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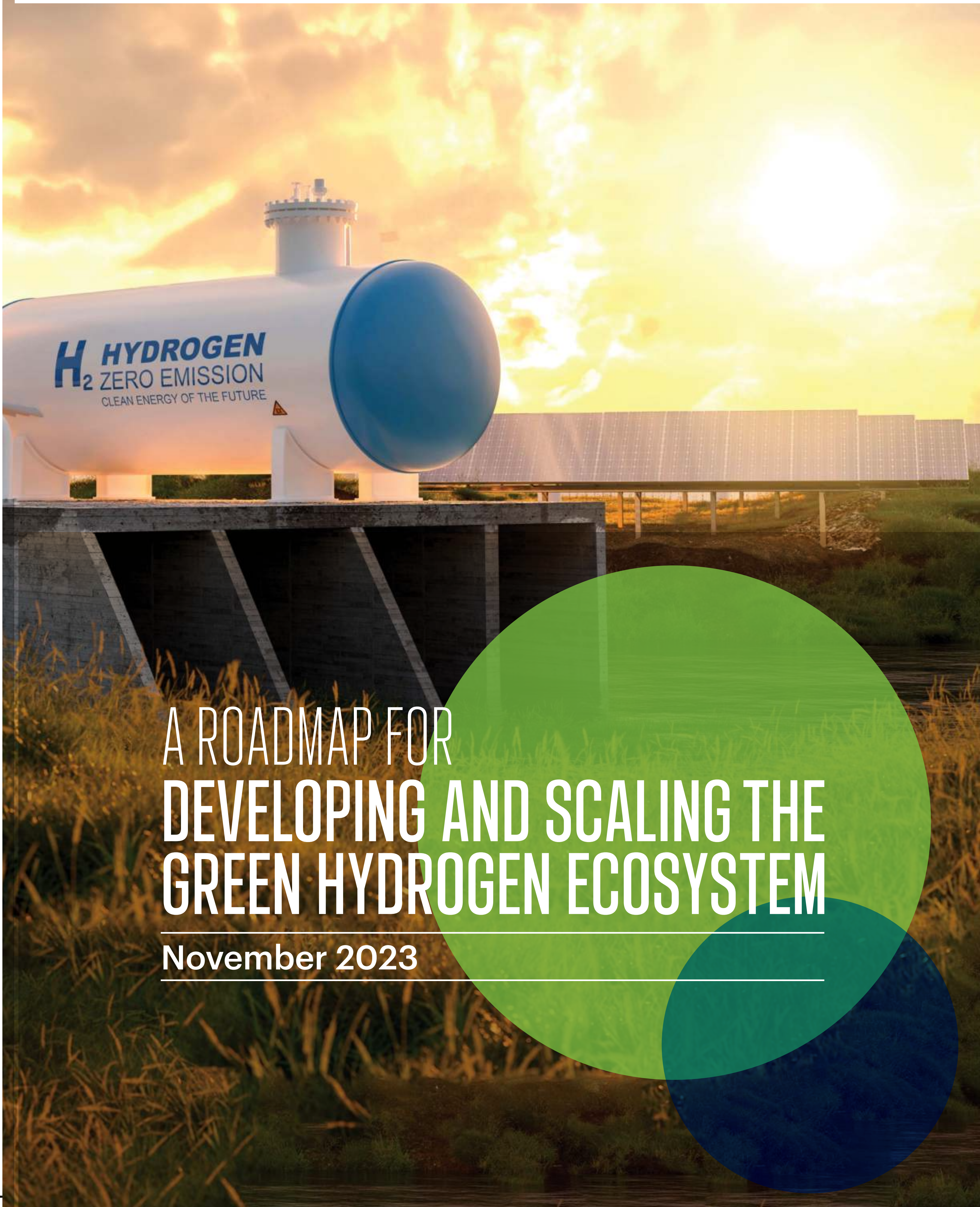

A ROADMAP FOR DEVELOPING AND SCALING THE GREEN HYDROGEN ECOSYSTEM

November 2023

This report was prepared with the support of New Energy and Industrial Technology Development Organization, Japan (New Delhi Branch Office) and under ADB's Knowledge and Support Technical Assistance for the ISA in implementing the Solar for Hydrogen Programme.

Acknowledgement

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The Project Team would like to thank KPMG for providing support in preparing this report and deeply appreciate the Green Hydrogen sector insights provided by various stakeholders during this study.

This publication was produced as a part of TA 9742-REG: Deploying Solar Systems at Scale, co-financed on a grant basis by the Clean Energy Fund, under the Clean Energy Financing Partnership Facility and administered by ADB. Financing partners: the governments of Australia, Norway, Spain, Sweden, and the United Kingdom.

Contents

List of Figures

List of Tables

Abbreviations

AEM	Anion Exchange Membrane
ATM	Atmosphere
BPCL	Bharat Petroleum Corporation Limited
CARB	California Air Resources Board
CUF	Capacity Utilization Factor
CAPEX	Capital Expenditure
CCUS	Carbon Capture Usage and Storage
CO2	Carbon Dioxide
CRT	Cavendish Renewable Technology
CGD	City Gas Distribution
CCGT	Combined Cycle Gas Turbine
DAP	Diammonium Phosphate
DRI	Direct Reduction of iron ore
EAF	Electric Arc Furnaces
ENAP	Empresa Nacional del Petróleo
EPZ	Export Processing Zone
GW	Gigawatts
$GtCO_2eq$	Global GHG emissions
GHG	Green House Gas
GH	Green Hydrogen
GDP	Gross Domestic Product
GOs	Guarantee of Origins
HPCL	Hindustan Petroleum Corporation Limited
H2O	Hydrogen
HDF	Hydrogene de France
HVO	Hydrotreated Vegetable Oil
IOCL	India Oil Corporation Limited
IF	Induction Furnaces
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
ISA	International Solar Alliance
kWh	Kilowatt hours
LTS	Low Carbon Development
MVA	Mega Volt Amp
MW	Megawatts

