# Hydrogen Roadmap of Bhutan

**Department of Energy**
**Ministry of Energy & Natural Resources**
**June 2024**

**In collaboration with:**

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**Ministry of Energy and Natural Resources**
**Royal Government of Bhutan**
**Thimphu**

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## Foreword

It is with great pride and optimism that we present to you the Hydrogen Roadmap for Bhutan. This document marks a significant milestone in our journey towards achieving a sustainable and resilient energy future. As the global community strives to combat climate change and reduce greenhouse gas emissions, Bhutan remains steadfast in its commitment to environmental stewardship and sustainable development.

The development of this roadmap has been a collaborative effort, reflecting the dedication and expertise of many individuals and organizations and we extend my deepest gratitude to the Department of Energy, the United States Energy Association (USEA), Tetra Tech and Roland Berger for their invaluable contributions. Their commitment to advancing hydrogen technology has been instrumental in shaping this comprehensive guide.

Hydrogen, particularly green hydrogen produced from renewable energy sources, holds immense potential for Bhutan. Our abundant hydropower resources position us uniquely to become a leader in green hydrogen production. This roadmap outlines a clear vision, targets and strategic steps for integrating hydrogen into our energy system, enhancing energy security, and driving economic growth.

The implementation of hydrogen technologies will not only contribute to reducing our carbon footprint but also open new avenues for economic development and job creation. It will support our transition towards a low-carbon economy and reinforce our status as a carbon-neutral nation.

As we embark on this transformative journey, we call upon all stakeholders- government agencies, private sector partners, and the international community to join hands in realizing the vision set forth in this roadmap. Together, we can harness the power of hydrogen to build a sustainable and prosperous future for Bhutan.

Thank you for your unwavering support and commitment to this important cause.

**Hon'ble Lyonpo**

Ministry of Energy and Natural Resources

## Acknowledgement

The Department of Energy (DoE) is pleased to acknowledge the invaluable contributions made towards the preparation of the National Hydrogen roadmap. This crucial document was developed with the collaboration and support from various esteemed organizations and dedicated individuals.

We extend our deepest gratitude to the United States Energy Association (USEA), Tetra Tech, and Roland Berger, whose expertise and commitment were instrumental in this endeavor. The project was funded by the U.S. Department of State, Bureau of Energy Resources (ENR), under the Energy and Mineral Governance Program (EMGP).

The core team, headed by Mr. Karma P. Dorji, Director of the DoE, demonstrated exceptional dedication and expertise. We would like to particularly acknowledge the following team members for their significant contributions:

- Mr. Ugyen, Mrs. Dawa Zangmo, Mrs. Dechen Dema, Mr. Pema Thinley and Mr. Jamyang Tempa from the Department of Energy
- Mr. Andrew Palmateer from USEA
- Mr. Frigyes Schannen and Mr. Marcell Paulitsch from Roland Berger
- Mr. Justin Goonesinghe from Tetra Tech

Furthermore, we express our heartfelt appreciation to all the stakeholders whose support and cooperation were vital in making this hydrogen roadmap a reality. Special thanks are due to:

- Druk Holdings and Investment
- Druk Green Power Corporation Limited
- Department of Surface Transport
- Department of Industry
- Bhutan Power System Operator
- Electricity Regulatory Authority
- Bhutan Power Corporation Limited
- Bhutan Construction and Transport Authority

The valuable contributions and unwavering support from these organizations have been pivotal to the success of this project. We look forward to continued collaboration as we advance Bhutan's energy sector and embrace sustainable hydrogen solutions for a greener future.

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## List of Abbreviations

| | |
|---|---|
| ALK | Alkaline Electrolyzer |
| BF-BOF | Blast Furnace-Basic Oxygen Furnace |
| CAGR | Compound Annual Growth Rate |
| CAPEX | Capital expenditure |
| CCS | Carbon Capture and Storage |
| CCUS | Carbon Capture, Utilization and Storage |
| $CO_2e$ | Carbon dioxide equivalent |
| DRI | Direct Reduced Iron |
| EAF | Electric Arc Furnace |
| EV | Electric Vehicle |
| FCEV | Fuel Cell Electric Vehicles |
| GHG | Greenhouse gas |
| HRS | Hydrogen Refueling Stations |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| IRENA | International Renewable Energy Agency |
| kW | Kilo watt |
| kWh | Kilowatt hour |
| LCOH | Levelised Cost of Hydrogen |
| Mt | Million tons |
| MW | Megawatt |
| O&M | Operation & Maintenance |
| P2G | Power-to-Gas |
| PEM | Proton Exchange Membrane |
| PtX | Power-to-X |
| R&D | Research & Development |
| SOEC | Solid Oxide Electrolytic Cell |

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## Introduction

Green hydrogen is a clean and sustainable energy source that has the potential to play a critical role in the transition to a low-carbon future. Unlike most other types of hydrogen, which are produced from fossil fuels, green hydrogen is produced through the electrolysis of water using renewable energy. As the world works to reduce greenhouse gas emissions and address the dangers posed by climate change, green hydrogen offers a promising solution that can help decarbonize various sectors, including transportation, industry, and power generation.

Currently, Bhutan's electricity supply is primarily from hydropower generation and alternative renewable energy sources such as wind and solar are being explored to diversify the supply and enhance energy security. The Power System Master Plan 2040 estimates that the country has a hydropower potential of 36,900 MW, out of which 32,600 MW are techno-economically viable. Installed capacity of hydropower generation is 2,334 MW in the country including small, mini and micro hydropower plants. Approximately, another 3,641 MW of installed capacity from hydropower and around 1,000 MWp from solar PV are envisaged to be added to the grid by the year 2030.

While majority of hydroelectricity generated is exported to India, the country imports power during the lean season to meet the soaring domestic load in winters just as generation declines from the run-of-river hydropower plants in the country. While the country exports clean electricity, there is a concern about the rising import of fossil fuel products in the transport and industry sectors and increasing for power supply. Bhutan does not have any known oil or petroleum reserves and imports all petroleum products such as petrol, diesel, LPG, kerosene, etc. from India. As per the Annual Trade Statistics 2021, revenue earned through export of hydroelectricity in 2021 was Nu. 24,435.44 million, however in the same year the import of fossil fuels was Nu. 8,348.37 million. Therefore, key advantages of introducing Green Hydrogen industry in Bhutan, could be availability of green hydrogen to decarbonize the hard-to-abate sectors such as transport and manufacturing industries, whilst ensuring a positive trade balance. This will also reduce greenhouse gas emissions and help Bhutan sustain its carbon-neutral status.

Green hydrogen offers diverse potential applications across different sectors. It can be used as a fuel for locomotives, heating for buildings, in industries including fertilizers, as an energy storage medium and for electric power generation. Considering the enormous opportunities hydrogen offers, countries across the world have committed a significant investment to ensure a secure, robust and resilient energy system, while also lowering carbon emission by replacing fossil fuels in 'hard-to-abate' areas of the economy.

Curtailing the import of fossil fuels through the promotion and development of electric and fuel cell-based mobility can improve the current account deficit. Further, the effort will help the country meet its carbon neutral strategy and national commitment to address the climate change goals. For Bhutan, pursuing a hydrogen economy is a natural choice given its abundance of hydropower resources with competitive cost of electricity, besides being green. The immense potential to produce green hydrogen at a competitive price in the region would enable Bhutan to become a global player in the international hydrogen market, significantly contributing to the global clean energy transition while addressing its national energy security.

Hydrogen will be an integral part of Bhutan's energy matrix in the coming years in view of energy security concern. Bhutan Sustainable Hydropower Policy, 2021 lays down the intent to develop a hydrogen economy to address the energy security concerns and impending impacts of climate change. Therefore, this roadmap presents the country's aspirations and ambitions in developing green hydrogen value chains.

The development and deployment of green hydrogen technology is essential to realizing its full potential as a clean energy carrier. To that end, this hydrogen roadmap outlines the targets needed to accelerate the transition to sustainable future. The roadmap lays out the objectives, key targets, and timeline for the implementation of green hydrogen technology. The goal is to provide a clear target for realizing the full potential of green hydrogen and its impact on the environment and the economy.

## Green Hydrogen

Hydrogen is the lightest and most abundant element in the universe present as compounds such as in water and fossil fuels. The global energy landscape is changing. Climate change net-zero commitments, and energy security are transforming the fossil-based economy and accelerating the shift to alternatives such as green hydrogen. According to IRENA's World Energy Transitions Outlook, hydrogen could account for 12% of global energy demand and cutting 10% of $CO_2$ emissions by 2050. The majority of the economic giants are developing policy initiatives, technology, manufacturing capacities, and export facilities to promote green hydrogen value chains. Transportation, shipping, fertilizer, chemical, steel, cement, refinery among others are the target sectors for Hydrogen interventions.

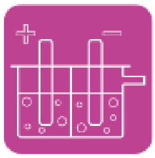
## Why Green Hydrogen?

Hydrogen is a clean, versatile, and efficient energy carrier that can be produced from a variety of renewable resources, including solar, wind, hydro, and biomass. It is a crucial part of the energy transition, which aims to reduce carbon emissions and achieve a sustainable energy future. Hydrogen can be used as a fuel for transportation, power generation, and industrial processes, and it can be stored and transported easily in different forms, such as compressed gas or liquid. Hydrogen fuel cells, which generate electricity through a chemical reaction between hydrogen and oxygen, are an attractive alternative to traditional internal combustion engines as they produce zero emissions and offer higher energy efficiency.

Hydrogen also has the potential to support the integration of renewable energy into the grid, by storing excess renewable energy during periods of low demand and releasing it during peak demand periods. Moreover, hydrogen can facilitate the decarbonization of energy-intensive industries such as steel and cement production, where traditional decarbonization methods may not be feasible. Countries across the world have committed significant investment to ensure a secure, robust, and resilient energy system while lowering carbon emissions by replacing fossil fuels in key areas of the economy. Green hydrogen can enable decarbonization across the mobility and industrial sectors and reduce the dependence on imported fossil fuels contributing to the achievement of global climate goals.

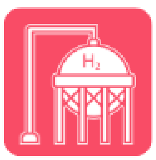
## Hydrogen Value Chain

Hydrogen value chains refer to the entire process of producing, transporting, storing, and utilizing hydrogen as an energy carrier. It encompasses various stages and stakeholders involved in the hydrogen economy, from production to end-use applications.



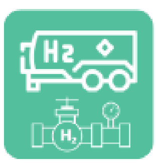
### Production

There are different pathways for hydrogen production. Depending on the production technologies.




### Storage

Hydrogen can be stored in various forms; in pure form it can be stored in the form of compressed gas, liquid and solid/cryo states. While in mixed/novel form it can be stored in form of ammonia,Liquefied organic hydrogen (LOHC), and methanol.




### Distribution

Depending on the quantity and distance,hydrogen can be delivered via pipeline, or by truck, rail or ship in cryogenic liquid tankers and gaseous tube trailers.



### End Use Application

Hydrogen offers diverse potential applications across different sectors. it can be used as fuel in mobility and industry sectors, in power generation and for domestic applications.

## Hydrogen Production

There are different pathways for hydrogen production and a wide range of literature is established for various possible pathways for hydrogen production. Each production pathway has its own technical, environmental, and economic opportunities and challenges. The most widespread methods of producing hydrogen today are natural gas reforming and coal gasification. 95% of hydrogen is produced from natural gas and coal and the remaining 5% as a by-product from the production of chlorine through electrolysis[1].

Figure 1: Nomenclature of hydrogen is given based on the different types of production technologies used

**Green Hydrogen**

- Produced from employing power/electricity derived from renewable sources such as solar, wind, hydro etc.
- No carbon emission during the production process, hence the Green Hydrogen

**Blue Hydrogen**

- Produced from fossil fuels
- CO2 emission but CO2 emission reduced by the use of carbon capture, utilization and storage (CCUS) technology
- The production process is usually categorized as carbon neutral

**Grey Hydrogen**

- Produced from fossil fuel (methane and natural gas) and is produced via Steam Methane Reforming (SMR) process
- During this process, the CO2 is eventually released into the atmosphere.
- Accounts for roughly 95% of the hydrogen produced in the world.

**Brown or Black Hydrogen**

- Produced from coal via the process known as gasification of coal.
- The brown or black colour refers to use of bituminous(black) and lignite(brown) coal for production of hydrogen.

Figure 1: Nomenclature of hydrogen is given based on the different types of production technologies used

The most common and emerging hydrogen production technologies with major share in the total hydrogen production are black/brown hydrogen, grey hydrogen, blue hydrogen and green hydrogen.

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[1] Hydrogen: A renewable energy perspective, 2019 - IRENA

Based on the literature review of hydrogen production technologies that are existing and emerging globally, production of hydrogen through electrolysis is, as identified globally, the key solution towards clean energy transition.

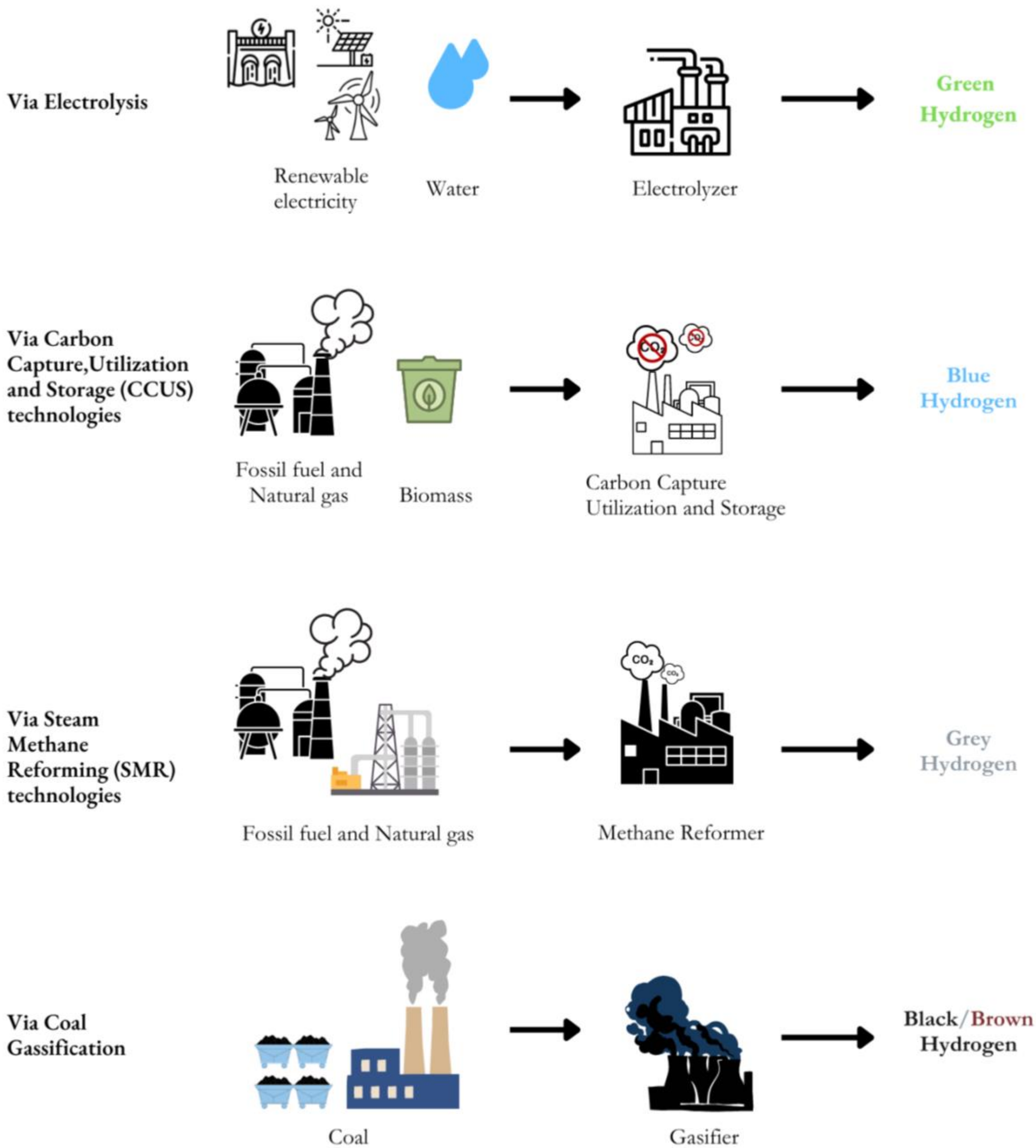


Figure 2: Various hydrogen production routes

Electrolysis of water, also known as electrochemical water splitting, is the process of using electricity to decompose water into its constituent elements, oxygen and hydrogen gas. The reaction takes place in a unit called electrolyzer. In this process, a DC electrical power source is connected to two electrodes, or two plates (typically made from an inert metal such as platinum or iridium) which are placed in the water. In the water at the negatively charged cathode, a reduction reaction takes place, with electrons (e−) from the cathode being given to hydrogen cations to form hydrogen gas:

$$\text{Cathode (reduction): } 2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq);$$

At the positively charged anode, an oxidation reaction occurs, generating oxygen gas and giving electrons to the anode to complete the circuit:

$$\text{Anode (oxidation): } 2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-;$$

Combining these two reactions yields the overall decomposition of water into oxygen and hydrogen:

$$\text{Overall reaction: } 2H_2O(l) \rightarrow 2\mathbf{H_2}(g) + O_2(g)$$

An electrolyzer is a crucial component in producing green hydrogen. At present there are four different types of electrolyzers, of which ALK (Alkaline Electrolyzer) and PEM (Proton Exchange Membrane) are commercially available while SOEC (Solid Oxide Electrolytic Cell) and AEM (Anion Exchange Membrane) are under early demonstration and research stages.

PEM and ALK technologies are commercially and technically matured. ALK and PEM electrolyzers have their respective varying performance and thus use of either of the electrolyzer is dependent on application scenario. For the electrolytic hydrogen production, water is one important source to derive hydrogen and it is used as a feedstock. Generally, about 9 liters of water is consumed to produce 1 kg of hydrogen.

