National Solar Energy Federation of India (NSEFI)	Industry	Hydrogen Economy - policy
104	Dr	Sanjay Bajpai	Head	Technology Mission Division (EW)	Department of Science & Technology (DST)	Government	Hydrogen Economy - policy
105	Dr	Ranjith Krishna Pai	Director	Technology Mission Division (EW)	Department of Science & Technology (DST)	Government	Hydrogen Economy - policy
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115	Dr	M. Lakshmi Narasu			JNTU Hyderabad		
117	Dr	P.S. Sai Prasad			JNTU Hyderabad		
118	Dr	G. Sasikumar			SPIC Science Foundation, Chennai		
119	Dr	Pratima Gupta			National Institute of Technology Raipur		
120	Dr	K. N. Sheeba			NIT Tiruchirapalli		
121	Dr	P. Selvam			IIT Madras		
122	Dr	Sundararajan			IIT Madras		
123	Dr	K. Mohanty			IIT Guwahati		
124	Dr	Nageswara Rao Peela			IIT Guwahati		
125	Dr	Rajesh B. Biniwale			CSIR-NEERI		
126	Dr	Amit Dhir			Thapar university, Patiala		
127	Dr	Raj Ganesh S. Pala			IIT Kanpur		
128	Dr	S Ravichandran			CSIR-CECRI Karaikudi		
129	Dr	N Sathaiyan			CSIR-CECRI Karaikudi		
130	Dr	Prakash D. Vaidya			ICT Mumbai		
131	Dr	Sanjay Kumar Singh			IIT Indore		
132	Dr	P. K. Patro			BARC		
133	Dr	Ashok K Ganguli			IIT Delhi		
134	Prof	Vibha Rani Satsangi			DEI, Agra		
135	Prof	Sahab Dass Kaura			DEI, Agra		
136	Dr	Ravi Kumar Asthana			BHU		
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S.No.	Title	Name	Designation	Department	Affiliation	Sector	Typology of work
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143	Mr	Ankan Paul			IACS, Kolkata		
144	Mr	Praveen Kumar			IACS, Kolkata		
145	Dr	Yogesh S. Mahajan			Dr. Babasaheb Ambedkar Univ. Lonere, Maharashtra (BATU)		
146	Prof	G.D.Yadav			ICT mumbai		
147	Dr	Ankush B. Bindwal			CSIR-IIP, Dehradun		
148	Dr	Subham Paul			CSIR-IIP, Dehradun		
149	Dr	Shailendra Tripathi			CSIR-IIP, Dehradun		
150	Dr	Rohit Kumar Rana			IICT Hyderabad		
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