MCH	Methylcyclohexane
Mt	Metric ton
MMT	Million Metric Tons
MTPA	Million Tons Per Annum
MME	Ministry of Mines and Energy
MNRE	Ministry of New and Renewable Energy
MOP	Muriate of Potash
NGHM	National Green Hydrogen Mission
PNH2	National H2 Program
INEL	National Institute of Clean Energies
NITI	National Institution for Transforming India
ANP	National Petroleum Agency
NTPC	National Thermal Power Corporation
NDCs	Nationally Determined Contributions
NTP	Normal Temperature and Pressure
OIL	Oil India Limited
OECD	Organisation for Economic Co-operation and Development
PEM	Proton Exchange Membrane
RE	Renewable Energy
RED	Renewable Energy Directive
R&D	Research and Development
Solar PV	Solar Photovoltaic
SPV	Solar Photovoltaic
SMR	Steam Methane Reforming
SCEP	Strategic Clean Energy Partnership
TUV	Technischer Überwachungsverein
TWh	Terawatt hour
TW	Terawatts
UNFCCC	United Nations Framework Convention on Climate Change
USISPF	US India Strategic Partnership Forum

Executive Summary

Hydrogen is set to play a leading role in enabling decarbonization. Producing "green" hydrogen (GH) using renewable energy makes it highly attractive for enabling energy transition in hard-to-abate sectors. Green hydrogen can play a significant role by 2040 across the world, to support global efforts towards the achievement of the Paris Agreement decarbonisation goals and contribute to the diversity and security of their energy portfolios. Green hydrogen today, accounts for less than one percent of global hydrogen production. However, the declining costs of renewable electricity and electrolysers indicate the investment readiness of the sector. Interest in low-carbon hydrogen continues to grow rapidly. Many countries have already shown commitment towards accelerating solutions and have already declared supply side and demand side measures. Year 2021-22 saw over 25 countries having announced strategies that included hydrogen as a clean energy vector in their clean energy transition plans. In addition to the strategies already adopted, more than 20 governments announced that they are working on a national hydrogen strategy. Several countries have announced targets for the use of low-emission hydrogen in industrial applications, particularly to replace unabated fossil fuel-based hydrogen in uses such as refining and chemicals. Many governments have defined hydrogen targets for specific transport segments, with most focus on buses and medium- and heavy-duty trucks.[1]

Although this emerging technology is gaining traction across industries, it faces certain challenges including, but not limited to, shortage of specialized manpower, high operational costs, lack of knowledge, underdeveloped infrastructure, absence of dedicated policy for GH and limited access to affordable financing. Interventions such as increased investment, government support, engineering development and skilled workforce development, are some of the critical levers for accelerating a smooth transition to GH economy.

1 *IEA Global Hydrogen Review 2022*

Recent advancements in electrolysers technology have focused on improving efficiency, reducing costs, and increasing scalability. Proton Exchange Membrane (PEM) electrolysis has gained popularity due to its high efficiency and rapid response time. These technological advancements are contributing to the overall competitiveness and sustainability of green hydrogen production.

Governments and International organizations are actively developing regulations and standards to support the deployment of green hydrogen and ensure its safe integration into existing energy systems. Standards for hydrogen purity, storage, transport, and safety are being established to build trust in the industry. Regulatory frameworks are evolving to provide long-term incentives, such as carbon pricing mechanisms, and subsidies, to promote the adoption of green hydrogen technologies. These benchmarking regulations and standards are essential for creating a level playing field and encouraging investment in the green hydrogen sector.

Countries are taking different routes in deploying low-carbon hydrogen, accommodating individual characteristics. Country-level market assessments are crucial for understanding the unique opportunities and challenges in specific regions. Factors such as renewable energy potential, existing industrial infrastructure, policy support, and local demand for decarbonization solutions play a vital role in determining market readiness.

The **International Solar Alliance (ISA)** supports its membership in accelerating this energy transition through solar energy and its derivative applications. Against the backdrop of global momentum for GH as a viable energy transition vector, the ISA has launched a dedicated Programme - Solar for Green Hydrogen – to support its membership with analytics on potential for GH deployment across various end-use sectors. ISA is being supported by the Asian Development Bank (ADB), under ADB's Knowledge and Support Technical Assistance, in implementing the programme. The programme will also assess and support ecosystem readiness, including appropriate standards and certifications, to channelize investments in the sector, and build capacity to create/strengthen domestic as well as cross-border hydrogen value chain.

The ISA had developed a Blueprint on GH readiness across shortlisted ISA member countries. The report was launched at COP27 in November 2022 in Egypt [2], wherein a subset of ISA member countries was assessed. The selected ISA member countries also accounted for the majority share of the total global hydrogen demand of 94 MTPA in 2021. Countries were assessed and placed into four broad categories based on their level of readiness for adopting GH (Figure 1).

Frontrunners	Progressives	Prospectives	Potentials
USA	Italy	UAE	Trinidad & Tobago
Australia	India	Brazil	Indonesia
France	Egypt	Poland	Somalia
Spain	Netherlands	Morocco	Qatar
Germany	Saudi Arabia	Iran	Nigeria
Japan	Republic of Korea	Peru	Bangladesh
Chile	Oman	Mexico	
United Kingdom	Argentina	Namibia	
	Algeria	Sudan	
	South Africa		

Figure 1: Categorization of Countries Based on Readiness Framework

Source: ISA Blueprint for Ecosystem Readiness Assessment for Green Hydrogen 2022

2 *ISA Blueprint for Ecosystem Readiness Assessment for Green Hydrogen 2022*

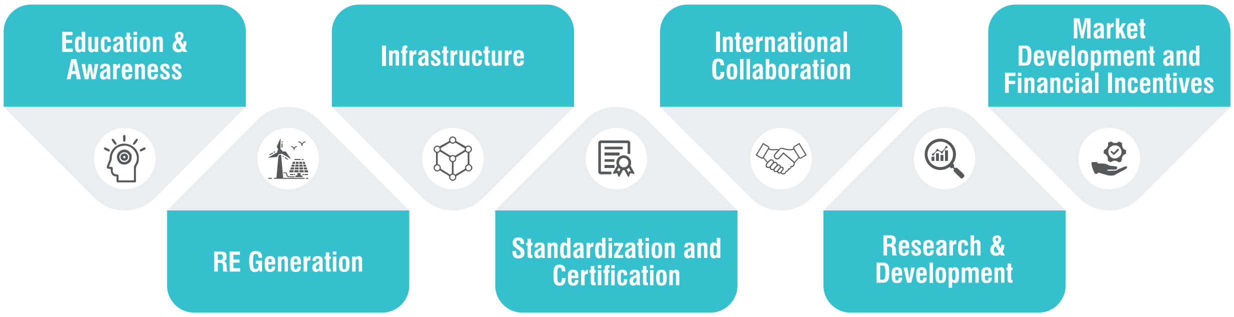


Figure 2: Broad Contours to Strengthen Green Hydrogen Supply Chain

Plenty of public support for low-carbon hydrogen development continues to be seen in developed regions like Europe and the US, however the momentum is also growing in Latin America, the Caribbean, Africa and the Middle East. This report dwells deeper into three potential green hydrogen economies – **Chile, India, and Brazil**. With excellent RE potential, infrastructural capabilities, strategic intent, and hydrogen demand, all three countries are attractively positioned to not just act as major exporters, but also focus on domestic consumption of low carbon hydrogen.