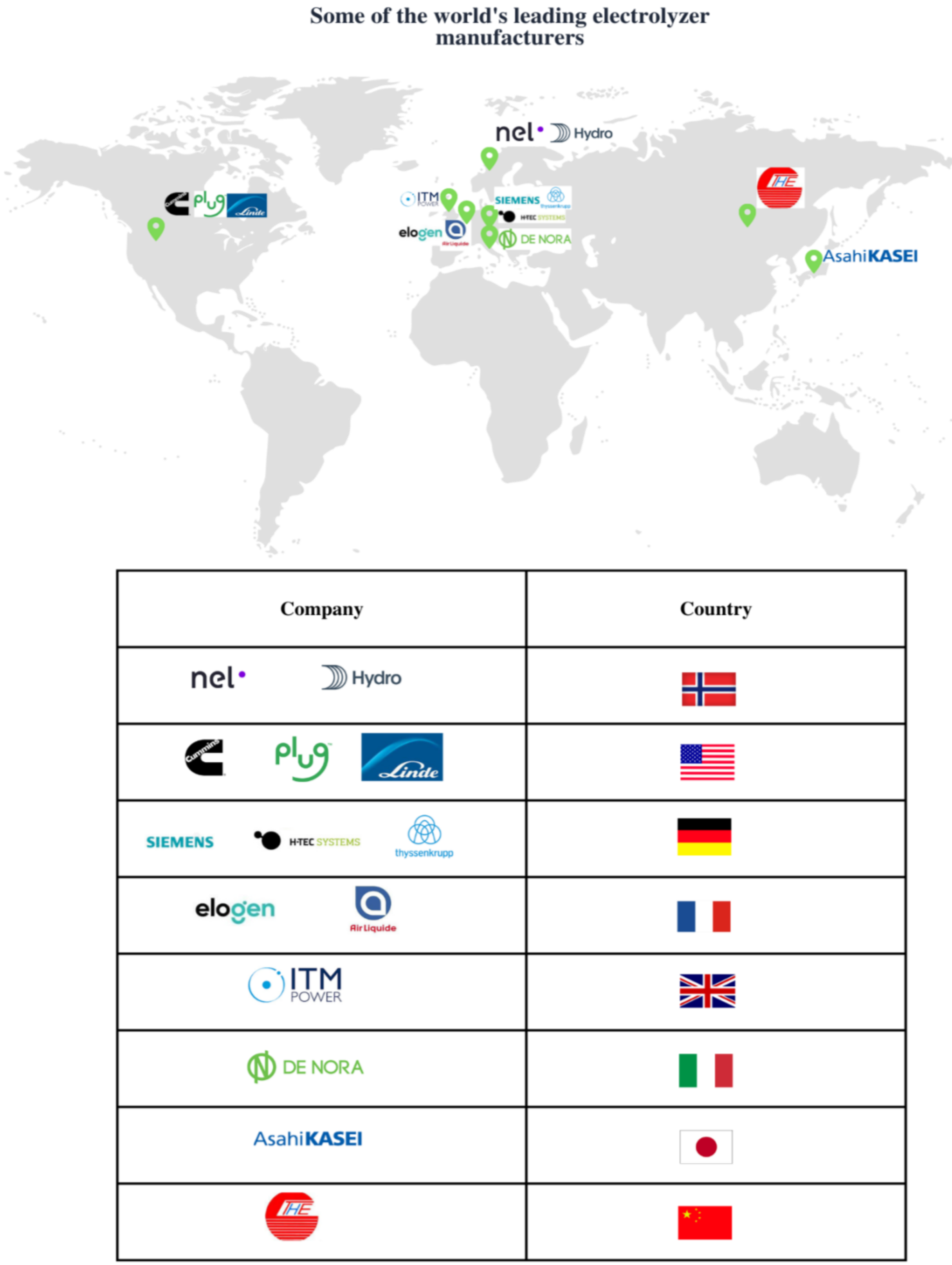


Figure 3 Some of the leading Electrolyzer manufacturers in the world.

Some of the renowned and leading electrolyzer (ALK and PEM) across the world can be seen in the previous page. It is mostly concentrated in the EU region. It is also to note that the new Hydrogen Mission of India aims to be a Global hub of hydrogen production though domestic manufacture of electrolyzers. This will make the cost of electrolyzer much cheaper for the country. Some companies manufactured both ALK and PEM electrolyzers such as nel and Cummins as shown in Figure 4.

| **Company** | **Technology** | |
|---|---|---|
| | **Alkaline** | **PEM** |
| nel | ● | ● |
| Hydro | ● | |
| Cummins | ● | ● |
| plug | | ● |
| Linde | ● | |
| thyssenkrupp | ● | |
| SIEMENS | | ● |
| H-TEC SYSTEMS | | ● |
| elogen | | ● |
| AirLiquide | | ● |
| ITM POWER | | ● |
| DE NORA | ● | |
| AsahiKASEI | ● | |
| THE | ● | |

Figure 4: Electrolyzer manufacturing companies

## Hydrogen Storage & Distribution

Hydrogen, being the lightest element has one of the lowest volumetric energy densities whereby making it a challenge to store in a vessel. Under normal temperature and pressure, 1 kg hydrogen gas occupies around 11$m^3$ of space. Hydrogen has the highest energy per mass of any fuel, however, its low ambient temperature density results in a low energy per unit volume, therefore requiring the development of advanced storage methods that have potential for higher energy density.

Hydrogen storage technologies are therefore critical for advancement of hydrogen and fuel cell technologies. Selection of the most appropriate storage technology represents a trade-off between the quantity of hydrogen, storage footprint (e.g., tank size) and energy usage while storing the hydrogen. Hydrogen can be stored in a variety of forms; in pure form it can be stored in the form of compressed gas, liquid, solid states and in other components known as the hydrogen carrier such as ammonia, liquid organic hydrogen carrier etc.

Similarly, due to its low volumetric energy density, transporting hydrogen from the point of production to the point of end usage is extremely challenging. Therefore, hydrogen in compressed or liquefied and other forms (i.e., novel hydrogen carriers like ammonia and liquid organic hydrogen carrier) of delivery options has become very crucial. Currently, hydrogen is transported from generation point to distribution point via pipelines and in cryogenic liquid tankers or via gaseous tube trailers and then can be transported via truck, rail, ship and pipeline. The choice of technology depends on the quantity, intended purpose and the distance between the production site and the site of end use. Figure 5 shows some of the hydrogen storage and distribution routes.

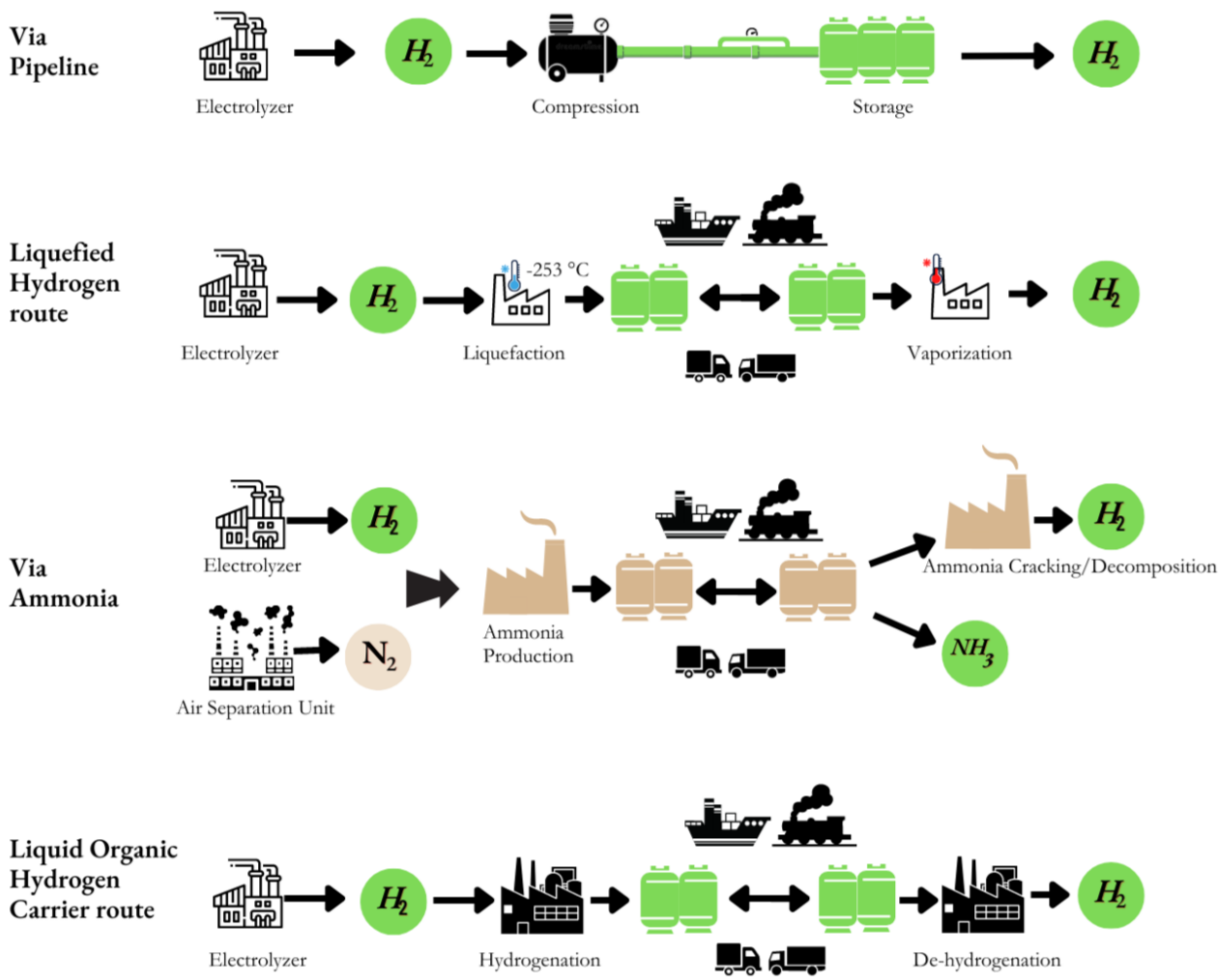


Figure 5: Hydrogen storage and distribution routes

## End-use applications of Green Hydrogen

Green hydrogen offers diverse potential applications across different sectors: It can be used as a fuel for mobility, fuel for buildings, in industries, as an energy storage medium and for electric power generation as shown in Figure 6. Considering the enormous opportunities hydrogen presents, countries across the world have committed a significant investment to ensure secure, robust and resilient energy system while also lowering the carbon emission by replacing fossil fuels in key areas of the economy.

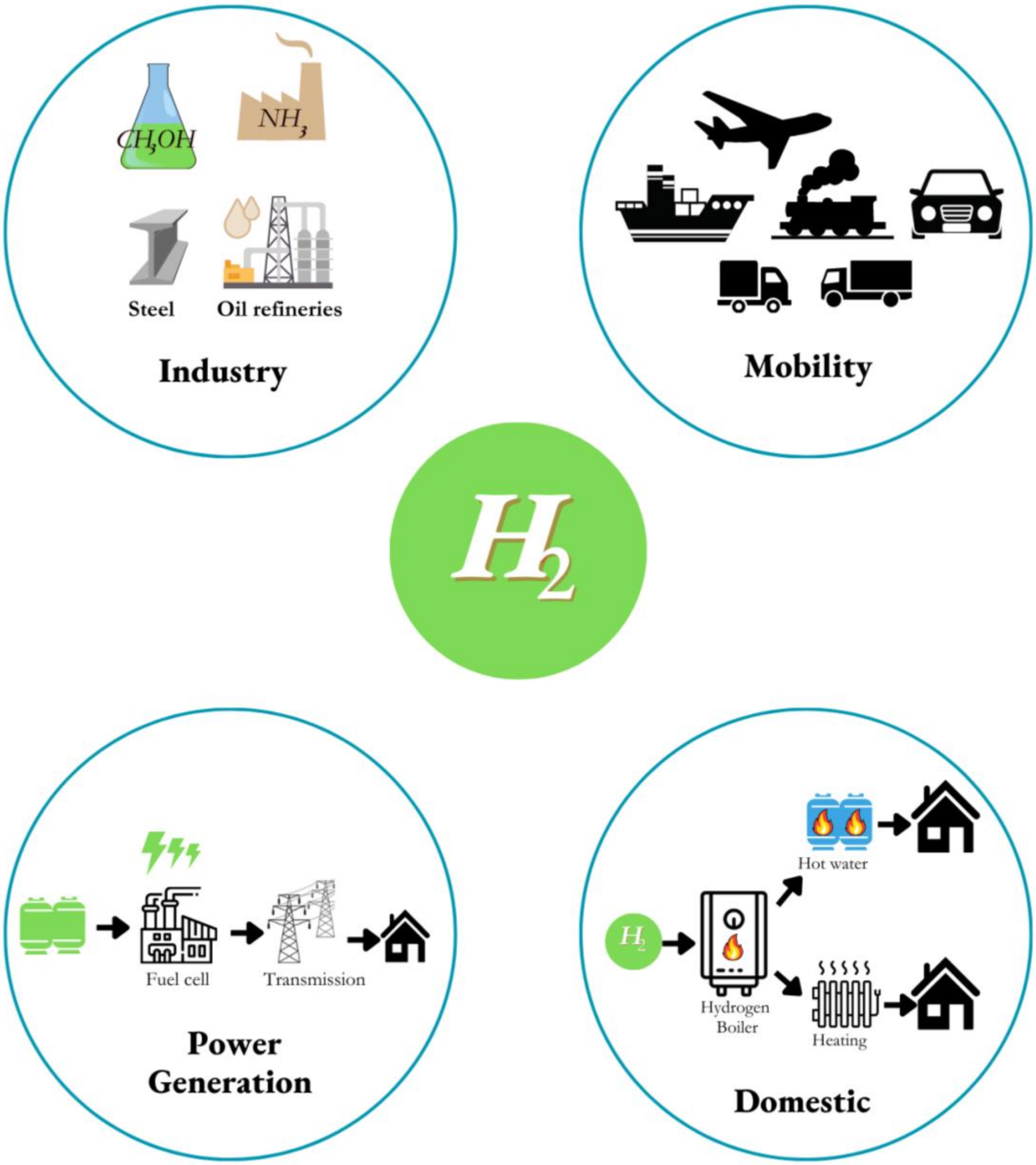


Figure 6: Hydrogen applications

## Mobility

Hydrogen can be used as an energy carrier for the mobility sector in two ways. These are (a) direct use of hydrogen in the internal combustion engines (H2ICE), and (b) indirect use of hydrogen through fuel cells. The first way uses internal combustion engines that burn hydrogen as fuel similar to the conventional ICE vehicles. The latter uses fuel cell technology to generate electricity using hydrogen, which then powers the electric motor and are known as Fuel Cell Electric Vehicles (FCEV). The use of hydrogen in ICE with some modification is still under development and is in demonstration phase, however, it has never reached into commercial scale till date. This technology will be a breakthrough if it becomes commercially available.

**H2ICE:** ICE burns hydrogen as fuel

**FCEV:** converts hydrogen into electricity to power the electric motors

FCEV uses a series of fuel cells (fuel cell stacks) fed with compressed hydrogen gas stored in a fuel tank to produce electricity by converting chemical energy to electrical energy. Hydrogen entered in the anode comes in contact with a catalyst that promotes the separation of hydrogen atoms into an electron and proton generating electricity. The electricity is then used to power the electric motor of the vehicle. The use of green hydrogen as a fuel for mobility sector decarbonizes at two levels: Firstly, the production of hydrogen uses renewable sources of energy and secondly the tailpipe emissions are zero during its application with water as the wastage. FCEVs can be refueled with hydrogen at special Hydrogen Re-fueling Stations (HRS) consuming less time (within 3-5 minutes)[2]. FCEVs are commercially available in the form of light vehicles, heavy vehicles such as trucks & buses, and trains. Some of the internationally recognized FCEV OEM are Toyota, Hyundai, New Flyer etc.

According to IEA, as of 2022, there are 72,000 FCEVs worldwide. To ensure the successful deployment of FCEVs, it is essential to establish a supportive infrastructure for hydrogen refueling. In view of this, numerous countries have made commitments to deploy hydrogen refueling stations (HRS) alongside FCEVs. There are currently 1,020 hydrogen refueling stations worldwide according to the IEA, as shown in Table 1, Table 2, Figure 7 and Figure 8.

[2] Hydrogen Fueling Overview

Table 1: Regional distribution of FCEV and hydrogen refueling station (HRS) stock in 2022[3]

| | Korea | United States | China | Japan | Germany | Rest of the world |
|---|---|---|---|---|---|---|
| Fuel cell electric vehicles | 41.10% | 21.10% | 18.70% | 10.70% | 3.20% | 5.20% |
| Hydrogen refueling stations | 20.80% | 6.90% | 31.30% | 16.00% | 9.30% | 15.60% |

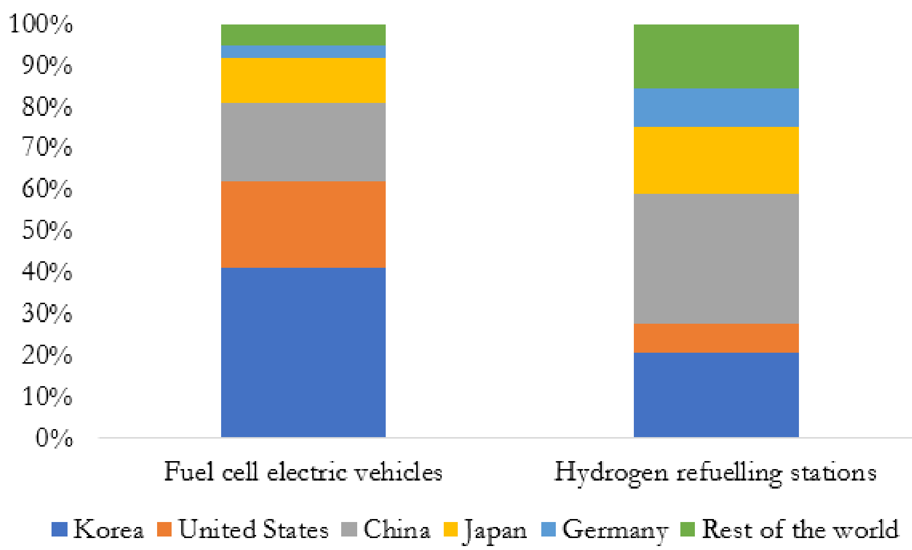


Figure 7: Regional distribution of FCEV and hydrogen refueling station (HRS) stock in 2022[3]

Table 2: FCEV stock by region and by mode, 2022[3]

| | United States | China | Japan | Korea | Germany | Rest of the world |
|---|---|---|---|---|---|---|
| Passenger light-duty vehicles | 15,000 | 200 | 7,600 | 29,300 | 2,200 | 3,200 |
| Light commercial vehicles | - | 800 | - | - | - | 100 |
| Buses | 200 | 5,400 | 100 | 300 | 100 | 400 |
| Trucks | - | 7,000 | - | - | - | 100 |

[3] Data taken from IEA

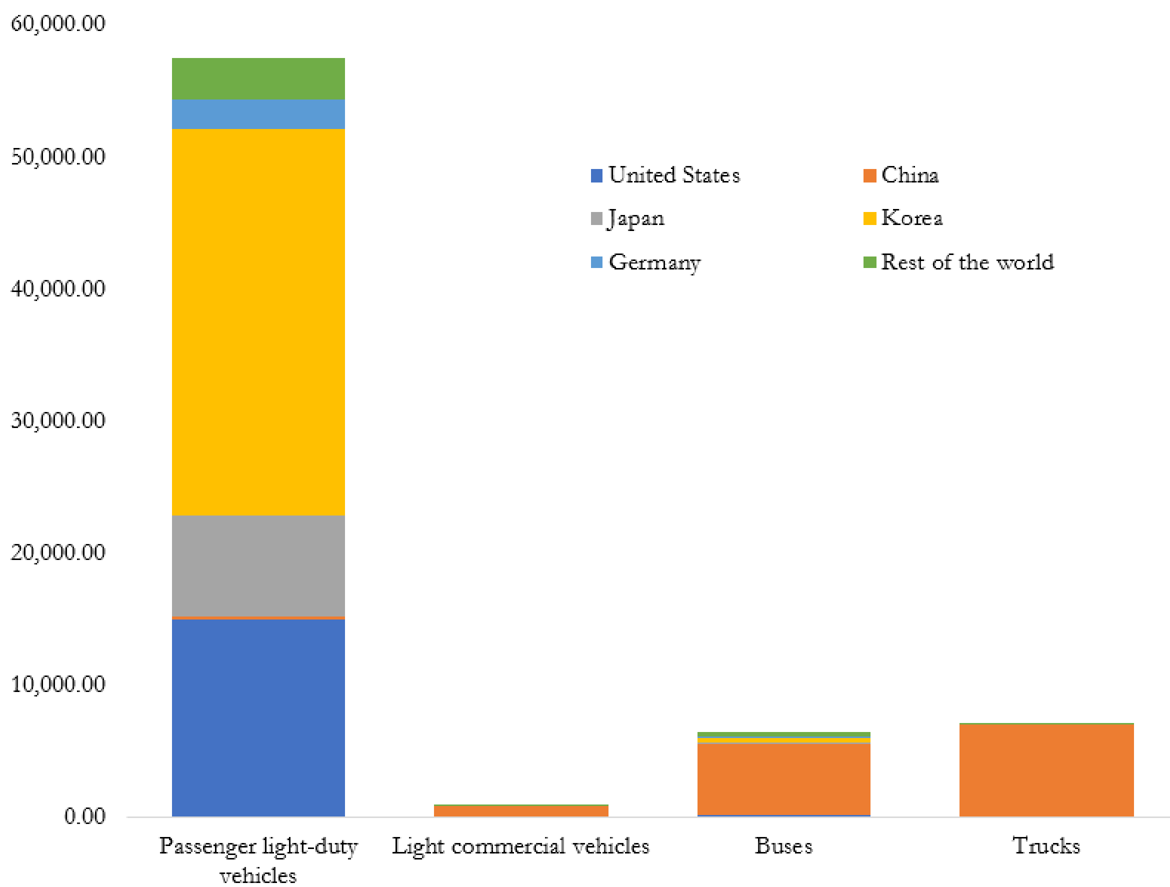


Figure 8: FCEV stock by region and by mode, 2022[3]

According to IEA[4], targets for FCEV deployment account for 1.5 million by 2030 and nearly 5 million by 2040.