Prices for green hydrogen are expected to drop significantly over the course of the decade in India, making it a much more economic source of energy. The drop in prices of green hydrogen produced using solar energy is much sharper than that of wind energy, making it a preferred technology to produce green hydrogen. **In Chile, green hydrogen produced using solar energy** is observed to be significantly cheaper than that produced using wind energy despite the high wind energy potential available in the country. The difference could be attributed to the expected fall in cost of solar PV technology vis-à-vis changes in the cost of wind energy equipment, the technology for which has matured. Given the cost levels, the green hydrogen produced in Brazil might not be able to compete with other suppliers in the international markets or the South American regional markets in terms of costs. However, given the continent's proximity to the African continent, export of green hydrogen from Brazil across the southern Atlantic for decarbonization of the African continent provides an opportunity that could be tapped to move towards global decarbonization.

Developing a robust green hydrogen supply chain is critical for its widespread adoption. The pathway involves multiple stages, including renewable energy generation, electrolysis, hydrogen purification, storage, transportation, and utilization. To establish an efficient supply chain, strategic partnerships among renewable energy developers, electrolyser manufacturers, infrastructure developers, and end-users are essential. Furthermore, integrating green hydrogen into existing gas infrastructure and exploring novel transportation methods, such as pipeline networks, maritime shipping, or ammonia carriers, can help scale up the supply chain. Collaboration between public and private entities, supported by favorable policies, is crucial for realizing the full potential of the green hydrogen supply chain.

This report not only dives deeper into recent technological advancements in green hydrogen production, but also provides an overview of emerging regulations and standards, dwells into county-level market assessments, and helps create a pathway for the development of the green hydrogen supply chain (Figure 3).

These advancements are driving the transition towards a more sustainable energy future, unlocking opportunities for economic growth, and mitigating climate change. Continued collaboration among governments, industry stakeholders, and research institutions is vital to accelerate the adoption of green hydrogen technologies worldwide.

1. Introduction

The global energy landscape is undergoing a significant transformation as countries strive to reduce greenhouse gas emissions and mitigate the impacts of climate change. In this pursuit, renewable energy sources have emerged as a crucial solution, with their potential to provide sustainable and clean power. Green hydrogen, produced through the electrolysis of water using renewable energy, has emerged as a promising solution to decarbonize various sectors, including transportation, industry, and heating.

Global hydrogen demand reached 94 Mt in 2021, mainly for petroleum refining, and production of chemicals and fertilizers. The existing demand for hydrogen in these sectors indicates that the molecule is not entirely novel. GH currently accounts for less than one percent of the total amount of hydrogen produced[3], however, the global demand for GH and its applications is expected to increase exponentially over the next 20 years as the pressure to decarbonize continues to mount. It is expected that in the Net Zero scenario (IEA) the demand will likely be over 200 Mt by 2030 (Figure 3). Green Hydrogen Market was valued at USD 676 million in 2022 and is projected to reach USD 7,314 million by 2027, growing at a CAGR 61.0 percent from 2022 to 2027.[4] The market's growth is attributed to the lowering cost of producing renewable energy by all sources, development of electrolysis technologies and high demand from FCEVs and power industry.

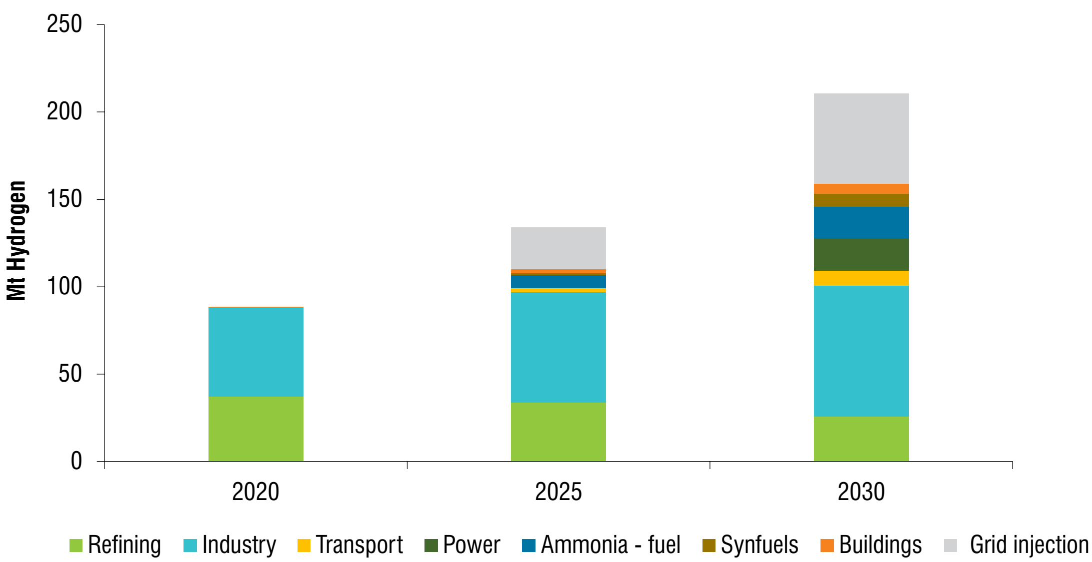


Figure 3: Global Hydrogen Demand by Sector in the Net Zero Scenario, 2020-2030
(Source: IEA, 2022)

In recent years, there has been a growing global interest in green hydrogen, with numerous countries and industries recognizing its potential to accelerate the transition to a low-carbon economy. Governments are implementing policies and incentives to support the development of green hydrogen infrastructure, while industries are exploring innovative applications and investing in research and development, and research institutions worldwide are increasingly focusing on developing and scaling up green hydrogen production and utilization.

However, significant challenges must be resolved. The hydrogen value chain is both complex and capital-intensive, many segments are still in a nascent stage. The global electrolyser manufacturing capacity is miniscule compared to the total

3 *IRENA-Coalition Green Hydrogen 2021*
4 *MarketsAndMarkets- Green Hydrogen Market Report 2022*

expected demand. However, with increasing capacity the cost of electrolyser is expected to reduce sharply due to inherent manufacturing economies of scale. There is a need to adapt to evolving technologies and regulations. Many countries have already shown commitment towards accelerating GH solutions and have already declared electrolyser targets as well as taken other supply side and demand side measures.

Other barriers such as lack of robust carbon pricing mechanism, lack of monitoring and reporting framework for GHG accounting, regulatory gaps/barriers, lack of global standards and lack of adequate incentives, must be addressed to ensure the scalability and sustainability of the market. Overcoming these barriers and transitioning to GH will require dedicated support and policy action. Stakeholders will need to come together to grasp this opportunity and develop green hydrogen value chains across geographies.

This report aims to provide a comprehensive pathway for developing and scaling up green hydrogen technologies. It presents an overview of the existing green hydrogen technologies, including production methods, efficiency, and applications. It highlights recent advancements, research, and pilot projects, and identifies key challenges and opportunities. Addressing the infrastructure and supply chain challenges associated with green hydrogen is crucial for its widespread adoption. The report also examines the necessary infrastructure requirements, and explores various policies, incentives, and regulations implemented by governments to promote green hydrogen. It also analyzes international collaborations and initiatives to facilitate knowledge sharing and standardization. In addition, the report dwells deeper into three potential green hydrogen economies to enable an understanding of the unique opportunities and challenges that the regions entail. Building upon these sections, the report presents a comprehensive pathway for developing and scaling up green hydrogen technologies, outlining the key contours for focus and priority areas for action (depicted in Figure 3 above), providing a strategic guide to stakeholders interested in advancing the green hydrogen agenda.

The development and scaling up of green hydrogen technologies holds immense potential to contribute to a sustainable and low-carbon future. By following the pathway presented in this report, policymakers, industry leaders, and stakeholders can navigate the complex landscape of green hydrogen and foster its integration into various sectors, enabling a cleaner, greener, and more resilient energy system.

2. Technological Advancements

Hydrogen energy technologies and products are vast and multiple. This section summarizes the most common, promising, and advanced hydrogen technologies, with the majority being in the commercialization stage or close.

The subsequent sections provide details on types of electrolysers technologies used for hydrogen production.

Electrolysers

At present, water electrolysis is considered by many experts to be a pivotal technology for large- scale storage of renewable energy, aiming for a transition to a clean economy. An electrolyser uses power and water (H2O) as its inputs and produces hydrogen, oxygen (O2), and heat as outputs. Hydrogen is said to be green if it is produced from an electrolyser connected to a renewable source of energy. A typical electrolyser consists of an anode and a cathode, both separated by an electrolyte. Figure 4 shows a simplified overview of an electrolyser.

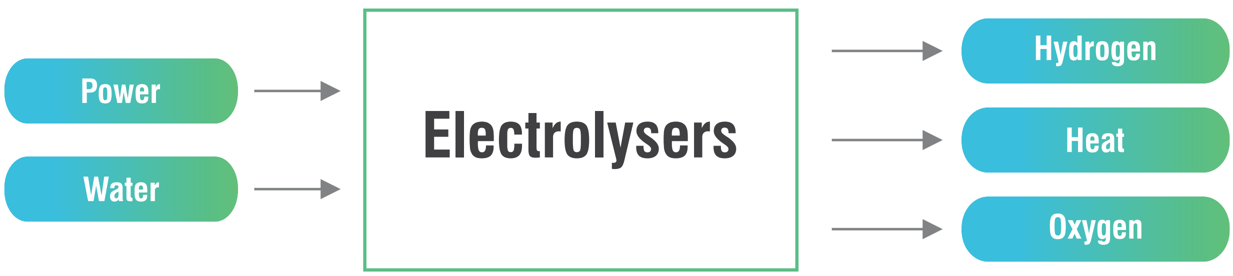


Figure 4: A Simplified Overview of an Electrolyser

The three most common and commercially available electrolysers are listed below:

a. Alkaline electrolysers

b. Proton exchange membrane (PEM) electrolysers

c. Anion exchange membrane (AEM) electrolysers

Another type of electrolyser is at near commercialization stage, namely solid oxide electrolysers (SOEs). Figure 5 below shows different types of electrolysers.

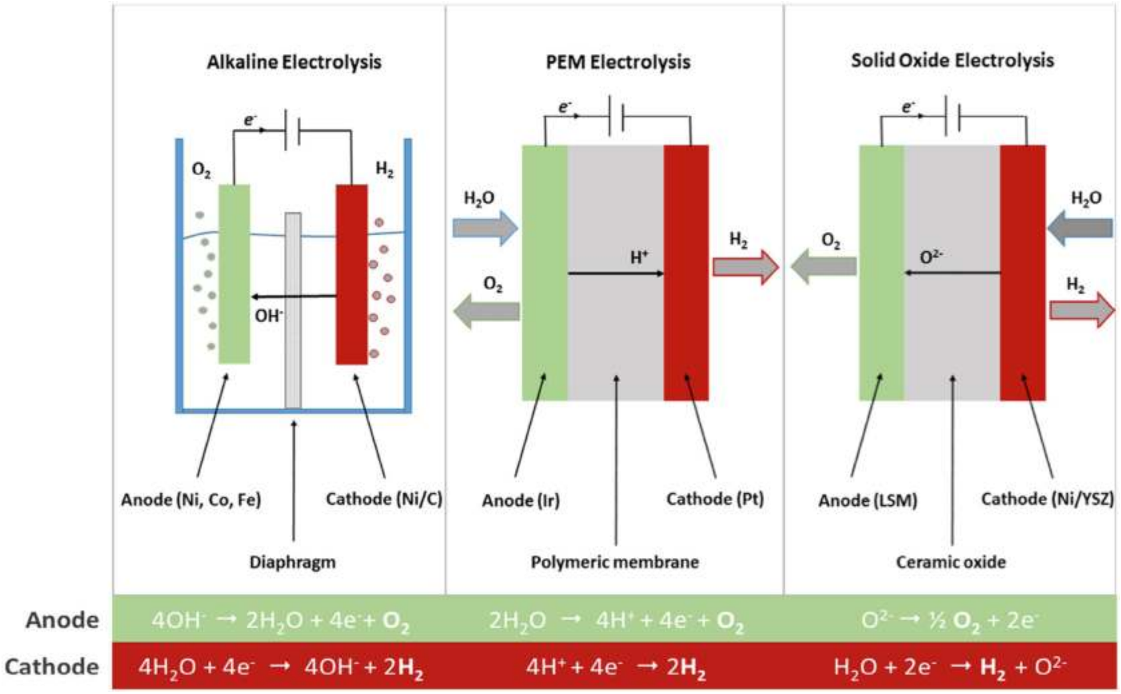


Figure 5: Operating Principles of Three Types of Electrolysis Technologies

Source: Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas (ScienceDirect, 2017)

a. Alkaline electrolysers

The electrolyte used in an alkaline electrolyser is liquid based. The liquid is either sodium hydroxide or potassium hydroxide. When water is split, hydrogen is generated at the cathode while the O2 is produced at the anode. The photo below shows a hydrogen alkaline electrolyser as installed in Morocco.