## Domestic purpose

Countries with well-established natural gas grids are exploring the possibility of blending hydrogen with their natural gas. With this, they will be able to decarbonize the gas sector without the requirement for significant infrastructure upgrades. HyDeploy at Keele University has already launched a trial of delivering 20% Hydrogen blend to 100 homes and 30 faculty buildings in 2019. Also, the UK's leading boiler manufacturer Worcester Bosch and Baxi has introduced 100% Hydrogen ready combi-boilers which is being tested on two houses of Hystreet in Northumberland and as per their Hydrogen strategy 2021, neighborhood Hydrogen trial will be conducted in Fife, Scotland.

[4] Global hydrogen targets – IEA, 2022

## In Power Generation (Power-to-Power)

Electricity can be generated using green hydrogen with the help of Power-to-Power technology. Power-to-Power employs electrolysis technology to generate hydrogen from renewable resources and the hydrogen is then stored for future use and converted back into power through the use of a fuel cell when required. The PtG technology converts renewable energy into hydrogen through the electrolysis process, which can be used for generation of green electricity through fuel cell technology. Another technology known as the power-to-liquid process can also be deployed to produce hydrogen, which is then combined with carbon dioxide from air and converted to eFuel or synthetic liquid fuel that can be transported with relative ease.

Such technology has increasingly been deployed recently in pursuit of larger global clean energy transition goals. Hydrogen can help overcome the energy availability issue due to the intermittent nature of the renewable energy resources such as solar and wind.

In pursuit of these efforts, developed countries around the world have embarked into Research & Development (R&D) and adoption of hydrogen technology for power generation. For instance, Japan has begun generating green hydrogen in 2020 using 10 MW electrolyzer fueled by 20 MW solar system[5]. The commencement of operation of one of the largest P2G systems has set the wheels of large-scale green hydrogen generation in Japan. Green hydrogen is used for supplying green electricity and as a means to address intermittent issues. In another record achievement, a hydrogen-fueled combined cycle power plant in Venice, Italy, has demonstrated the world's first industrial-scale facility to generate electricity from hydrogen[6]. The facility generates 60 million units of energy per year, providing energy need for about 20,000 households while also averting 17,000 MT of $CO_2$ emission per year. In Kenya, about 800 telecom base stations have switched to fuel cell systems for electricity supply, and the use of fuel cell in stationary power supply as big as up to 5 MW for uninterrupted and back-up power supply is emerging in California[7].

## Energy Storage

hydrogen can also act as an energy storage medium that could provide the power grid with a long-term energy storage option. This would mitigate the seasonal variations in renewable generation and also supplement intermittency. Most of the current renewable energy (RE) sources suffer from its inherent intermittency due to their heavy dependencies on weather conditions while battery banks are only suitable for short term storage with its life span highly dependent on rate of charging-discharging cycles. Hydrogen offers higher energy storage for longer duration of time.

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5 Japan's hydrogen society ambition: 2020 status and perspectives
6 Inauguration of first industrial-scale hydrogen plan in the world
7 The Future of Hydrogen, 2019. International Energy Agency

## In Industry

The industrial sector currently stands as the primary consumer of hydrogen, surpassing 50 million tons (Mt) in 2020. This prominent position of industry as a hydrogen consumer is widely acknowledged in various strategies and national plans, which prioritize the decarbonization of existing hydrogen demand within the sector. Furthermore, these initiatives underscore the increasing importance of low-carbon hydrogen in addressing the challenge of reducing $CO_2$ emissions from heavy industry.

### In production of Green Steel

It can be used in the production of steel known as *Green Steel.* In steel industry, hydrogen could play a significant role in decarbonizing the steel industry in two major pathways.

i. Hydrogen use in BF-BOF (Blast Furnace-Basic Oxygen Furnace) route

   Hydrogen can be injected into the BF as a source of heat and reducing agent by removing oxygen from the raw iron ore in place of traditionally used coke.

ii. Hydrogen use in EAF (Electric Arc Furnace) route

   Hydrogen can also be used as the main reducing agent in the process of making sponge iron through direct iron reduction (DRI) in a furnace. The resulting sponge iron is then used in the production of steel in an EAF. The DRI with green hydrogen can deliver significant emission reductions of approximately 90-95%. Even though the first part of this process is carbon-free, a carbon source is still required to produce steel from the EAF. Figure 9 shows the current steel production routes and green steel production routes via DRI-EAF using green hydrogen.

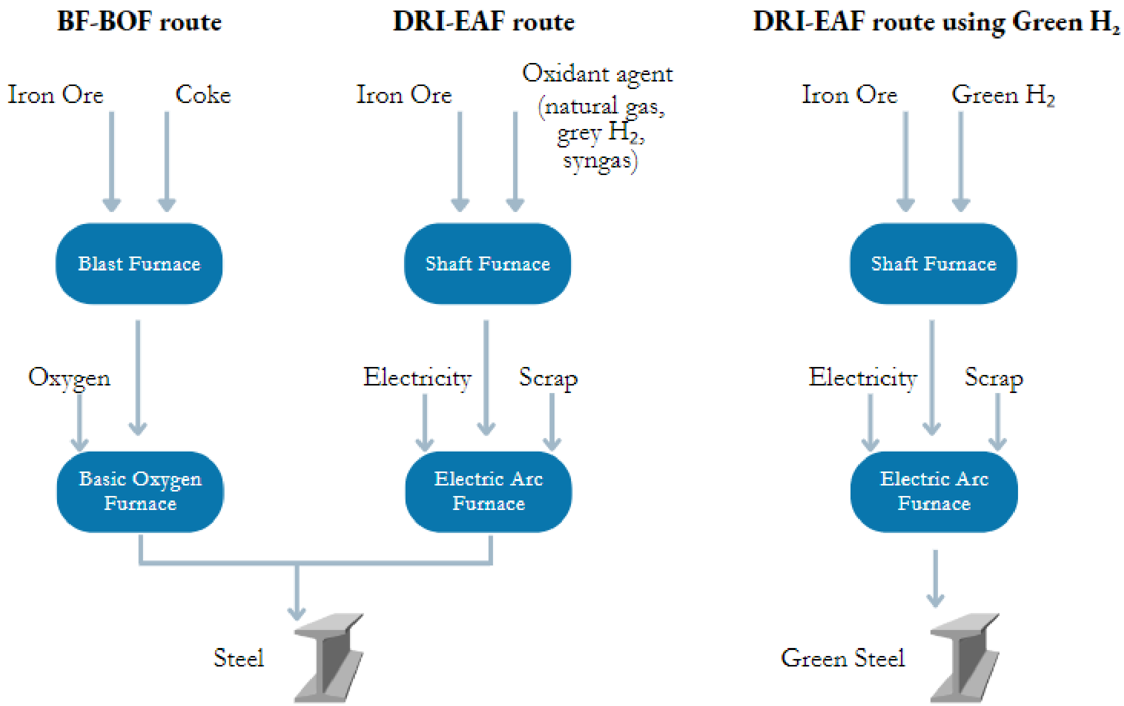



Figure 9: Steel production route[8]

## In Refineries

Hydrogen is generally used to improve the quality of oil and gas products or the desulphurization of conventional fuels. In 2020, almost 40 Mt of hydrogen produced was used for oil refining purposes mainly in the hydrocracking and hydrotreating processes[8].

1. Hydrocracking
   It is a process to convert low quality gas oil into more valuable fuels such as diesel, gasoline, and jet fuel in the presence of hydrogen and catalyst.
2. Hydrotreating
   It is a process of treating fossil gas or refined petroleum products (diesel, gasoline, jet fuel) by means of removing Sulphur (desulfurization) and other contaminants by mixing with hydrogen.

## Production of e-Fuel

Hydrogen can also be used in producing e-fuel or also known as synthetic fuel from electricity, green hydrogen and carbon dioxide. Currently, technology is immature and therefore expensive. Hydrogen

[8] Green hydrogen for industry: A guide to policy making, IRENA (2022)

that is produced from electrolysis reacts with the captured carbon dioxide and is then further refined into synthetic fuel such as methanol. $CO_2$ is either abstracted from industries or using direct capture from air technologies. This process is not completely emission free due to the fact that the use of this fuel will emit $CO_2$ during its combustion. However, the emission reduction can be done during its production process.

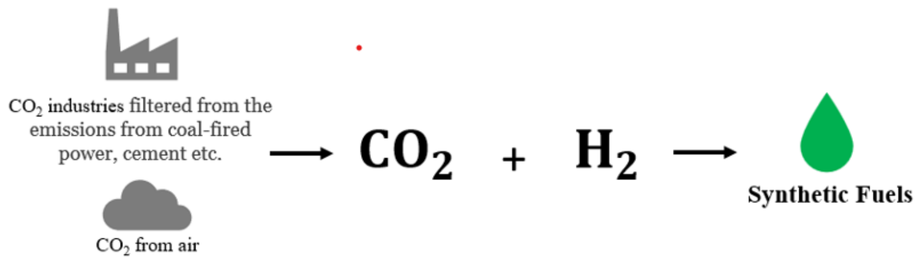
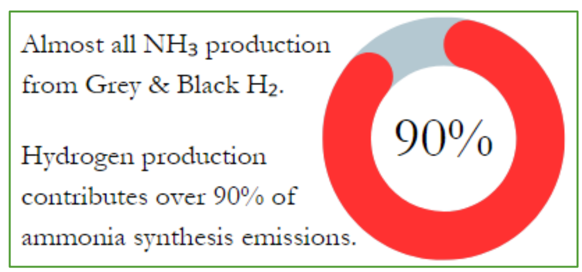



Figure 10: Production of synthetic fuel from hydrogen

Some of the examples of e-fuels are e-Diesel, e-Gasoline, e-kerosene, e-methanol etc. which can be used in the internal combustion engine to replace the use of conventional fuels such as diesel and gasoline for mobility purposes as a climate neutral alternative.

## Production of Ammonia

Other applications include production of green ammonia. Ammonia is a pungent gas that is widely used to make agricultural fertilizer and also it can be used as zero carbon fuel and as energy storage as ammonia can be easily stored in bulk quantity. Almost all (99%) the ammonia production relies on the black and grey hydrogen. These hydrogen production accounts for more than 90% of the total ammonia synthesis emissions.




Green ammonia production is where the process of making ammonia is 100% renewable and carbon-free. One of the methods to produce green ammonia is by using hydrogen from water electrolysis and nitrogen separated from the air. These are then used to produce green ammonia by the most popular method known as Haber-Bosch process, where hydrogen and nitrogen are reacted together at high temperatures and pressures to produce ammonia. It comprises of three major units, electrolyzer for green hydrogen production, nitrogen production unit and ammonium synthesis.

$$N_2 + 3H_2 \rightarrow 2NH_3$$

The cost of setting up a new green ammonia plant according to IRENA is estimated to range from USD 720-1,400 per ton, compared to the cost of fossil-based ammonia, which ranges from USD 110-

340 per ton. Furthermore, producing green ammonia through the Haber-Bosch process necessitates an uninterrupted power supply, which may require the installation of a captive power plant.

## Production of fertilizers

The utilization of green hydrogen in the production of fertilizers presents an innovative and environmentally friendly approach by which, the fertilizer production process can be decarbonized. Green hydrogen can serve as a precursor for the synthesis of ammonia, a crucial component in fertilizer manufacturing. This eco-friendly approach not only reduces carbon footprints but also contributes to mitigating climate change. According to the World Economic Forum[9], globally, 70% of the global ammonia is used to produce fertilizer. More than half of the global ammonia production is currently produced in four countries: China, USA, India and Russia. Furthermore, the use of green hydrogen in fertilizer production aligns with the broader goal of transitioning towards a carbon-neutral economy and promoting sustainable agricultural practices.

By embracing this innovative solution, we can foster a more sustainable future while supporting agricultural productivity and ensuring global food security. Ammonia is traded around the world, with global exports equating to about 10% of total production. Some examples of ammonia-based fertilizer include urea and ammonium nitrate. Urea, its most common derivative, is traded even more widely, at just under 30% of its production.

[9] World Economic Forum, 2022 (The Net-Zero Industry Tracker)

## Global Hydrogen Outlook

### Global Hydrogen Demand

Around 120 million tons of hydrogen is produced globally, two-thirds of which is pure hydrogen and one-third of which is a mixture with other gases[10]. China is the world's largest producer and consumer of hydrogen. It produces almost 24 million tons of pure hydrogen per year, accounting for nearly one-third of dedicated global production.

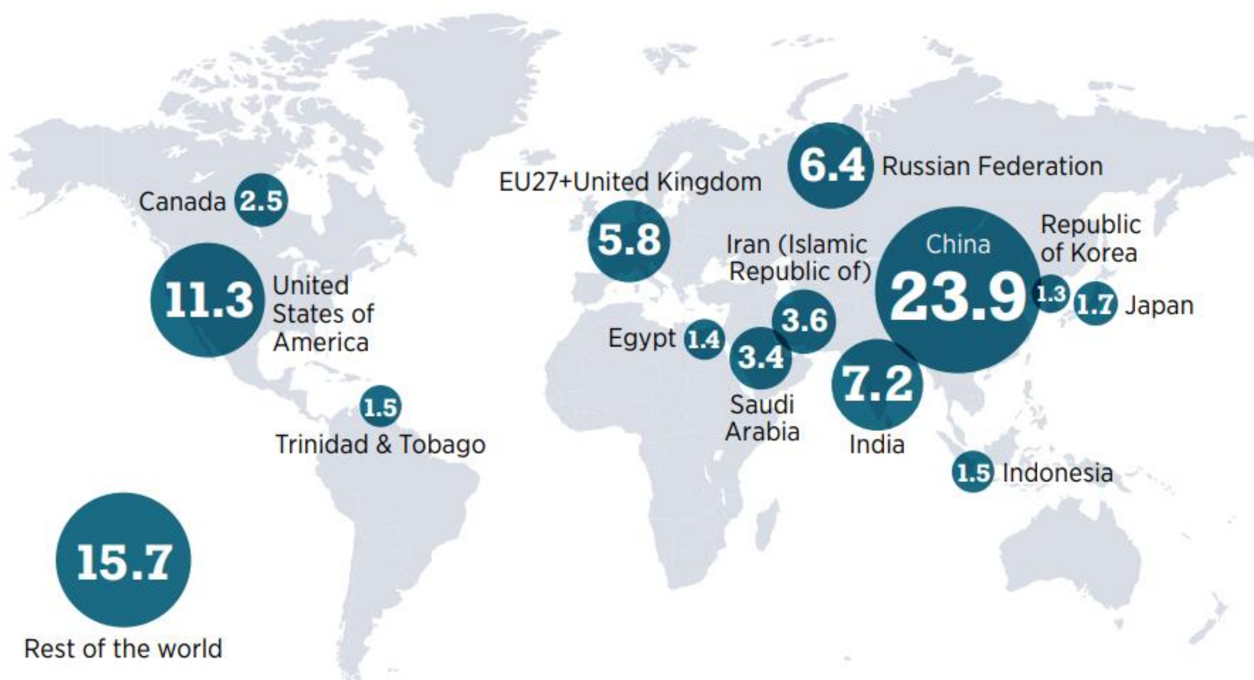



Figure 11: Hydrogen consumption in 2020 (in million tons per year)

The demand is mainly driven by the chemical and refining sectors with limited demand in the new applications. Demand in new applications such as mobility, high temperature heat in industry, hydrogen-based iron and steel industry, and electricity generation reached about 40 kilo tons of hydrogen i.e., increase by 60% in 2021, which makes only 0.04% of the global hydrogen demand. This demand was mostly in road transport with about 75% (30 kilo tons), which was more than 60% higher than the previous year.

[10] Hydrogen, IEA (2022)

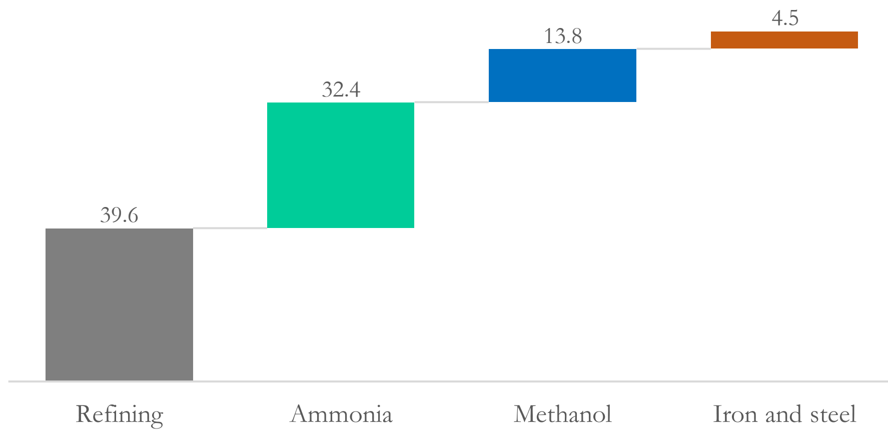



Figure 12: Global hydrogen demand[11]

As discussed in the previous sections, hydrogen production is mainly from the technologies based on fossil fuel and from by-product hydrogen from petrochemical processes. Barely one percent of the total hydrogen production is constituted by the low-emission production (green and blue hydrogen). As per the IEA, low emission hydrogen grew by 9% in 2021 mainly attributed to the commissioning of more than 200 MW of electrolyzers i.e., 160 MW in China and more than 30 MW in Europe[10].