Alkaline electrolysers (Figure 6) are the most mature technology and have been commercially available for more than half a century. Alkaline systems are available in small, medium, and large sizes. This type of electrolyser operates at a conversion efficiency ranging from 60 percent–82 percent.[5] [6]They can produce hydrogen gas at up to 30 bar of pressure without any external compression. Hydrogen production at such a high pressure leads to reduced compression cost in the long run, which is likely to contribute substantially to the overall cost of hydrogen.

Figure 6: Hydrogen Alkaline Electrolysers (Photo Courtesy: Pure Energy Centre)

5 *O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few. 2017. Future Cost and Performance of Water Electrolysis: An Expert Elicitation Study. International Journal of Hydrogen Energy. 42 (52): pp. 30470–30492.*

6 *Ratio between the useful output of an energy conversion machine and the input*

b. Proton exchange membrane (PEM) electrolysers

Polymer electrolyte membrane also known as proton exchange membrane (PEM) electrolysers use a solid catalyst and solid polymer electrolyte. PEM catalysts are, at times, more expensive than competing technologies. As such, it is often the case that PEM electrolysers are more expensive than alkaline ones. However, of late, PEM electrolysers are becoming competitive against more established alkaline technology. In a PEM system, hydrogen is released at the cathode and oxygen at the anode.

PEM electrolysers are now commercially available (Figure 7). They are available on small, medium and large scales and are the preferred option when there is a shortage of space. PEM systems have a smaller footprint than alkaline. They do not have a large amount of field operational history as they are a relatively new commercial product. As of now, the PEM electrolyser has achieved over 100,000 hours of continuous operation.

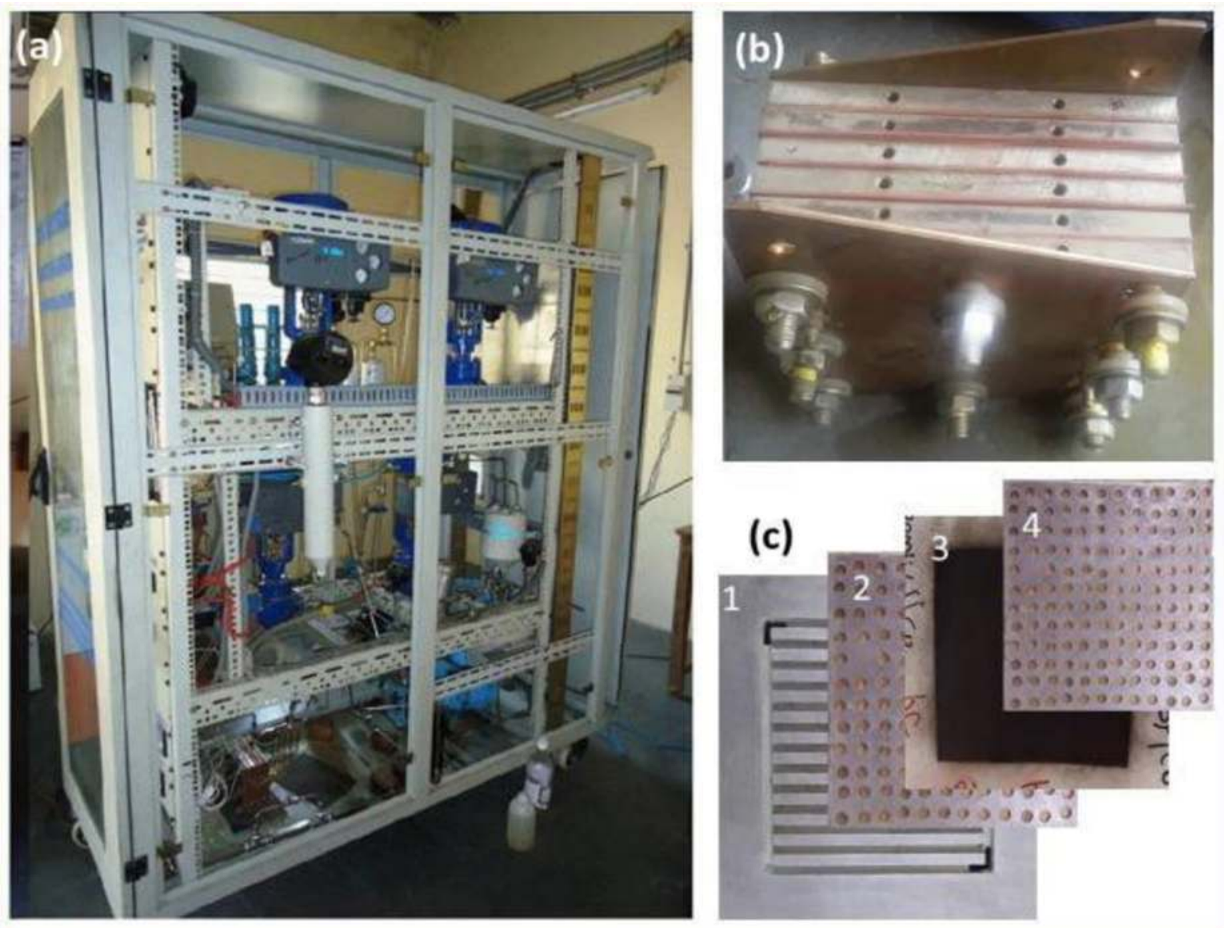


Figure 7: (a) PEM Water Electrolyser (b) PEM Stack (c) Different Cell Components

Source: (1) Bipolar plate, (2) Anode current collector, (3) MEA, (4) Cathode current collector (photo from S. Shiva Kumar and V. Himabindu. 2019. Hydrogen Production by PEM Water Electrolysis – A Review. Materials Science for Energy Technologies. 2 (3): pp. 442 –445).