Hydrogen could provide up to 22% of global energy demand by 2050, growing to almost 700 million tons per year[12]. This represents an almost eight-fold increase from the current global consumption of over 94 million tons in 2020. Meeting this global demand requires more than US$ 11 trillion of investment in production, storage, and transport infrastructure. The global sale of hydrogen could exceed US$ 700 billion by 2050, with billions more spent on end-use equipment[12]. The global hydrogen growth can be attributed to the growing government initiatives to support the development of a hydrogen economy.

| | |
|---|---|
| Market share of hydrogen to meet global energy demand by 2050 | 22% |
| Expected annual sales of hydrogen by 2050 | $700 billion |
| Investment by 2050 to produce, transport and store hydrogen | $11 trillion |

Figure 13: Hydrogen could meet 24% of global energy demand by 2050, but needs over US$ 11 trillion investment in Infrastructure

[11] Data taken from data and statistics of IEA
[12] Hydrogen Economy Outlook, Bloomberg NEF

## Green hydrogen certification

Green hydrogen certification is a crucial process that verifies the environmentally friendly production and transport of hydrogen. Hydrogen is essential for achieving climate targets. It emits no $CO_2$ during combustion and material use, making it a climate-friendly alternative to fossil fuels. Certified green hydrogen provides transparency, traceability, and confidence in its sustainable production and use.

**Requirements for Certification:** To certify hydrogen produced from renewable energy sources, several requirements must be met:

- Temporal Correlation: The electricity used for electrolysis must come from renewable sources
- Geographical Correlation: There should be a physical link between the hydrogen production site and renewable energy sources
- Avoidance of Fossil-Generated Electricity: Higher shares of fossil-generated electricity elsewhere in the system should be minimized
- Transparency and Information: Full transparency regarding the resources used in hydrogen production

TÜV Rheinland, a leading certification body, has introduced the TUV Rheinland Standard H2.21 Carbon-Neutral Hydrogen. This standard provides an independent verification for the documentation of renewable and low-carbon hydrogen fuels. It allows manufacturers, distributors, and users of hydrogen to demonstrate its environmentally friendly production. The certification strengthens customer confidence and provides a competitive advantage. The standard defines a greenhouse gas emission reduction threshold of 70% compared to a specified comparator value (94 g $CO_2$-eq/MJ). It differentiates between two major hydrogen classifications:

**Renewable Hydrogen**: Produced by electrolysis of water or aqueous solutions using electricity from renewable non-biological sources. The reduction target must be at least 70% of the comparator value.

**Low Carbon Hydrogen**: Encompasses all hydrogen production routes, allowing various technologies and processes to be certified. The reduction target is also at least 70% of the comparator value. Additionally, other optional criteria can be certified, including Green Hydrogen, Blue Hydrogen (CCS/CCU), Turquoise Hydrogen, Pink Hydrogen, and Carbon Neutral Hydrogen. The standard is also applicable to hydrogen derivatives like ammonia, methane, and methanol.

## Green hydrogen certification process

The green hydrogen certification process involves several steps to ensure the environmental sustainability and reliability of hydrogen production:

**Eligibility Assessment:** Includes evaluating the energy sources used, geographical correlation, and temporal correlation. The hydrogen production site must have a physical link to renewable energy sources (geographical correlation) and use electricity exclusively from renewable sources.

**Documentation Review:** This documentation includes information on energy sources, emissions, and other relevant data.

**Independent Verification:** An independent certification body (such as TÜV Rheinland, DNV, or TÜV SÜD) reviews the documentation. They verify that the hydrogen production system meets the required standards for greenhouse gas reduction.

**On-Site Inspection:** Inspectors visit the hydrogen production facility to verify the information provided in the documentation. They assess the physical infrastructure, energy sources, and compliance with environmental criteria.

**Emission Reduction Calculation:** For green hydrogen, the reduction target should be at least 70%.

**Certification Decision:** Based on the assessment, the certification body decides whether the hydrogen production system qualifies for certification.

**Labeling and Transparency:** Certified green hydrogen is labeled accordingly, indicating its sustainable production.

**Periodic Audits:** Certification is not a one-time process and regular audits ensure ongoing compliance. Producers must maintain the required standards throughout hydrogen production.

## Certification bodies for green hydrogen in Asia

**1. Japan and Germany's Mutual Recognition Agreement:** Japan and Germany, along with other countries, have committed to a "mutual recognition of certification" agreement for clean hydrogen. This agreement aims to ensure that certified green hydrogen meets stringent environmental standards. It involves approximately 30 countries, including India, the US, Brazil, Saudi Arabia, and Chile.

**2. DNV (Det Norske Veritas):** DNV certifies green hydrogen production systems and collaborates with various stakeholders in the industry. Notable companies like Asahi Kasei Corporation, BP, Equinor, Shell, Siemens Energy, and Total Energies are part of this certification process.

**3. TÜV SÜD in India:** TÜV SÜD offers its own CMS 70 Green Hydrogen certification alongside external standard certifications such as ISCC Plus and CertifHy. This certification ensures that hydrogen is substantially sustainable, with low to no carbon dioxide emissions throughout the production process.

## Carbon trading mechanism and green hydrogen

Carbon trading, also known as emissions trading, is a market-oriented policy tool used to control carbon emissions. It allows companies to buy and sell carbon credits, which represent allowable emissions. A significant example of this is the European Union Emissions Trading System (EU ETS), the world's largest carbon market.

Carbon trading provides financial incentives for companies and industries to reduce greenhouse gas emissions. This system sets a cap on total emissions and allows for the trading of carbon credits, encouraging businesses to transition to cleaner practices and renewable energy sources. Carbon trading, which relies on market dynamics rather than strict regulations, fosters innovation and competition. It indirectly supports the growth of renewable energy sectors as companies can earn carbon credits by investing in renewable energy sources, which can be traded or used to offset emissions from fossil fuel operations. As carbon prices increase, industries that heavily rely on fossil fuels face economic pressure to seek low-carbon alternatives. Globally, carbon trading promotes cooperation among nations and aligns with international climate agreements like the Paris Agreement, aiding in the collective reduction of emissions and movement towards a sustainable future.

Recently, green hydrogen, produced through electrolysis using renewable energy sources, has become important in transitioning towards a low-carbon economy. The carbon emissions trading market can incentivize green hydrogen adoption by trading carbon credits earned from its production. This encourages investment in green hydrogen infrastructure and aids in meeting climate targets. To make green hydrogen globally available, infrastructure and trade environments need to be developed. International efforts are ongoing to understand how trade policies can support green hydrogen development. In essence, the interaction between carbon trading mechanisms and green hydrogen has immense potential for achieving a sustainable and low-carbon future.

### Implementation steps of a carbon trading system

1. **Setting the scope:** Carbon trading starts by defining the geographic area, sectors, emission sources, and greenhouse gases to be regulated, establishing the boundaries of the trading system
2. **Cap and trade system:** An Emissions Trading System (ETS), or cap-and-trade system, caps the total level of greenhouse gas emissions and allows companies with lower emissions to sell their extra allowances to larger emitters, thereby creating a market price for greenhouse gas emissions
3. **Allocating permits:** Governments issue permits up to the agreed emission limit, which can be allocated for free or auctioned to companies in various sectors
4. **Trading the right to pollute:** These permits represent the 'right to pollute', which companies can trade amongst each other
5. **Capped permits and reduction targets:** The number of permits is capped and decreases over time, encouraging companies to invest in cleaner production options and reduce CO2 outputs

6. **Combining carbon pricing with offset credits:** Carbon pricing can be combined with offset credits, allowing companies to invest in emission reduction projects elsewhere instead of within their country of operation

## Green hydrogen for Bhutan

Green hydrogen economy will create new jobs especially in renewable energy sector, contribute to economic growth, ensure a cleaner environment, strengthen industrial competitiveness and enhance Bhutan's energy security. The following are some of the major benefits of green hydrogen for Bhutan.

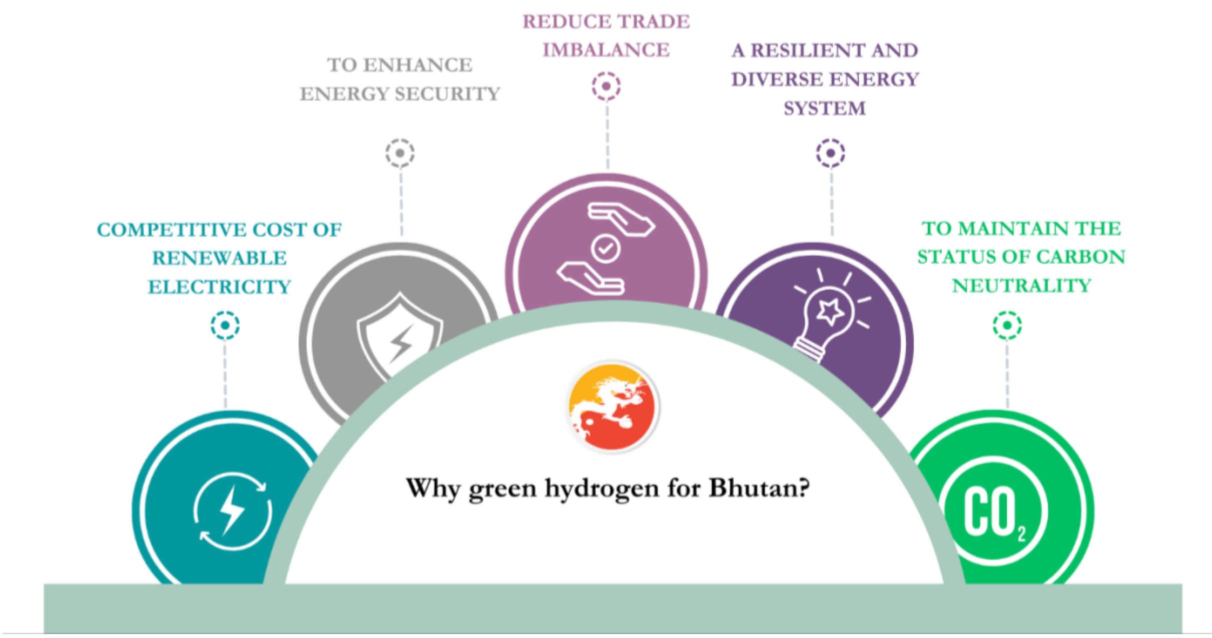



Figure 14: Benefits of green hydrogen in Bhutan

### a) Competitive cost of renewable electricity

Renewable electricity sources, such as hydroelectric power, can play a significant role in reducing the cost of hydrogen production, as they offer a low-cost and environmentally friendly source of electricity. The cost of renewable electricity generation has been decreasing globally due to advancements in technology, economies of scale, and supportive government policies.

The Levelized Cost of Hydrogen (LCOH) is a metric used to assess the cost competitiveness of hydrogen production methods. Electricity cost is one of the key factors contributing to the LCOH. Electricity represents roughly 40%-70%[13] of the LCOH.

[13] Lazard

### b) To enhance energy security

Using domestically made green hydrogen can help reduce the country's heavy dependence on imported fossil fuels, especially for the mobility and industry sector. This would potentially strengthen the country's strategic security and maximize our energy resilience to disruptions in supply-chain and maintain fuel self-sufficiency.

### c) Reduce trade imbalance

Considering the implication on the overall trade of the nation due to import of fossil fuel and the Bhutan's commitment to remain carbon neutral, it is important to recognize the potential of hydrogen as an alternative fuel in the transport sector. Initiating a strategic pilot project will play an important role in stimulating uptake of FCEVs, by providing the initial infrastructure and demonstrating the usability and safety of FCEV technologies to gain the confidence of the public.

However, the cost of FCEVs is prohibitively high to be competitive with electric and conventional internal combustion vehicles. The cost is expected to go down significantly when the technology matures.

Similarly, production of synthetic fuels or eFuels for mobility purposes could be explored depending on the global technological maturity, in the future. The production of synthetic fuel will not have any emission, however, the use of this fuel for mobility purposes will have emissions just like the conventional vehicle with internal combustion engines unlike the FCEVs. Nonetheless, the use of synthetic fuel will significantly reduce the reliance on the imported fuels for mobility purposes.

### d) A resilient and diverse energy system

Hydrogen technologies are well-suited to balancing supply and demand in an electricity grid that increasingly relies on variable renewable sources such as solar and wind. If managed well, this could lower electricity costs for consumers. In a rapid demand-response scenario, when electricity supply exceeds conventional demand, hydrogen electrolysis can be ramped up within seconds; when electricity demand exceeds supply, hydrogen electrolysis can be equally rapidly ramped down. This makes hydrogen production from electrolysis well-suited to renewable electricity generation. It can run when renewable electricity is abundant and use electricity which would otherwise be curtailed. This can improve project economics. In areas where renewable energy varies with the seasons, hydrogen can be produced in large volumes during times of plentiful supply, such as in summer seasons. It can then be used in times of limited supply to generate electricity through fuel cells.

## e) To reinforce the status of carbon neutrality

Transport sector is one of the major consumers of energy, which is mainly derived from the imported fossil fuels in the country. As per the Third National Communication, 2015[14] to the UNFCCC, the mobility and industry sector accounts for 11% and 20% of the total national emission respectively. Every year, country imports huge quantity of fossil fuels for mobility and industry sector. Besides the trade imbalance, growing emissions from transport and industry sectors in the country pose a threat to the current carbon neutral/negative status.

Bhutan's potential to produce green hydrogen does not only support carbon emission reduction but hydrogen as transport and an industrial fuel provides a pathway to eliminate the nitrous oxides, sulfur oxides and particulate pollution associated with burning fossil fuels. Improved air quality is likely to reduce a range of respiratory ailments, cancers, and the health costs associated with them.

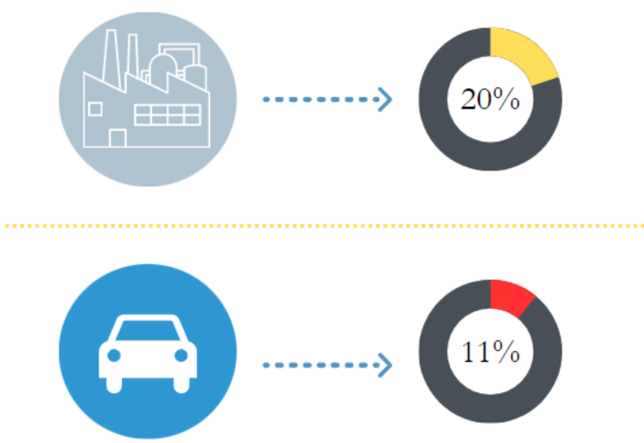



Figure 15: GHG emissisons from Industry and Mobility sector (TNC 2015)

[14] National Environment Commission, 2020

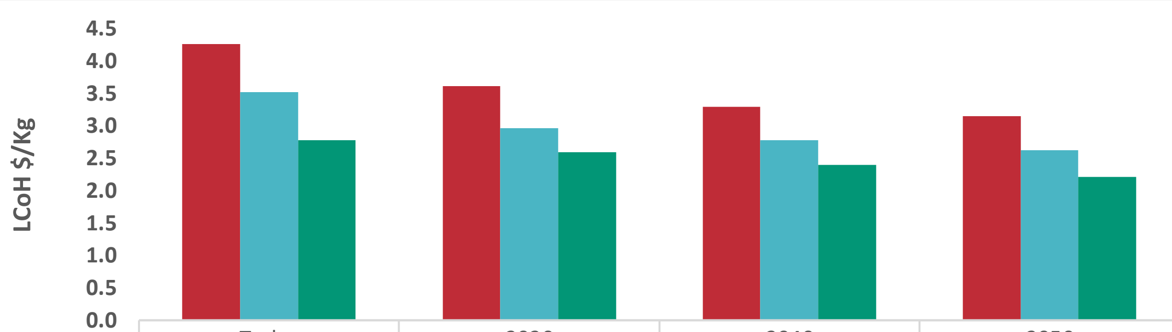
# Green Hydrogen in Bhutan

## Green hydrogen production in Bhutan

Given the huge hydropower potential accounting to ~37 GW, production of green hydrogen using water electrolysis is undoubtedly a promising pathway. In addition to hydropower, alternative renewable energy sources such as solar, wind, etc. could also play a transformative role in green hydrogen production albeit the cost of electricity from these sources would be higher than hydroelectricity at the current juncture.

Considering that 40% - 70%[13] of the cost for producing green hydrogen depends on cost of electricity, given the low electricity price in the region, it is an opportunity for Bhutan to produce green hydrogen at comparatively lower cost. Moreover, with the global interest in green hydrogen as a climate change solution, capital cost of electrolyzer is expected to be reduced significantly over the years. According to the analysis by Roland Berger and Tetra Tech[2], cost of hydrogen with hydropower electricity in Bhutan has a competitive advantage compared to neighboring country like India due to already existing renewable assets.

It is anticipated that the levelized cost of hydrogen (LCoH) will decline with an increase in the scale of electrolyzer as can be seen in Figure 15. This is due to the reduction in capital costs per production unit. Moreover, greater efficiency is achieved in larger electrolyzers as opposed to those with smaller capacities.




| | Today | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Small | 4.3 | 3.6 | 3.3 | 3.1 |
| Medium | 3.5 | 3.0 | 2.8 | 2.6 |
| Large | 2.8 | 2.6 | 2.4 | 2.2 |

Figure 16: Levelized cost of hydrogen (USD/kg)

Disclaimer: The LCoH is subjected to change with change in the electricity tariff. The cost of electricity tariff taken was 32 USD/MWh.

## Green hydrogen storage and distribution in Bhutan

Storage and transport technologies are not governed by specific thresholds. Factors such as available infrastructure and distance play a role in determining the suitable method. Compression is commonly used for transporting hydrogen by truck, especially for shorter distances. Higher pressures are utilized in such cases. However, for longer distances, liquefaction methods, including cryo-compression, are employed. The choice between compression and liquefaction depends on the distance, with compression being used for shorter distances and liquefaction for longer hauls. These methods ensure the safe and efficient transport and storage of hydrogen for its use as a versatile energy source.

For domestic use, pipelines are important for transport of larger quantities of compressed gaseous hydrogen as well as distribution to multiple points of use in a network. However, due to the absence of natural gas pipeline infrastructure and non-navigable rivers, road transport stands as the sole option for hydrogen transportation in Bhutan, which can be through compressed and liquified hydrogen.

| | Truck (Gaseous form) | Truck (Liquid form) | Pipeline |
|---|---|---|---|
| Capacity | Low | Medium | High |
| Distance | Low | High | High |
| Energy Loss | Low | High | Low |
| Fixed Costs | Low | Medium | High |
| Variable costs | High | Medium | Low |

Figure 17: Comparison of distribution routes

The cost of storage and compression depends upon the amount, duration of storage and pressure required for the storage as shown in Table 3

Table 3: Cost of Storage including compression at 350 and 700 bar ($/kg)

| | 350 Bar | 700 Bar |
|---|---|---|
| **Daily storage** | $0.58 | $0.7 |
| **Weekly** | $3.5 | $4.1 |
| **Monthly** | $6.8 | $8.0 |

Whereas the transportation of hydrogen depends upon the amount, distance and the pressure that is to be transported as shown in Table .

Table 4: Cost of transportation at variable distance

| | $/kg |
|---|---|
| **Roundtrip distance: 200km** | $0.5 |
| **Roundtrip distance: 300km** | $0.8 |
| **Roundtrip distance: 500km** | $1.2 |

Nevertheless, of e-Fuels and other hydrogen derivatives as the end products could be the answer to addressing the challenges of storage and transportation.

## Bhutan's Hydrogen Markets

### Industry

Bhutan's economy is largely driven by its agricultural and hydroelectric power sectors but the country is also home to a small but growing industrial sector. The government has made efforts to diversify the country's economy and has implemented policies to promote the development of new industries such as ferro-alloys, steel and cement among the large ones. The increasing demand for energy in these expanding industries presents a challenge that can be addressed through the potential utilization of green hydrogen. By exploring the integration of green hydrogen in industrial processes, we can not only enhance energy security and reduce carbon emissions but also drive sustainable growth and economic development in these sectors.

#### Iron and Steel Industry

Iron and steel products are used in many construction and industrial applications, such as appliances, machinery, bridges, buildings, highways, tools, and vehicles. There are about eight steel industries in the country. Currently, the main raw material DRI/sponge iron for producing steel in the country is imported. One of the country's largest steel industries, Lhaki Steels & Rolling Pvt. Ltd. produced 120,000 MT of Thermo-Mechanically Treated (TMT) steel in 2021 using an induction furnace mainly from the imported sponge iron.

According to the statistical yearbook of 2020, import of 'ferrous products obtained by direct reduction of iron ore' (known as DRI - Direct Reduced Iron/sponge iron) which is a raw material for steel production is listed under the top ten merchandise commodity of import. The country imported DRI worth Nu. 1.88 billion in 2020. Therefore, the use of hydrogen in steel production is not applicable at the moment considering the lack of existing production processes. However, the steel industry in the country could venture into the upstream process to take up the production of sponge iron through use of hydrogen when technology becomes technically matured and commercially viable. The iron and steel industry contributed only about 7.395 Gg $CO_2$ in 2015. If Bhutan takes up the hydrogen application in steel industry, it would require a total hydrogen of 4,200 tons of green hydrogen, with electrolyzer capacity of 24 MW.

According to IRENA (2021), the consumption of green hydrogen in the steel industry is currently limited to demonstration projects. Similarly, SSAB (steel producer), LKAB (iron ore pellet manufacturer) and Vattenfall (power company) in Sweden formed a HYBRIT (Hydrogen Breakthrough Ironmaking Technology) joint venture to explore the feasibility of hydrogen-based steelmaking using the DRI-EAF process and it is expected to have first commercial plant only by 2036.

### Cement Industries

As per the TNC - 2015 (2020), cement industries in the country are one of the most significant sources of GHG emissions with around 378.924 Gg of $CO_2$ emissions annually. The three cement industries in the country, Dungsam Cement, Penden Cement and Lhaki Cement produce clinkers using rotary kilns and mostly use fossil fuels as heat source for clinker production. In cement industries, the GHG emission can be significantly reduced through clinker substitution and use of clean energy in place of fossil fuels.

Hydrogen as a substitute for heating in the process of clinker production is still under development phase and its direct use in the existing industries would turn out to be cost intensive owing to technological limitations in retrofitting the heating kilns and lack of hydrogen distribution networks.

For use of hydrogen in cement industry, it would require a total of 12,000 tons of green hydrogen with electrolyzer capacity of 70 MW. This would require changes in the industrial technologies.

## Mobility

The mobility sector, including the aviation is predominantly dependent on petroleum fuels, which are imported in large quantities every year. The mobility sector, construction sector (machineries), energy generation, and manufacturing industries are the primary consumers of these imported fuels.

## Mobility scenario

It is expected that there will be a continued increase in the number of vehicles at an annual growth rate of 5.2% between 2022 and 2025. The number of passenger cars and taxis is anticipated to increase at rates of 5.2% and 3% resulting in a total of 344,785 and 13,935 units respectively. The number of both public and private buses is projected to grow by approximately 4% annually and reach a total of 3,606 units by 2050. Medium trucks (MDVs) are expected to increase at a rate of 4.9%, while heavy trucks (HDVs) will increase at a rate of 4.3%, resulting in a combined total of 41,926 units by 2050, indicating an increase in freight trade. Furthermore, work vehicles such as EME (Earth Moving Equipment), power tillers, and tractors are estimated to increase at rates of 6.4% and 6.2%, respectively, with a total number of units reaching 22,435 and 23,142 by 2050.

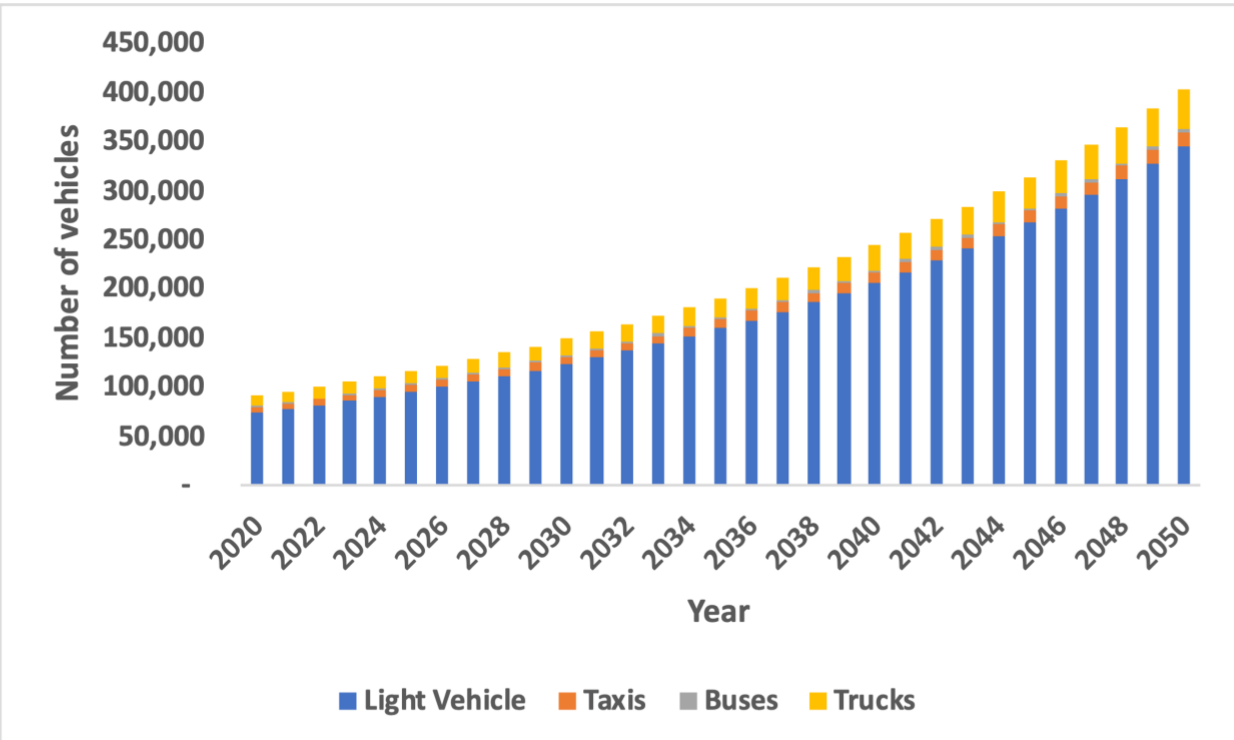



Figure 18: Vehicle growth (data from LEDS)[15]

Regarding greenhouse gas emissions, projections indicate that transport sector-related emissions in the country will steadily increase over the next 30 years to 1.2 million tons of $CO_2e$ by 2050 in the business as usual (BAU) scenario, driven by a compound annual growth rate of around 4%. This however do not take into account of the emission that is produced from work vehicles such as EME, power tillers and tractors.

[15] Low Emission Development Strategy (LEDS, 2020, MoIT)

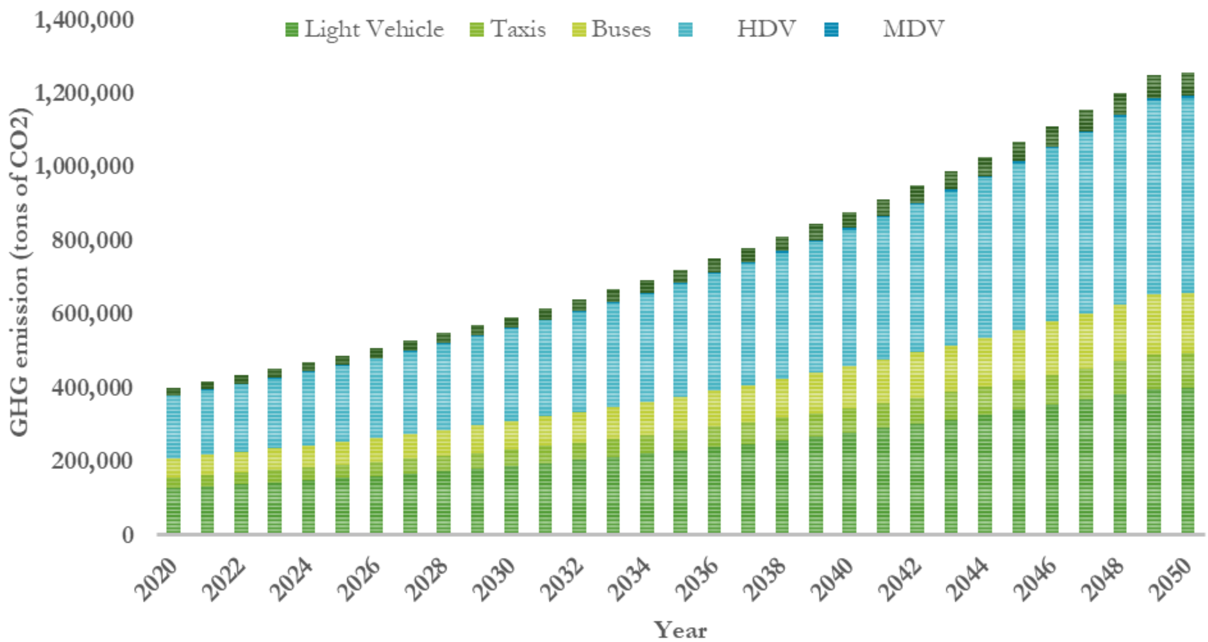



Figure 19: GHG emission projection[16]

The Low Emission Development Strategy (LEDS) places significant emphasis on the reduction of greenhouse gas (GHG) emissions and the balancing of trade deficits by conversion of existing fossil fueled cars to EVs. To achieve these goals, the prioritization of various sectors has been carefully considered. The passenger car, taxi sector and buses have been identified as the most crucial areas for attention and will receive a high level of priority. The heavy duty and medium duty vehicle sectors will receive less focus in the LEDS. It is worth noting that this prioritization is not arbitrary but based on the technological feasibility and readiness of each sector for the transition to electric vehicles.

The anticipated electric vehicle targets based on various vehicle segments according to LEDS is shown in Figure 19. According to the LEDS, the anticipated figures for 2050 indicate that out of the projected total of 344,785 light vehicles and 13,935 taxis, 293,067 light vehicles and 11,845 taxis are expected to be electric vehicles (EVs). Likewise, among the estimated 3,606 buses, it is projected that 2,705 will be EV buses. However, for trucks, including both Heavy-Duty Vehicles (HDV) and Medium-Duty Vehicles (MDV), only 5,870 out of a total of 41,296 units are anticipated to transition to electric vehicles.

[16] Low Emission Development Strategy (LEDS, 2020, MoIT)

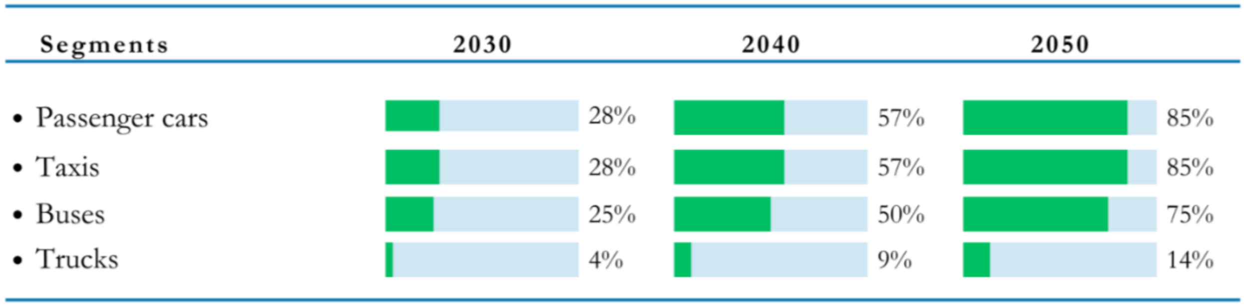


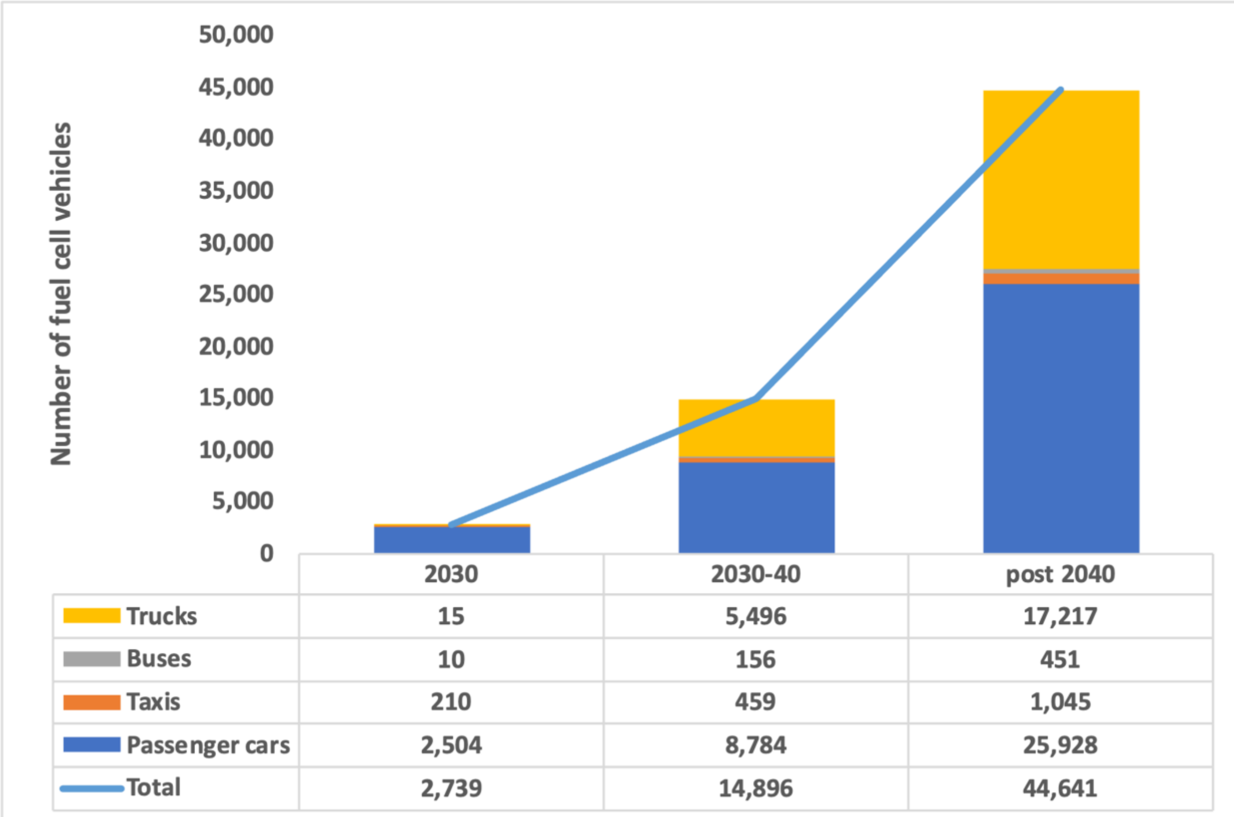

Figure 20: Anticipated EV targets according to LEDS

## Hydrogen potential in mobility sector

The integration of hydrogen mobility presents a substantial opportunity to address the import dependence on fossil fuels, thereby improving the trade balance and achieving noteworthy emission reductions. FCEVs have gained significant attention worldwide due to their potential to significantly mitigate emissions within the transportation sector. FCEVs offer distinct advantages over Electric Vehicles (EVs), including faster refueling times and extended travel distances. However, it is important to acknowledge that cost remains a prevailing challenge in the present scenario. An advantageous aspect of introducing hydrogen-fueled mobility lies in the availability of green hydrogen derived from abundant renewable energy sources. This not only facilitates substantial emission reductions but also diminishes the reliance on fossil fuel imports, resulting in a notable improvement of the trade imbalance.

In the Business as Usual (BAU) scenario, the vehicle projection aligns with the GTM model outlined in the Low Emission Development Strategy. This model considers the projection under the assumption that things continue to operate and progress in a normal or expected manner, without significant changes or disruptions. It reflects a state where existing processes, strategies, and activities remain relatively unchanged, with no major deviations from the established course.

On the other hand, the Business to Be (BTB) Scenario anticipates future shifts in the market due to the technological adoption of Fuel Cell Electric Vehicles (FCEVs) in the country. Consequently, it is projected that, based on the outstanding targets for electric vehicles (EVs) by 2050, 50% of the remaining 15% of the light vehicles and taxis, 25% of buses, and 86% of trucks will be met through the adoption of Fuel Cell Electric Vehicles (FCEVs) by that year.




| | 2030 | 2030-40 | post 2040 |
|---|---|---|---|
| Trucks | 15 | 5,496 | 17,217 |
| Buses | 10 | 156 | 451 |
| Taxis | 210 | 459 | 1,045 |
| Passenger cars | 2,504 | 8,784 | 25,928 |
| Total | 2,739 | 14,896 | 44,641 |

Figure 21: Projected growth of Hydrogen-powered vehicles

The Figure 20 above represents the projected number of hydrogen-powered vehicles in different categories for three time periods: by 2030, 2030-40, and 2040-50. By 2030, it is estimated that there will be a total of 2,739 fuel cell vehicles. Among these, the majority are passenger cars, with a count of about 2,500. Taxis account for 210 vehicles, buses for 10 vehicles, and trucks for 15 vehicles.

Moving into the 2030-50 time period, the number of fuel cell vehicles is expected to experience significant growth. The total count is projected to reach 14,896 by 2040. Passenger cars will continue to remain the largest category, with an estimated count of 8,784. Taxis are expected to increase to 459 vehicles, buses to 156 vehicles, and trucks to 5,496.

Looking ahead to the post-2040 period (2040-50), there will be further expansion of the hydrogen-powered vehicle market. The total number of fuel cell vehicles is projected to reach 44,641. Passenger cars are still the dominant category, with an estimated count of 25,928. Taxis are expected to increase to 1,045 vehicles, buses to 451, and trucks to 17,217.

## Reduction in fossil fuel import

According to the BAU scenario, it is projected that the import of petrol will increase to approximately 43 million liters by 2030, and further escalate to 112 million liters by 2050. Likewise, diesel imports are estimated to rise to 87 million liters by 2030 and reach 214 million liters by 2050. However, if we can successfully implement the BTB scenario, which involves a significant shift towards fuel cell vehicles, we can achieve a reduction in petrol imports to 41.8 million liters by 2030 and to 101.1 million liters by 2050. Additionally, diesel imports can be significantly reduced to 86.5 million liters by 2030 and to 179.4 million liters by 2050 under the BTB Scenario.