One of the main advantages of PEM electrolysers is that they do not require the management of a liquid electrolyte (required for alkaline system). They can produce a very high gas purity of up to 99.999 percent for hydrogen directly whereas other commercially available electrolysis (i.e., alkaline) require postproduction cleaning to remove impurities. Other applications such as internal combustion engines and gas turbines can cope with lower hydrogen gas purity levels.

PEM electrolysers are currently the only electrolysis technology (commercially available) that can manage the output variations in the intermittent renewable energy generators such as solar PV and wind.

c. Anion exchange membrane (AEM) electrolysers

Anion exchange membrane (AEM) electrolysers use a liquid electrolyte to produce hydrogen and oxygen. The main advantage of an AEM water electrolysis is the replacement of conventional noble metal electrocatalysts (used in PEM electrolysers) with low-cost metal catalysts. Their commercialization has only been achieved recently at small scales, while current developments are focused on designing and manufacturing larger systems. Figure 8 shows an AEM electrolyser as installed in a scientific laboratory.

Figure 8: AEM Electrolysers as Installed in a Laboratory (Photo from Pure Energy Centre, 2016)

Source: First Hydrogen Electrolyser Supplied to Croatia (Pure Energy Centre, 2016)

The use of non-noble metal catalysts reduces the capital cost of the AEM electrolyser relative to competing technologies. However, the performance of AEM electrolysis is still lower than that achievable with PEM electrolysis due to the higher internal resistance of the AEM membrane electrode assembly.[7]

d. Solid oxide electrolysers (SOEs)

Solid oxide electrolyser (SOE) cells, use a solid electrolyte to produce hydrogen. SOE are more efficient when compared to PEM, Alkaline, and AEM. This is because they operate at a higher temperature, thereby needing lower electrical power input to split water into hydrogen and O2. They are called SOE because they are mainly manufactured using solid oxide materials as the electrolyte.

SOE is also called high temperature electrolysis. Though they are described as highly efficient, there is a need to supply heat from an external source for their operation. The assumption is that the cost of heat is cheaper than electricity, and hence SOE operating expenditure is low. As an SOE operates at high temperature, less energy is required to split water. SOE operation can be between 500°C and 1,000°C. If there is a cheap source of high temperature heat, an SOE will out-perform other electrolysers. However, this type of electrolyser is not commercially available yet.

7 *Emmanuel Vincent and Dmitri Bessarabov. 2018. Low Cost Hydrogen Production by Anion Exchange Membrane Electrolysis: A Review. Renewable and Sustainable Energy Reviews. 81 (Part 2): pp. 1690–1704.*

SOEs are also able to combine both hydrogen and carbon dioxide to produce synthesis gas (syngas)[8] which consists mainly of hydrogen, carbon monoxide, and some amount of carbon dioxide. Syngas is often used as a first step to creating synthetic natural gas, synthetic petroleum, methanol, gasoline/petrol etc.[9] In other words, SOE can be used as a first stage in producing different types of fuels and feedstock.

Summary

Alkaline electrolysers work best under a steady-state operation, meaning that they operate better with as little electrical fluctuation as possible. Alkaline systems can operate at 20 percent of their maximum production capacity, although generally, manufacturers prefer this to be limited to a higher level.

The main drawback is found in their relatively low current density when compared to other technologies. The electrolyte being liquid limits the response time of the electrolyser and potentially increases the maintenance cost as there is a need to replace the electrolyte periodically. Alkaline electrolysers are currently cheaper per unit of gas production and have been sold commercially for many decades.

PEM's main drawback is the capital cost. Since PEM electrolysers use noble materials and polymer membranes, their associated cost is higher than the other two types. They also involve expensive manufacturing techniques and processes. On the other hand, they have faster electrochemical kinetics making them very suitable for handling fluctuating renewable energy sources.

AEM electrolysers use low-cost materials but are only commercially available at small scale. There is research investigating developing larger systems. SOEs are at the demonstration stage and require heat to be available to achieve high efficiency.

All electrolyser technologies consume about the same level of water. For instance, a 1 MW electrolyser produces about 200 normal cubic meters per hour of hydrogen (Nm³/h (16.75 kilograms/hour at normal temperature and pressure (NTP)—1atm, 20°C) and would consume about 170 litre/hour (L/h) of deionized water.

Table 1: Summary: Features and Characteristics of the Different Electrolyser Technologies

Electrolyser type	Electrolyte	Operating Temperature	Typical Size	Efficiency ∩ (LHV)v	Technology Maturity	Main Advantages	Challenges	Expected Lifetime (Hours as of 2020)	Operational Load Range (%)
Polymer electrolyte membrane (PEM)	Solid polymer membrane	50–80°C	< 1.6 MW	65%–82%	Demonstration project and Early market	• Solid electrolyte reduces corrosion and electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities	Lifetime: 20,000–60,000 hours	5%–100%
Solid oxide	Solid ceramic membrane	800–1,000°C	-	8%1–86% Up to 100% with heat recovery	Laboratory scale and demonstration project	• Enhanced kinetics, • Thermodynamics • Lower energy demand • Low capital cost	• Mechanical unstable electrodes (cracking effect) • Safety issue: improper sealing • Long start-up time	Lifetime: < 10,000 hours	Steady state operation

8 *Y. Zheng Y et al. 2017. A Review Of High Temperature Co-Electrolysis of H2O and CO2 to Produce Sustainable Fuels Using Solid Oxide Electrolysis Cells (SOECs): Advanced Materials and Technology. Chemical Society Reviews. 46 (5): pp. 1427–1463*

9 *P. Kazempoor and R.J. Braun. 2015. Hydrogen and Synthetic Fuel Production Using High Temperature Solid Oxide Electrolysis Cel ls (SOECs). International Journal of Hydrogen Energy. 40 (9): pp. 3599–3612.*

Electrolyser type	Electrolyte	Operating Temperature	Typical Size	Efficiency ɳ (LHV)v	Technology Maturity	Main Advantages	Challenges	Expected Lifetime (Hours as of 2020)	Operational Load Range (%)
Alkaline	Liquid electrolyte with Alkaline solution (NaOH or KOH)	40–90°C	< 2.7 MW	59%–70%	State of art and mature commercial	• Low capital cost • Relatively stable mature technology	• Corrosive electrolyte has impact on reliability/ durability • Gas permeation • Slow dynamics • Electrolyte management (aqueous)	Lifetime: 60,000–90,000 hours	20%–100%
Anion exchange membrane (AEM)	Solid polymer-based anion exchange membrane in KOH or K2CO3 solution	50–70°C	< 4.8 kW	62%	Laboratory scale and small demonstration project	• Non-noble metal catalyst • Noncorrosive electrolyte • Compact cell design • Low cost • Absence of leaking • High operating pressure	• Low current densities • Durability • Membrane degradation	Lifetime: 30,000 hours	20%–100%