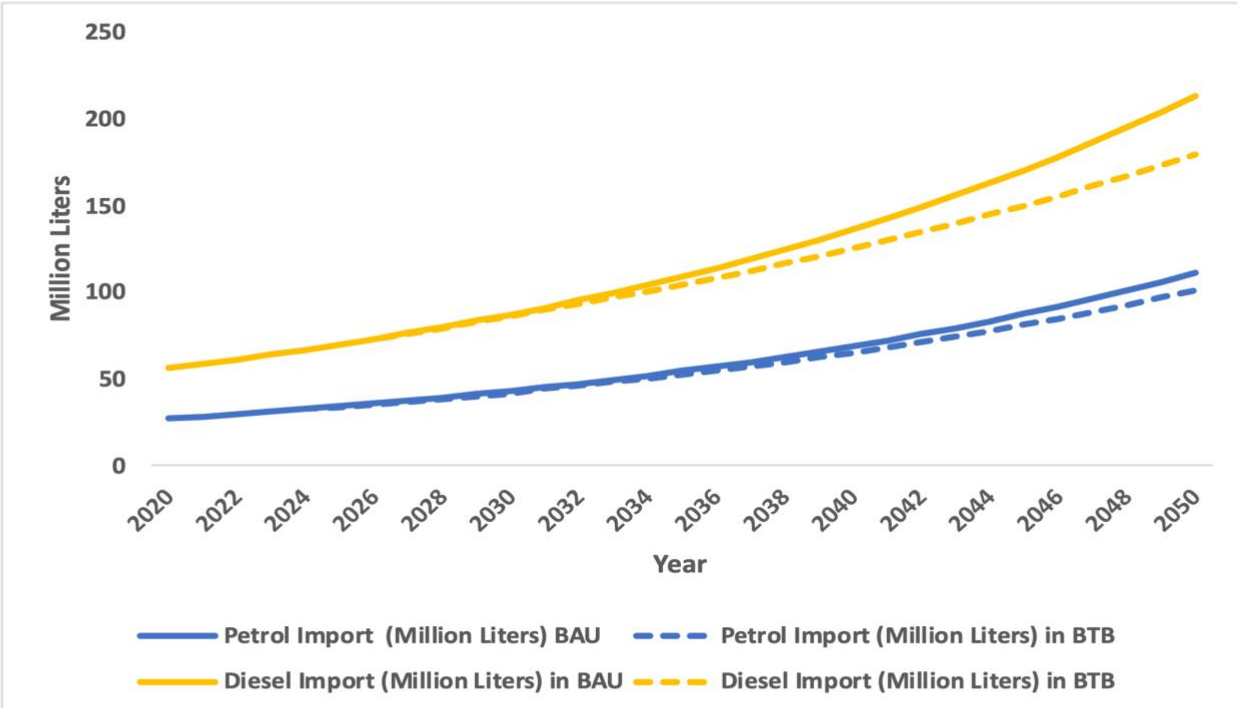



Figure 22 Potential fossil fuel import projection

## Improvement in trade balance

Accordingly, with the reduction in the import of fossil fuel, our country has the opportunity in reducing the gap of trade deficit. In the BAU scenario, the import of fossil fuel (including petrol and diesel) will increase to approximately $152.2 million by 2030 and reach to $562.3 million by 2050. However, under the BTB scenario, the import will be substantially reduced to $150 million in 2030 and by $485.3 million by 2050 narrowing the gap by $2.2 million  and $77 million respectively.

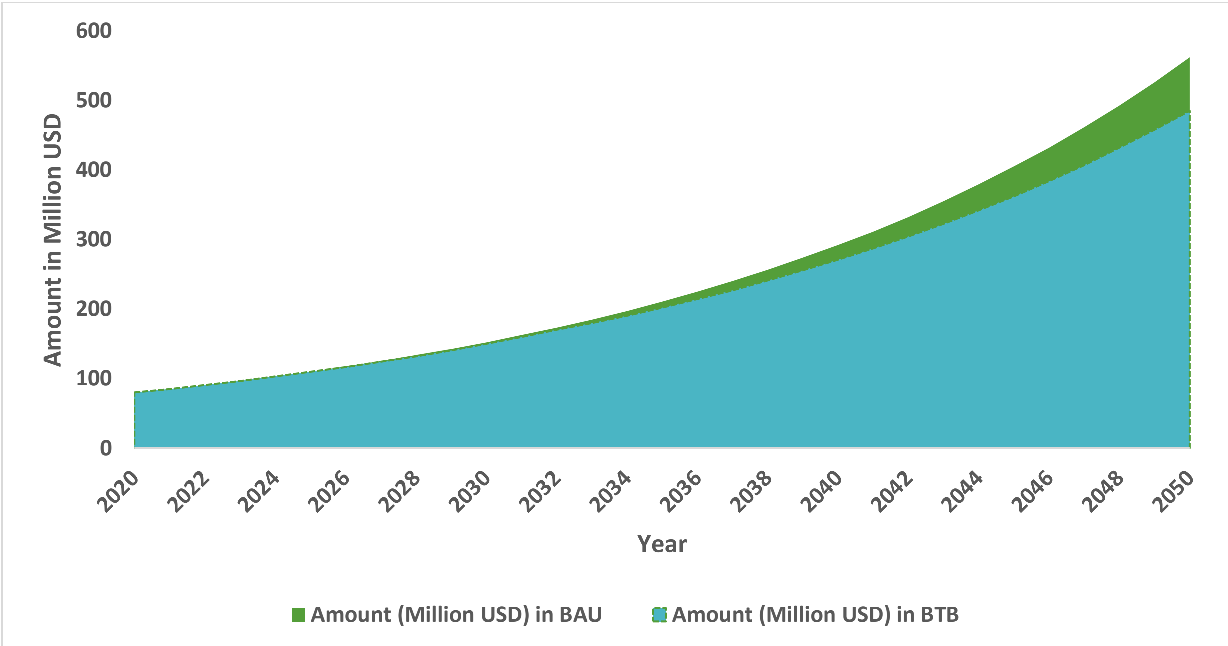



Figure 23: Potential fuel import reduction (value)

## Reduction of GHG emission

If the number of vehicles increases as per BAU scenario, the GHG emission from the transport sector would alone be approx. to 0.56 million tons by 2030 and 1.2 million tons by 2050 under the BAU scenario. However large amount of GHG emission could be reduced by successful conversion of fossil fuel-based vehicles into either FCEVs. If it is achieved then, the GHG emission could be reduced to approx. 0.9 million tons by 2050 under the BTB scenario.

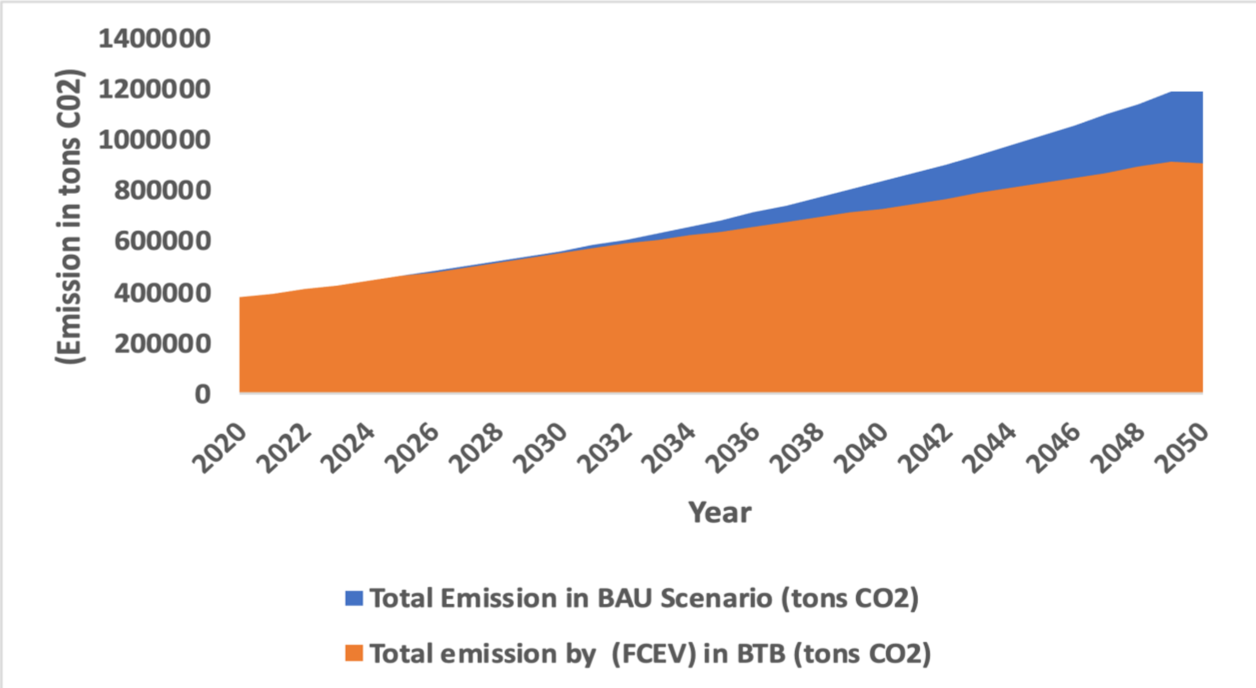



Figure 24: Potential reduction in GHG emission

## Fuel cell vehicles

A total of approximately 44,641 fuel cell vehicles, which is 11% of the total vehicle, is expected to be on road by 2050.

## Annual hydrogen demand for fuel cell vehicles

Under the BTB scenario, the successful conversion of 25,928 light fleet vehicle and 1,045 taxis on road into FCEVs, 450 buses and 17,217 trucks into Fuel cell buses and trucks would require approx. 52,500 tons of hydrogen by 2050.

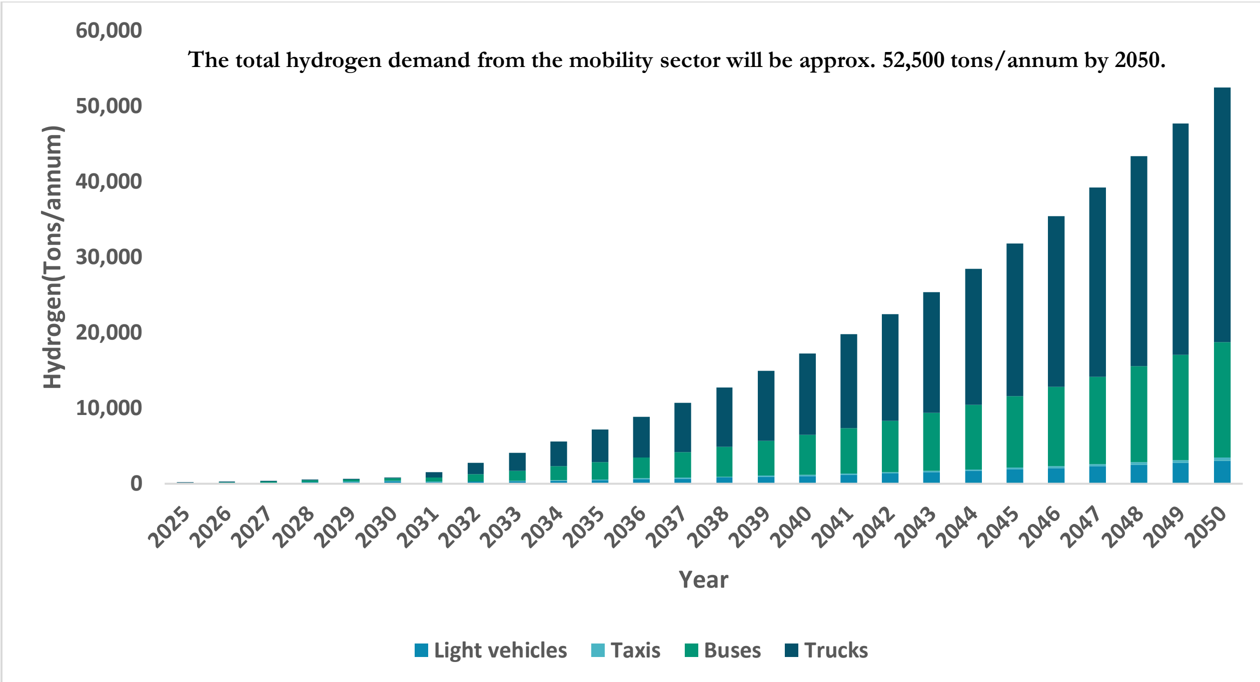



Figure 25: Hydrogen demand by 2050

## The electrolyzer capacity for fuel cell vehicles

To cater the hydrogen demand for the mobility sector, the electrolyzer capacity required would be around 370 MW by 2050 under the BTB scenario.

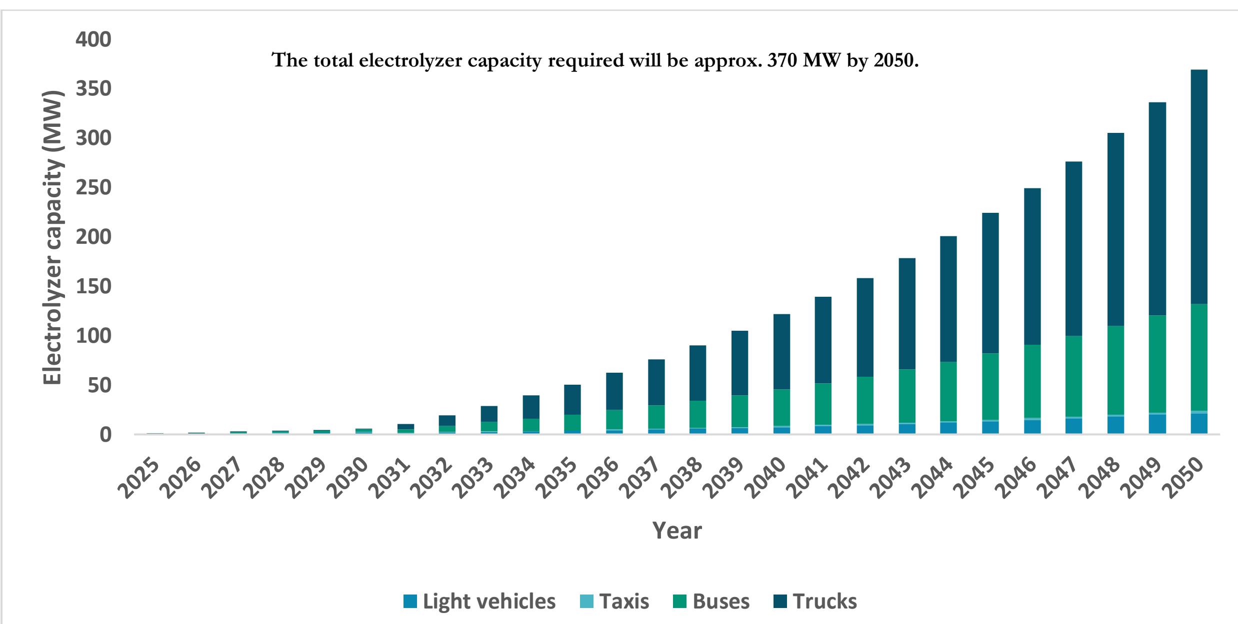



Figure 26: Electrolyzer capacity required for mobility sector

The annual energy demand from the renewable sources for the fuel cell mobility purpose would be about 48 MWh by 2030 and would increase to approx. of 2.9 GWh by 2050.

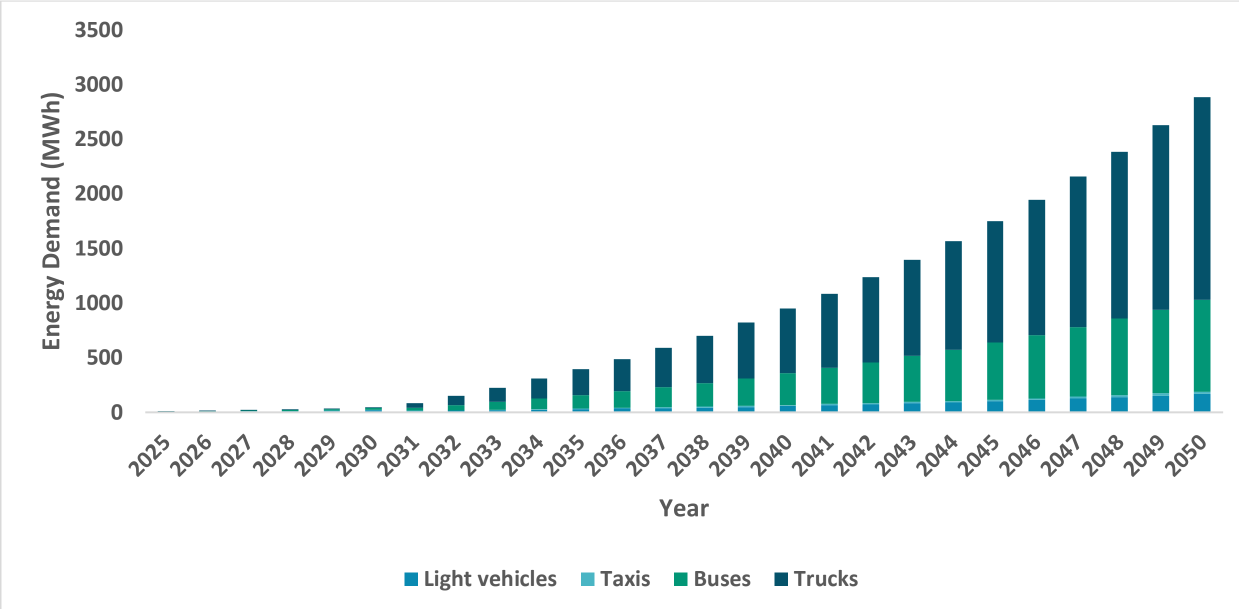



Figure 27: Annual energy demand for the mobility sector

## Synthetic Fuel for mobility

Hydrogen can be combined with carbon, sourced from industries or biomass, to produce synthetic fuels/e-fuels in Bhutan. Biomass carbon can be obtained from forests and wood processing units through Bioenergy with Carbon Capture and Storage (BECCS) methods. Additionally, carbon captured from cement and ferro-alloy industries using Direct Air Capture technologies can be utilized. Cement and ferro-alloy industries are significant contributors to $CO_2$ emissions, accounting for approximately 379 Gg $CO_2$e and 355 Gg $CO_2$e, respectively, according to TNC 2020 data.

However, the production of synthetic fuels using hydrogen is currently a complex process that requires refineries and is still in the demonstration and research stage. Therefore, the production of synthetic fuels may be considered in the future, pending technological advancements and commercialization. Once synthetic fuel or e-fuel production is more accessible and economically viable, it can potentially be used to power existing internal combustion engine vehicles, utilizing the already established infrastructure of refueling stations and other logistics. The potential of e-fueled vehicles is shown in Figure 27.

| Segments | 2040 | 2050 |
| --- | --- | --- |
| • Passenger cars | • 8,784 | • 25,928 |
| • Taxis | • 459 | • 1,045 |
| • Buses | • 156 | • 451 |
| • Trucks | • 5,496 | • 17,217 |
| • Total (e-fuel in million liters) | • 27.5 | • 84.5 |
| • Hydrogen demand (tons/annum) | • 205 | • 631 |

Figure 28. Potential of e-fueled vehicle in mobility sector

## Power Generation and long-term energy storage

As the disparity between firm power and peak demand continues to widen, the necessity for long-term energy storage has become increasingly evident. In this context, the integration of green hydrogen as a storage solution offers a highly promising opportunity within the electricity generation landscape. By capitalizing on excess hydroelectricity through electrolysis to produce green hydrogen and effectively utilizing it during periods of high demand or limited generation, a viable and sustainable approach to energy storage can be achieved.

### Electricity generation scenario

The country has the potential to generate huge quantum of electricity due to its rich hydropower resources. The electricity generated by these hydropower plants is more than enough to meet the country' electricity demand. As a result, Bhutan exports its excess electricity to neighboring countries like India, contributing significantly to the country's economy. Bhutan still has the capacity to generate another 30,000 MW of electricity.

Power System Master Plan 2040 estimates that the country has a hydropower potential of 32,600 MW that are techno-economically viable. Generation capacity is expected to reach 5,570 MW installed capacity after commissioning of the 118 MW Nikachhu Hydropower Project, 1,020 MW Punatsangchhu-II Hydropower Project, 600 MW Kholongchhu Hydropower Project, 1,200 MW Punatsangchhu-I Hydropower Project and 299 MW Phase-I & II Small Hydropower Projects. However, the resulting firm power addition from these mostly run-of-river hydropower projects will barely reach 975 MW.

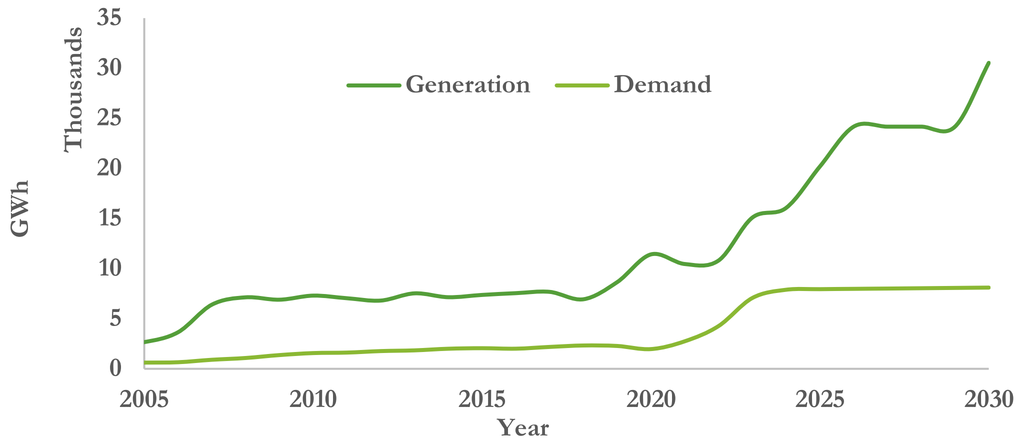


Figure 29: Energy generation and demand forecast

The peak demand is expected to increase from 369 MW in 2020 to 1,800 MW- 2400 MW in 2040, indicating a significant growth in electricity demand over time surpassing the firm power capacity addition, thus necessitating import of electricity to meet the gap between the firm power and peak demand.

## Long-term energy storage

Bhutan's electricity generation scenario, with its abundant hydropower resources, provides an ideal opportunity for exploring the potential of hydrogen in electricity generation. By producing green hydrogen through electrolysis during periods of excess hydroelectricity and utilizing it during high demand or lean seasons, Bhutan can enhance energy security, balance the grid, and optimize resource utilization. Integrating hydrogen into the electricity generation mix complements renewable energy efforts and contributes to a sustainable and resilient energy system for the country.

By 2030, the disparity between firm power and daily peak demand is projected to expand to 800-1,400 MW. To address this growing gap, it becomes imperative to have a seasonal hydrogen storage capacity that can effectively bridge this difference. By using hydrogen for bridging the gap, it would require about 15 tons of hydrogen storage capacity by 2030. As a consequence, the levelized cost of storage is driven up to approximately 4 USD/kg, pushing the levelized cost of electricity beyond the economically feasible range. Accommodating around 15 tons of hydrogen storage capacity would necessitate an investment of approximately 8 million USD.

## Fertilizer

Urea, an ammonia-based fertilizer, is widely used in Bhutan for agricultural purposes. Over the past 15 years, the Ministry of Agriculture has consistently supplied an average of around 1,300 MT of urea per year, which are all imported. Although ammonia is not currently utilized in any industries within the country, it holds potential as a raw material for the production of ammonia-based nitrogen fertilizers like urea and ammonium nitrate in the future, requiring the establishment of a new plant.

Presently, a significant portion of the ammonia available in the market is derived from non-renewable sources. This poses challenges for introducing green ammonia into the market due to its higher production costs. To meet the fertilizer demand of 1,300 MT, 740 tons of green ammonia per annum is required, which translates to 133 tons of hydrogen per annum. This would require electrolyzer capacity of 1 MW.

## Hydrogen trading and potential export-import routes in the region

The first routes for hydrogen import and export are expected to be established by 2030, with a primary focus on Asia. China and India are anticipated to generate cost-effective hydrogen for local use. However, importing ammonia might be a more economical option. Other nations may need to depend more heavily on imports. While local hydrogen production is usually more affordable, the inclusion of conversion costs suggests that creating derivatives and trading from economically viable locations is more advantageous. China is likely to focus more on producing and consuming its own hydrogen rather than manufacturing its own derivatives such as ammonia, green steel, methanol, and synthetic kerosene, which are less expensive to transport globally. The benefit of local derivative production is relatively minor as hydrogen conversion is location independent. Transportation costs are also comparatively marginal due to higher volume density.

### China

In China, hydrogen demand is projected to rise to approximately 40 million tons per annum by 2030 and 195 million tons per annum by 2050, according to the Hydrogen Council. The country's hydrogen production is expected to shift from grey (coal-based) hydrogen to blue hydrogen, with increasing renewable capacity likely leading to dedicated green hydrogen production. Given the high potential for green hydrogen production, China may not become a significant exporter or importer of hydrogen in the future.

China's main hydrogen clusters are located in the east of the country, near the Pacific coast. Hydrogen projects across the value chain are concentrating near the industrial areas, with a total of 53 announced ones. Key industrial areas where green hydrogen has a high potential to support decarbonization (e.g., steel, cement manufacturing) are located in the Central and Eastern part of the country. China will need to invest into infrastructure development (mainly pipelines) to enable the transport of green hydrogen/ammonia to the economic heartland. During the transition period, the country might require additional import of green products directly supplying the industrial clusters.

### India

India's hydrogen demand could more than quadruple by 2050 and 95% of it could come from green hydrogen. The country plans to establish five hydrogen hubs by 2025, grouping 25 green hydrogen projects with multi-sectoral demand. Industry body India Hydrogen Alliance (IH2A) has submitted plans for 25 renewable hydrogen projects under five national clusters generating 28,000 tons of green hydrogen by 2025. The designated hydrogen clusters aim to use hydrogen in fertilizer production, steel manufacturing, refining, transport and blending.

Several of the most significant clusters for hydrogen deployment are located close to India's renewable resources (e.g., Rajasthan, Maharashtra, Gujarat, Karnataka). Cluster identification should be guided by concentration of existing and expected end-use facilities and cost of hydrogen production given local dynamics. There is a possible early industry cluster in India focusing on fertilizer and petrochemical in the western coasts and iron and steel in the eastern belt. Several of the most economically significant clusters, from the perspective of hydrogen deployment, are located close to some of India's best renewable resources.

**South Korea**

Korea relies heavily on imports for hydrogen, as more than half of its hydrogen demand will come from overseas in 2030. The country is focusing on the industrial use of hydrogen in power generation. By 2050, ~50% of hydrogen is projected to be used in energy production.

Key hydrogen clusters are located on the coastlines, where possible hydrogen and ammonia hubs could develop:

- **Ulsan:** USD ~1 bn investments for demonstrating hydrogen pipelines, housing and mobility in 2020-2030
- **Ansan:** Constructing infrastructure for producing H2 from a local gas reforming and tidal power station
- **Wanju/Jeonju:** Deploying H2 production facilities for Hyundai's neighboring manufacturing plants

Additionally, six R&D Technoparks for building cutting-edge infrastructure, promoting regional industry, and connecting businesses and innovation actors.

South Korea's infrastructure is built out on the coastal areas where the main industrial hubs are located. The south-west coast of Korea, around the cities of Ulsan, Busan and Masan, is heavily industrialized with several major refinery, steel and chemical plants. The north-eastern coast of the country, where Seoul and Incheon are located, is also home to significant industrial clusters, as the country's dependence on imports has created the necessary infrastructure.

The ports of Busan, Ulsan and Incheon have already started hydrogen and ammonia pilot projects and could host future ammonia and hydrogen hubs.

**Japan**

Japan has the world's largest industrial centers with several potential hydrogen offtakers on its southern coast. Major industrial offtakers are often located near the coastlines, as these areas facilitate easy transportation of goods through ports and waterways. There are three major clusters of integrated hydrogen value chain activity currently in development in Japan:

- The Kansai Area houses several innovative hydrogen transport projects, such as HySTRA, a hydrogen supply chain pilot between Australia and Kobe
- The potential hydrogen demand of Chubu region will reach 40,000 t p.a by 2025 and 110,000 t p.a by 2030 (one-third of the Japanese national target). Power generation, refining and chemical sectors will account for 80% of total demand
- The City of Yokohama and ENEOS aim to develop a regional hydrogen hub with an established hydrogen pipeline and transport infrastructure
- AHEAD launched the world's 1st foreign-sourced hydrogen supply chain to transport hydrogen from Indonesia to Tokyo Bay for power generation

## Bhutan's potential to participate in the regional hydrogen trading

Bhutan also holds export opportunities in the emerging hydrogen market. With its abundant renewable energy resources and potential for green hydrogen production, the country can tap into the growing global demand for clean energy solutions. The availability of competitive and renewable electricity from hydropower plants provides a competitive advantage in producing cost-effective green hydrogen. Due to the low volumetric density of hydrogen in its pure form, a series of hydrogen carriers has to be utilized in order to improve the economics of storage. This can be realized through storage and distribution in the form of liquified hydrogen, green ammonia and methanol, however, it presents challenges due to huge energy loss (very low roundtrip efficiencies) and also requires significant investment in new infrastructures for the conversion to its derivatives.

Bhutan's strategic location in South Asia, offers proximity to large and expanding markets for hydrogen. Exporting green hydrogen not only contributes to the reduction of carbon emissions but also presents an opportunity to improve Bhutan's trade balance and strengthen its economy. However, to fully capitalize on these opportunities, the development of infrastructure and technology would be essential to enable efficient and reliable hydrogen trade. Furthermore, establishing international partnerships and leveraging Bhutan's reputation as a sustainable and environmentally conscious nation could further enhance the country's position as a reliable supplier of green hydrogen in the global market.

| | Today | Post 2030 | Post 2040 |
|---|---|---|---|
| **Surplus Electricity (in GWh)** | 2,940 | 7,356 | 23,568 |
| **Electrolyzer Capacity (in MW)** | 376 | 942 | 3,018 |
| **Hydrogen Potential (in tons)** | 53,418 | 133,651 | 428,207 |

Table 4 Overview of the Theoretical Hydrogen Production for export

Disclaimer: The Surplus Electricity generation is derived from the Demand-Supply forecasted by Power System and Market Division, 2023. For analysis, hydrogen production rate of 18 Kg/hour was taken into consideration for 1 MW plant with utilization factor of 90% in a year. The energy consumption for 1 Kg of hydrogen was considered as 55 kWh for Alkaline Electrolyzer.

## SWOT

The Strengths, Weakness, Opportunities and Threats (SWOT) of hydrogen in the country are as follows:

### Strength

- Abundance of renewable energy resources
- Well-established and interconnected grid
- Government support
- Bhutan's unique brand as a net carbon negative country
- Proximity to large potential markets
- Hydrogen as a viable alternative to fossil fuels and balancing opportunities

### Weakness

- Lack of demand within the country
- Seasonality and intermittency of renewable energy generation
- Enabling infrastructure for hydrogen value chain
- Limited technical expertise in hydrogen
- Access to finance and investment for hydrogen projects
- Need for comprehensive regulatory frameworks for hydrogen value chain.

## Opportunities

- Enhancing the energy security of Bhutan and energy diversification
- Significant contribution to maintaining Carbon-neutral status
- Business/investment opportunities, such as exporting green hydrogen to regional countries
- Trade balance
- Knowledge and technology transfer with local skill development
- Opportunity to generate foreign reserves
- Employment opportunities
- Contribute to regional and global decarbonization efforts
- Technology and innovation hub

## Threats

- Competition in the regional market
- Competing priorities for land-use
- A small population and lack of public acceptance to accept new technologies
- Fast-evolving technology and markets

## Targets

Key milestones and activities for the Near term (2023-30) to lay foundation, Mid-term (2030-2040) to roll out and diversification, and Long-term (2040-50) for expansion.

### Near Term: Laying the Foundation (2023-30)

In the coming years, the country will embark on the establishment of a hydrogen economy by focusing on demand creation and laying the necessary groundwork. The key objectives will involve strategic planning and the development of a robust supply and distribution infrastructure for hydrogen, which will support the early deployment of hydrogen from mature technologies and applications and enable demonstrations in emerging sectors.

To attract immediate investment and ensure a conducive environment for hydrogen development, the implementation of effective regulations will be crucial. This regulatory framework will provide clarity, guidelines, and incentives for industry stakeholders to participate in the hydrogen sector. Conducive policies and measures including regulations will be necessary to create a supportive framework for the growth of the hydrogen sector in Bhutan.

To achieve these objectives, the following targets can be set for the near term:

1. Develop Hydrogen Deployment Strategies:
   Formulate comprehensive strategies taking into account specific sectoral priorities and potential applications.
2. Develop Policy, Regulatory, Standards, and Codes:
   Create a range of policies, regulations, standards, and codes that facilitate the growth of the hydrogen sector. These measures should address market incentives, licensing, safety protocols, environmental considerations, and other relevant aspects as well as well as promote alignment and collaboration with international standards to ensure compatibility and interoperability.
3. Implement Demonstration Projects:
   Facilitate the implementation of demonstration projects to showcase the viability and benefits of hydrogen technologies across various sectors. These projects will help build confidence among stakeholders whilst testing the markets.
4. Establish Robust Supply and Distribution Infrastructures:
   Focus on developing a reliable and efficient supply and distribution infrastructure for hydrogen. This infrastructure should support the increasing demand for hydrogen and ensure its availability in different regions and sectors.
5. Engage with local, regional, and international stakeholders:
   Develop partnerships with technology providers, EPCs, Institutions, Funds, and renewable generation providers.

By prioritizing these activities and laying a solid foundation through strategic planning, policy development, and infrastructure establishment, the aim is to drive down costs, enhance technology know-how, and develop the necessary skills for the wider deployment of green hydrogen technologies. This approach will facilitate a smooth transition into the next phase of the hydrogen economy, where hydrogen can play a crucial role in achieving energy security, sustainability and decarbonization goals.

### Medium Term: Growth and Diversification (2030-2040)

The medium-term focus will be on implementing activities that stimulate the hydrogen sector, setting the stage for subsequent growth and diversification between 2030 and 2040. As the technology progresses and reaches commercial readiness levels across various end-use applications, the focus will shift towards prioritizing hydrogen utilization in key sectors. This strategic approach ensures that the deployment of hydrogen aligns with its full potential, maximizing its benefits in a cost-effective manner while also contributing to the environment.

### Long Term: Rapid Market Expansion (2040-50)

In the 2040-2050 timeframe, Bhutan envisions the realization of a thriving hydrogen economy, characterized by significant growth and diversification in the sector. As the technology matures and more end-use applications reach commercial readiness levels, is it envisaged to witness the expansion of hydrogen deployments and the emergence of new commercial applications. Supported by a robust supply and distribution infrastructure, Bhutan can harness the full potential of hydrogen as a clean energy carrier, driving sustainable development and contributing to the country's long-term energy goals. The rapid market expansion phase will be marked by widespread adoption of hydrogen technologies across various sectors.

In transportation, hydrogen fuel cell vehicles will become more prevalent, offering a zero-emission alternative to conventional vehicles. Bhutan's commitment to renewable energy sources will make green hydrogen a key component of the transportation sector, further reducing greenhouse gas emissions.

In the industrial sector, hydrogen will play a vital role in decarbonizing processes in iron, steel and cement production, as well as in the manufacturing of chemicals and other products. The availability of cost-effective green hydrogen will enable industries to transition away from fossil fuel-based processes, contributing to sustainable industrialization goals. Moreover, hydrogen will increasingly be integrated into the power generation sector, supporting the intermittent nature of renewable energy sources. Hydrogen-based energy storage and power-to-gas technologies will enable the storage of excess renewable energy during periods of high production and its subsequent conversion back to electricity when needed, ensuring a stable and reliable power supply.

As the hydrogen economy expands, Bhutan will continue to foster innovation and research in hydrogen technologies, driving further advancements and cost reductions. This will lead to improved efficiencies, increased competitiveness, and wider adoption of hydrogen solutions. The rapid market expansion of the hydrogen economy will not only drive economic growth but also contribute significantly to environmental sustainability. By replacing fossil fuels with clean hydrogen, Bhutan will reduce its carbon footprint, mitigate climate change, and preserve environment goals.

Furthermore, Bhutan's commitment to international collaboration and partnerships will enable knowledge exchange, technology transfer, and access to global markets. This will enhance Bhutan's position as a leader in the hydrogen sector and contribute to the development of a global hydrogen economy.

## Hydrogen production targets

| Production | SHORT TERM 2023-30 | MEDIUM TERM 2030-40 | LONG TERM 2040 -50 |
|---|---|---|---|
| ELECTROLYZER CAPACITY (MW) | 5 | 123 | 485 |
| $H_2$ PRODUCTION (TONS PER ANNUM) | ~710 | ~17,750 | ~69,580 |
| NU. LCOH (USD/KG) | 2.6-4.3 | 2.6-3.6 | 2.2-3.1 |
| INVESTMENT COST (COST IN MILLION USD) | ~8 | ~145 | ~395 |

Figure 30: Hydrogen production targets

## Hydrogen in Mobility sector

The following figure is the anticipated target of fuel cell vehicles in various vehicles segments. The figure below is the percentage of the fuel cell vehicles from the total vehicle fleets.

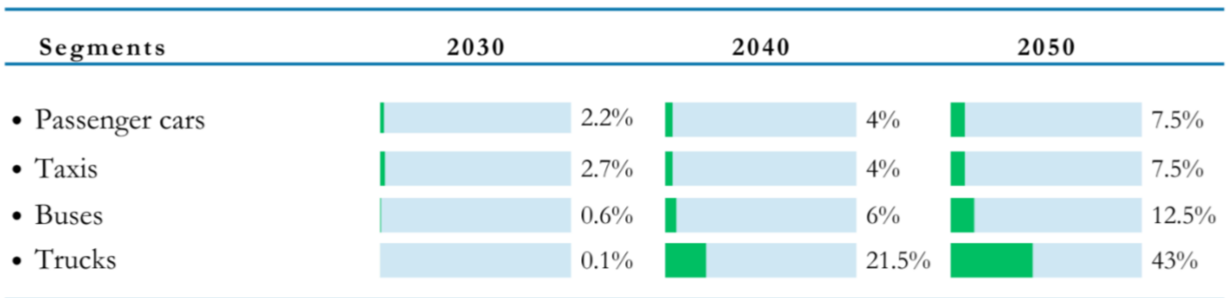



Figure 31: Fuel cell targets by segments

A total of approximately 44,641 fueled vehicles, which is 11% of the total vehicles are expected to be on road by 2050. In order to cater to the hydrogen demands of these FCEVs, a total of 188 hydrogen refueling stations are required across the country.