3. Regulations, Codes and Standards for Green Hydrogen Production and Use

Green hydrogen is gaining great attention globally and as such several international standards organizations are in the preliminary stages of investigating the requirements for putting a framework in place. As hydrogen is mainly a fuel commodity, it is not sufficient to have local, national, and regional mechanisms; there is also a need for an international one. A lot of the discussions are currently being undertaken at the global level which focus on how to make hydrogen "low-emissions". Additionally, there are efforts to converge on the thresholds by which hydrogen can be considered as "green". Also, topics like types of feedstock and production technology can be included in any hydrogen trading mechanism are being discussed in depth. Decisions surrounding these questions will be influenced based on the local feedstock available, the local supply chain and the technology currently available in the country.

The need for an international trading system of certified hydrogen is pushed by a few large-scale projects. These, at times not only focus on green hydrogen, but on blue hydrogen as well. For instance, there are potential situations where green hydrogen will be produced in Africa, Ukraine and the Middle East and exported to the EU via pipelines.[10] There are also several projects co- owned by Australia and Brunei to export hydrogen to Japan and the Republic of Korea. Note that currently, only two projects are in an advanced stage of development. These are co-owned by Australia and Japan, and Brunei and Japan.

10 Source: Hydrogen–The Bridge Between Africa and Europe (Springer Link, 2021)

The Hydrogen Australia - Japan project is in a very advanced stage. Hydrogen will be produced from brown coal and exported to Japan in liquid form. Kawasaki is leading the project from Japan and is building the liquid hydrogen terminals in Japan and Australia.[11] A ship has been manufactured to transport the produced liquid hydrogen.[12]This is the first phase of the plan, as Australia has plans to produce dedicated green hydrogen from electrolysis at a large scale, with large quantities being set for export purposes.[13]

The Brunei - Japan project is already operational. It was launched in 2020 and hydrogen is produced from natural gas. The hydrogen is then hydrogenated into methylcyclohexane (MCH) using toluene. The MCH is a liquid that is easily transportable in a ship. The MCH is dehydrogenated in Japan, separating toluene and hydrogen[14]. Hydrogen is used in Japan as a fuel while Toluene is transported back to Brunei to be re-used in the hydrogenation process. Though the initial projects are not yet CO2 free, these are the precursor projects to set up the initial infrastructure for export/import and marine vessels. The next stage of this infrastructure will be to set up a green hydrogen production and supply chain, which will be facilitated by international trading of certified CO2 emissions reductions.

There is already widespread global hydrogen production, distribution, and use as a chemical feedstock, with no significant market barriers or impediments to supply-chain growth. However, the global hydrogen energy market is nascent. As demand for conventional and low carbon hydrogen energy increases, long-distance and large-scale international transport and trading of hydrogen will be needed to link areas of surplus and deficit. Competition will intensify with the growth of hydrogen trade, as seen in more mature commodity markets. It is crucial that the global hydrogen market develops in an efficient, inclusive, and transparent manner. Technical, legal and commercial challenges may arise, for which a rules-based approach is logical, governing aspects such as the carbon intensity of hydrogen, customs procedures, market frameworks and many other features.

Green Hydrogen (GH) or even low carbon hydrogen is an industry in its infancy. Green hydrogen and low-carbon hydrogen are, at present, more expensive than hydrocarbon-based hydrogen. However, green hydrogen can be cost-competitive in renewable energy systems which displace petroleum-fired generation, e.g., HDF's projects in Latin America and the Caribbean and its project under development in Indonesia. As such, and under the condition that green hydrogen is to receive incentives or carbon credits, green hydrogen will need comparable standards and legislation to the renewable energy sector. To do so, there is a need for the following to be clearly defined:

- Appropriate definitions of green hydrogen.
- Standards being developed for green hydrogen.
- What are the different forms of Guarantee of Origins (GOs) and which one is currently being used?
- What are the different challenges for hydrogen GOs?

3.1. Green hydrogen definitions

Unless there is a unanimous local, nationwide, region-wide or worldwide agreed definition as to what is green hydrogen, it will be difficult for legislators to put together standards and legislation frameworks. There is a good reason behind this.

There are many ways of producing hydrogen. As such, does hydrogen from natural gas using SMR and CCS technologies qualify as being low-carbon hydrogen? Similarly, does hydrogen produced from coal gasification with CCS technology qualify too? Or is it only renewable hydrogen that qualifies for being called green hydrogen? What about biomass hydrogen produced using SMR reactors? Biomass is defined as green, sustainable, or low carbon technology by the sustainable/ renewable industry but would the production of biomass hydrogen be using SMR technology makes biomass not accepted as being green hydrogen? Is nuclear hydrogen considered green?

11 Japan's Kawasaki set to trial Australian hydrogen exports in 2020(Reuters, 2019)

12 Japan launches first liquid hydrogen carrier ship (Financial Times, 2019)

13 Strong interest for green hydrogen in Australia (Renews.Biz, 2020)

14 Methylcyclohexane (MCH) is regarded as an excellent hydrogen energy carrier due to its reasonable theoretical hydrogen storage content (6.22 wt%) and physicochemical performance. Methylcyclohexane-toluene-hydrogen (MTH) cycle realizes the recycling of materials and energy and has a good prospect of industrial application. MCH is a liquid organic hydrogen carrier that contains over 500 times the volume of hydrogen. It has advantages in the long-time storage over seasons and is high in transportability, because of its stable chemicals at room temperature and atmospheric pressure.

The definition of green hydrogen is therefore critical, as it will lead to the decision as to which technology is selected to qualify and receive any future incentives.

There is currently no standard definition for green hydrogen. This lack of common definition is making the production of international standards difficult, in turn making green hydrogen trading cumbersome. Grey, black, and brown hydrogen have been clearly defined through the years, where hydrogen is produced from hydrocarbon and the CO2 released in the atmosphere. Grey hydrogen is hydrogen produced from natural gas using SMR and CO2 released in the atmosphere. Brown hydrogen is hydrogen produced from brown coal. Black hydrogen is hydrogen produced from black coal.