Figure 32:Fuel cell mobility targets

Through this, 14.1% of fossil fuel import by 2050 worth $79.5 million can be reduced. Similarly, approximately 0.29 million tons of carbon emission per annum can be reduced.

Investing in hydrogen as a fuel source faces challenges in competing economically with traditional fuels, especially in areas like transportation. Further research and development are needed to reduce costs and make hydrogen more competitive. To attract industry players and move towards self-sustainability, investments in infrastructure and subsidies over the next 5-10 years are crucial. Initially, the focus will be on passenger cars, with around $150 million earmarked out of a planned $180-190 million. Investments in trucks and broader transportation will increase in the mid- to long-term, ultimately becoming the main focus by 2050. Approximately $263 million is estimated to be invested in hydrogen refueling stations by 2050.


Figure 33: Required investment for mobility sector

## Hydrogen in Industry Sector

A total of 16,200 metric tons of hydrogen will be required for the steel and cement industry. For this, a total of 115 MW of electrolyzer will be required.

| Industry | Hydrogen demand | Electrolyser Capacity |
|---|---|---|
| • Cement | 12,000 tons | 85MW |
| • Steel | 4,200 tons | 30MW |

Figure 34: Hydrogen in Industry sector

## Pilot project

With Bhutan having a strong focus on the mobility applications of hydrogen a feasibility study has been carried out, with the purpose of preparing the first pilot project of the country. The project will include procurement of vehicles for offtake and a hydrogen production unit.

The project will aim to procure a number of fuel celled vehicles in the coming years and appropriate policies and schemes will follow to extend the fleet in the future.

In 2024 the construction and commissioning of a 5 MW plant is going to be introduced that will cater to the demand of the fuel cell vehicles that were purchased.

In the project's feasibility study, site selection and plant layout were also considered and as the main offtake sector would be transport, it is most appropriate to start up with the installation of a green hydrogen plant near populated areas.

Thimphu Dzongkhag being the most populated city and having the highest number of vehicles, hence being a major contributor to emissions was chosen as the ideal site for the pilot project. After considering the number of vehicles a 5 MW green hydrogen plant with an on-site refueling facility was chosen to be set up in Gidawom located next to the Gidakom Mini power Plant between Thimphu and Paro with the purpose of offsetting emissions. The site location is shown in the figures below.

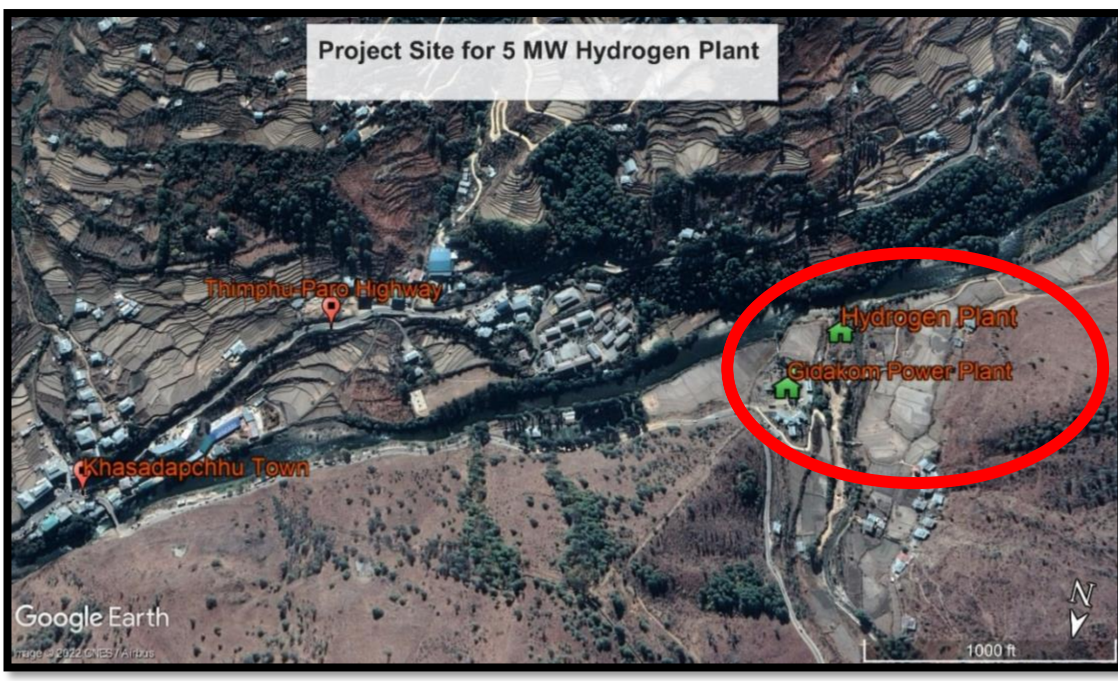



Figure 35: Site for 5 MW hydrogen Plant

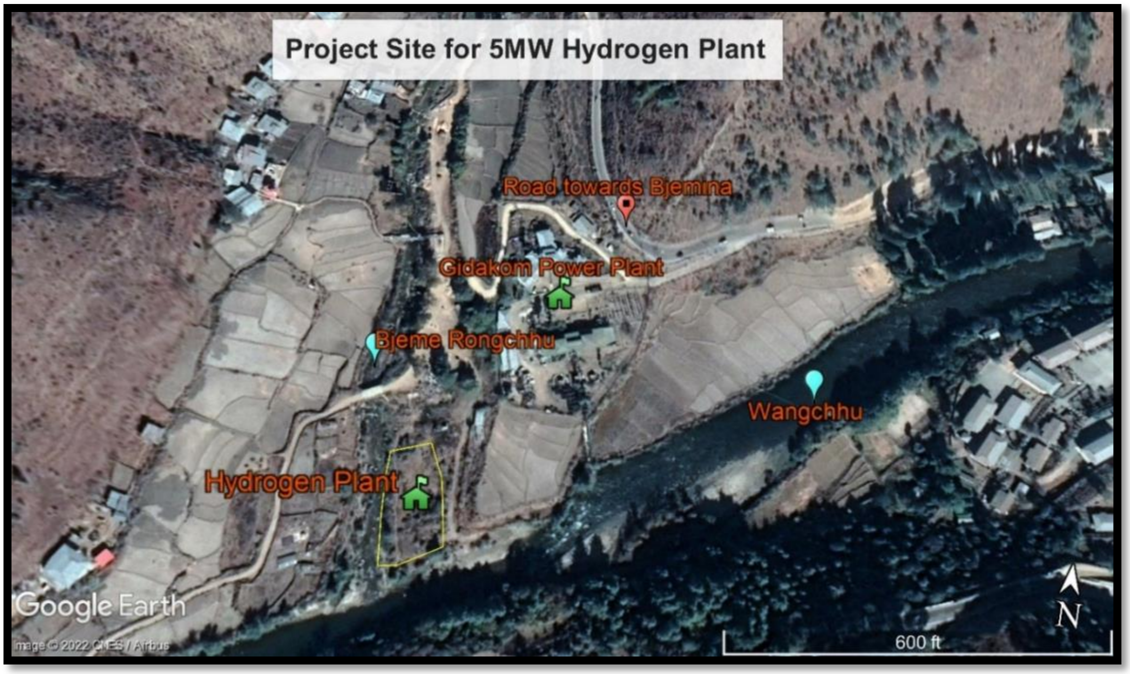



Figure 36: Closer view of the project site

Given the locations ground profile excavation and labelling work will begin to prepare the area. River training work will be carried on Bjeme Rongchhu to feed water into the distillation unit and additional water storage tanks. The site will also feature hydrogen storage units and a fueling station as shown in the figure.


Figure 37: Project site details

## Key Enablers

### Economic and Investment

The economic competitiveness of hydrogen is currently a key limitation compared to conventional fuel options. Despite its potential as a low-cost alternative for reducing carbon emissions, hydrogen remains more expensive than natural gas in various applications. Achieving scale and predictable, long-term demand are crucial for the economic viability of the hydrogen sector. Cost barriers in end-use applications, such as transportation and heating, require further research and development investment to achieve cost parity with alternatives. Temporary support, including investments in infrastructure and subsidies, is necessary in the next 5-10 years to attract industry investment and drive the sector towards self-sustainability.

Such support can only be achieved with the involvement of Bhutanese government bodies and through the establishment of new governmental programs. The government will play a key role in enabling hydrogen development, through supporting hydrogen initiatives and overall establishing a financially attractive environment. For this a wide variety of instruments are at the disposal of the country. Allocating research grants and funding to local institutions, such as the Royal University of Bhutan, will facilitate the cultivation of a domestic talent pool, thereby enhancing the country's capacity for independent development. Strategic infrastructural investments will play a pivotal role in advancing the development, testing, and implementation of emerging hydrogen technologies. These investments will not only contribute to the enhancement of production but will enable efficient transportation and storage which will be crucial in reaching the mid- and long-term vision of the country. Furthermore, it is the goal of the Bhutanese government to attract certain foreign entities and motivate their involvement alongside the green hydrogen value chain. This could be achieved through offering incentive and subsidy packages, tax breaks and credits making it economically feasible and attractive for said entities to enter the Bhutanese sustainable energy market.

Given Bhutan’s developing nature external financing sources are likely to be introduced to its monetary base. Multiple development banks and banking groups offer hydrogen related investment opportunities with many of them focusing on emerging economies. Bhutan has the opportunity to engage with relevant institutions and pursue participation in specific programs, seeking financial partnerships to facilitate its green hydrogen development initiatives.

### Technology and Innovation

Sustained support for R&D is crucial to reduce costs, develop solutions in emerging applications, and discover new breakthrough technologies in the hydrogen sector. However, Bhutan faces a policy gap in long-term R&D commitment, which may limit private sector investment and hinder innovation. Local deployments are essential for collaboration, hands-on experience, and practical solution development, but the lack of domestic deployments will hinder innovation in the sector.

## Policy Measures

Bhutan can benefit from developing comprehensive policies and regulations that incorporate hydrogen. The hydrogen policy landscape varies across countries, with Europe (particularly the UK, Netherlands, and Italy), South Korea, and China leading the way. Some of these could be useful for Bhutan to emulate. Some policy measures are as shown in Table 5.

Table 5: Policy Measures

| Policy Measure | Objectives | Description |
|---|---|---|
| **Funds** | Support for clean hydrogen and market scale up | Provision of financial resources to support the development and deployment of clean hydrogen technologies and stimulate the growth of the hydrogen market. |
| **Tax exemption** | Support for clean hydrogen and market scale up | Granting tax exemptions or incentives to businesses and individuals engaged in clean hydrogen production, distribution, and utilization. |
| **Free grid connection** | Support for clean hydrogen and market scale up | Providing free or subsidized grid connection for clean hydrogen projects to facilitate integration into the energy infrastructure. |
| **Research and Development partnership** | Training and Capacity building | Establishing partnerships for research and development activities to enhance technical expertise, foster innovation, and build capacity in the sector. |
| **Research and Development partnership** | International collaboration | Encouraging international collaboration and knowledge exchange in clean hydrogen research and development. |
| **Emission Trading Scheme** | Phase out polluting fuels | Implementing an emission trading scheme to gradually reduce and phase out the use of polluting fuels in favor of cleaner alternatives like hydrogen. |
| **Flat carbon tax** | Phase out polluting fuels | Implementing a flat carbon tax on polluting fuels to discourage their use and promote the adoption of cleaner alternatives such as hydrogen. |

## Hydrogen and Infrastructure

The successful deployment of green hydrogen relies on the development of robust infrastructure to support its production, storage, transportation, and utilization. Key infrastructure components include electrolyzers for hydrogen production, storage facilities to ensure reliable supply, and an extensive network of pipelines or other transport systems to distribute hydrogen to end-users. Furthermore, refuelling stations or charging infrastructure for hydrogen-based vehicles and equipment are crucial to enable widespread adoption.

Developing such infrastructure requires careful coordination between industry stakeholders, policymakers, and investors. It also necessitates upfront investments to establish the necessary infrastructure and ensure its scalability as demand for green hydrogen grows. By prioritizing the establishment of a comprehensive and integrated hydrogen infrastructure, we can accelerate the transition to a sustainable and decarbonized energy system powered by green hydrogen.

## Codes and Standards

The deployment of hydrogen in Bhutan is non-existent at present. To see a widespread adoption of hydrogen applications, there is a need to develop/adopt codes and standards to provide a seamless adoption of hydrogen technologies. Resolving complex local and regional challenges related to certification and deployment of new hydrogen technologies may require significant effort and time. Harmonizing codes and standards across jurisdictions, both within Bhutan and internationally, will ensure consistent practices and facilitate trade and collaboration in the hydrogen sector. By actively participating in international efforts and aligning with established methodologies, Bhutan can pave the way for the successful deployment of hydrogen technologies and contribute to a sustainable future.

## Awareness

Currently, there is a lack of awareness about the potential opportunities and safety aspects of hydrogen among the general public in Bhutan. Successful pilot projects are crucial to demonstrate the safety and reliability of hydrogen technologies. Increasing awareness about hydrogen as a safe and economically beneficial decarbonization pathway is vital for the development hydrogen. Targeted awareness campaigns, including user-friendly tools to evaluate hydrogen options, can play a significant role in promoting adoption. Moreover, it is important to create awareness about the career opportunities available in the hydrogen economy and provide training for both mid-career workers transitioning into the low-carbon technology sector and the next generation of skilled labor.

## Partnerships

The establishment and cultivation of stakeholder relationships will be essential for Bhutan to reach its setout targets. Potential stakeholders are present both locally on a nationwide level but also internationally.

On a local level key stakeholders to be included in Bhutan's hydrogen transition are Druk Holding and Investments and its subsidiaries, Bhutan's selected Authorities and the Bhutan Power System Operator.

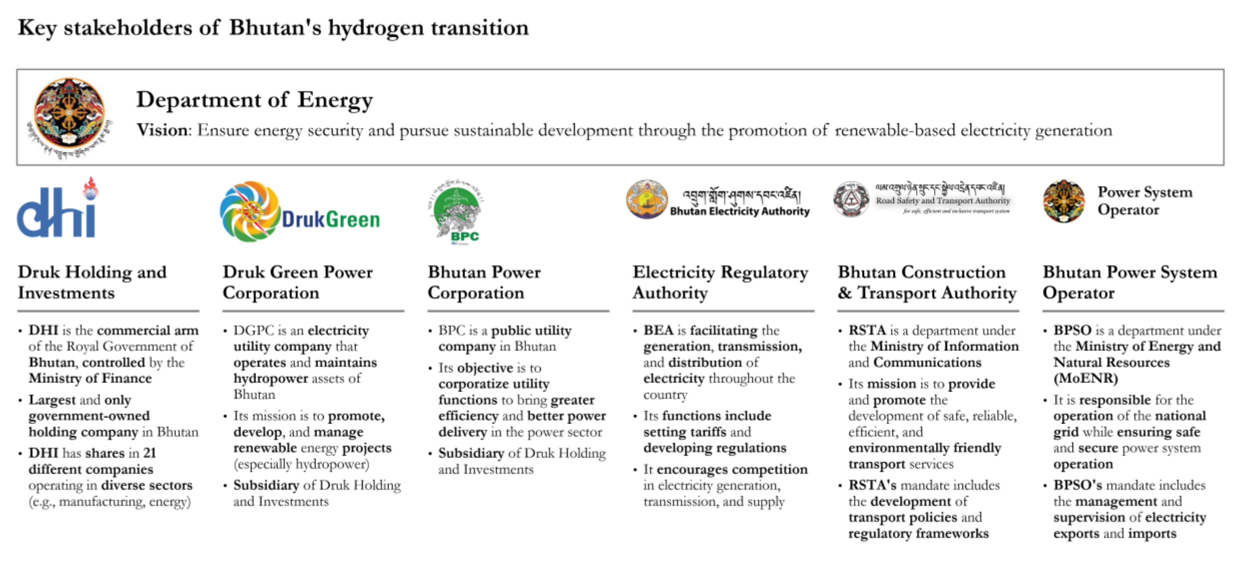



Figure 38: Local Bhutanese hydrogen transition stakeholders

Potential global stakeholders can be grouped in four main categories. Given the countries developing nature and its industrial experience carrying out hydrogen developments can only be possible with the involvement of external technology providers and experienced engineering, procurement, and construction companies. Technology providers mainly electrolyzer manufacturers and renewable energy generation companies will enable the availability of state-of-the art solutions needed for green hydrogen production, whilst EPCs will contribute to the successful and efficient integration of hydrogen facilities into Bhutan's value chain. Finding external financial partners will be necessary to secure the financing needed for the transition and engaging with reputable hydrogen institutions will ensure access to the latest research, expertise, and regulatory frameworks.

By fostering strong partnerships across these categories, Bhutan can create a robust and sustainable hydrogen ecosystem, driving its country towards a cleaner and more resilient energy future.

## Conclusion

In conclusion, this roadmap outlines a strategic plan for the development of a hydrogen economy in Bhutan. The roadmap sets targets and milestones for the near term (2023-30), medium-term (2030-2040), and long-term (2040-50) periods, with a focus on laying the foundation, growth and diversification, and rapid market expansion.

In the near term, the roadmap emphasizes the establishment of a hydrogen economy by creating demand and laying the necessary groundwork. This includes developing strategies, regulations, policies, and standards, as well as implementing demonstration projects and building a robust supply and distribution infrastructure. These activities aim to drive down costs, enhance technology know-how, and develop the necessary skills for wider deployment of green hydrogen technologies.

Moving into the medium-term, the focus shifts towards stimulating the hydrogen sector and prioritizing hydrogen utilization in key sectors. As the technology progresses and reaches commercial readiness levels, the roadmap aims to maximize the benefits of hydrogen in a cost-effective manner, contributing to environmental sustainability.

In the long term, Bhutan envisions a thriving hydrogen economy characterized by significant growth and diversification. The roadmap highlights the role of hydrogen in transportation, industrial processes, and power generation, emphasizing its potential to reduce greenhouse gas emissions and contribute to sustainable development. The expansion of hydrogen deployments, supported by a robust supply and distribution infrastructure, will drive economic growth and environmental sustainability.

However, the roadmap also identifies several challenges that need to be addressed. Economic competitiveness, technology and innovation, policy measures, infrastructure development, codes and standards, and awareness are highlighted as key areas requiring attention. The roadmap emphasizes the need for investments, research and development, policy support, infrastructure coordination, harmonization of codes and standards, and awareness campaigns to overcome these challenges and enable the successful development of the hydrogen sector.

Overall, this roadmap provides a strategic framework for Bhutan to leverage the potential of hydrogen as a clean energy carrier. By implementing the outlined targets and milestones, Bhutan can make significant progress in achieving its energy security, sustainability and decarbonization goals, while also positioning itself as a leader in the global hydrogen economy.

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