However, there are groups that have defined a new color for hydrogen called blue hydrogen. Blue hydrogen is hydrogen produced from fossil fuels and industrial waste gases, and their CO2 emissions are deemed to be low by coupling the hydrogen production with CCS/CCUS.[15]

In summary, the definition of green hydrogen must be clearly defined with thresholds for acceptance of associated CO2 emissions per ton of hydrogen produced using a given process. For instance, biomass hydrogen may need a clearer definition with acceptance of CO2 emission criteria to be met for different biomass feedstock. The same applies to the different blue hydrogen production pathways.[16]

3.2. Existing green hydrogen standards

To date, there is no commonly agreed standard for green hydrogen. This demonstrates that the differences in defining, interpreting, and describing green hydrogen from country to country have a negative effect on standardization. Having a globally (or even regionally) agreed definition would pave the

15 Across the spectrum, it is important to note that GHG reductions provide global benefits regardless of where they occur; this location-independent nature of GHG reductions is a fundamental enabler from cross-border GHG emissions trading as enshrined in the Kyoto Protocol.

16 An additional factor for consideration for hydrogen produced from fossil fuels, especially natural gas, is how to account for associated and fugitive emissions of methane which has much higher global warming potential than CO2. This is not a trivial issue nor is it a trivial exercise. The use of liquid natural gas for cleaner marine propulsion is a solution for reducing stack emissions from individual ships, but the associated" methane slip" means that GHG emissions targets specific by the International Maritime Organization will not likely be met using liquid natural gas.

way for the development of a standard, thus allowing for a legislative framework to be produced, and different incentives provided.

There are different levels of standards. These can be divided into three groups: (i) national standards (UK, United States, Germany, France, etc.), regional standards (i.e., EU), and international standards (i.e., ISO, IEC). Usually, national, and regional standards feed into international ones.

It is generally the case that standards are directly interlinked to a piece of legislation; again, national, regional, or global. Global standards are more difficult to implement than regional or national ones in that they must be linked to national legislation to be enforceable.

One piece of legislation that is key to supporting the wide deployment of hydrogen is therefore the production of a standard focused on tradeable GOs. The green hydrogen GOs could be of similar nature to renewable energy certificates and certified emissions reductions in the renewable energy industry. The aim is to provide the appropriate security to the purchasers that they are buying green hydrogen and not highly polluting hydrogen. There is, today, an operational GOs certification scheme, namely the **CertifHy**[17] which is the first scheme to issue GOs for low-carbon hydrogen.

There are currently several organizations that are developing new green hydrogen standards, some being national and others being international. However, there are substantial challenges facing the standardization community, as each of the different organizations developing a standard has its own definitions and its own system boundary. This is causing inconsistencies between the different standards, and when legislative frameworks are created based on the standards, these may not be able to reach cross-border trading, limiting the outreach and international trading for green hydrogen.

For instance, **CEN-CENELEC/TC 6** (CEN is the European Committee for Standardization and collaborates with ISO while CENELEC is the European Committee for Electrotechnical Standardization and collaborates with IEC—TC6 means Technical Committee 6) is aiming at developing an international green hydrogen standard. The TC 6 focuses its efforts on defining the terminologies, and how to deal with the Guarantee of Origin, and safety. It also aims at investigating cross-cutting issues including, but not limited to, operational conditions, training, education, and social aspects.[18] The TC 6 has opted to use the CertifHy as a starting point for their work.

In **France**, Afhypac is developing a standard focused on the production of hydrogen. The system boundary is at the point of production, meaning hydrogen must be from a 100 percent renewable source. This type of work is motivated by GOs.

TÜV SÜD, in **Germany**, is working to develop a German national standard. The overall aim is to reduce emissions, and the baseline is hydrogen from SMR. To qualify for the scheme, the technology being used should demonstrate a decrease in CO2 emission between 35 to 75 percent (Production process dependent). The system boundary is the point of use. The standard includes renewable electrolysis, SMR, biomethane and pyro-reforming of glycerin.

The **California** Low Carbon Fuel Standard is a mechanism developed for the transport fuels focused on the carbon content of fuels including alternative fuels (such as ethanol). In 2018, the California Air Resources Board (CARB) defined that renewable hydrogen within California can be produced from several feedstocks including (i) water electrolysis and other aqueous solutions using renewable power, (ii) catalytic cracking or steam methane reforming of biomethane, and (iii) thermochemical conversion of biomass (this includes the organic portion of local municipal solid waste).

The definition of the CARB differs from Europe, creating major issues between EU and California legislation as related to the minimum carbon intensity for hydrogen. In California, this is set at 76.1 gCO2e/MJ for on-site reforming with renewable feedstocks (i.e., biomass), and this is much higher than the allowed threshold in the EU CertifHy scheme. Such a difference in carbon tolerance and the difference in accounting methodologies means that GOs based trading between both the United States and the EU is not possible at present. Therefore, the definition of green hydrogen is important and hence consensus must be reached internationally (or at least, at a regional setup).

17 CertifHy. CertifHy Enters into Phase 3 to build a H2 GO Market As Well As a H2 Certification Scheme for REDII. https://www.certifhy.eu/.

18 CEN-CENELEC/TC 6, May 2016. F. De Jong, NEN Standardisation, Hydrogen Workshop "Power-To-Hydrogen: Key Challenges and Next Steps". European Standardisation.

3.3. Guarantees of origin (GO)

In essence, a GO is a tracking instrument within the renewable energy sector to (i) define the origin of the power and (ii) the evidence that the power is from a given source of generation (i.e., wind, solar, biomass, etc.). GOs are traded (sold) nationally or regionally. Globally, there are several GO schemes.

For instance, in Europe, GOs for renewable energy can be traded across borders with different participating countries. To do so, the European Union has created a legislative framework for trading GOs, all defined in the Renewable Energy Directive 2 (RED II).

In the United States, the GOs are defined as renewable energy certificates or better known as credits. These credits are instruments that define who own the social, environmental, and other non-related energy criteria of renewable energy sources.

The RED I mainly focused on renewable energy. However, RED II made a critical change to RED I by embracing renewable gases, including green hydrogen and bio-methane. RED II also includes low carbon non-renewable based sources of energy.

The RED II directive ensures that most of the framework that applies to renewable energy GO also applies to green hydrogen. However, there is a significant difference between the two different energy mediums. The method for tracking the GOs will differ, and the reason is that electricity tracks electrons, while for hydrogen, there is a need to track molecules.

The methodology used to track these GOs is widely known as the "chain of custody". There are three main types of chain of custody, namely (i) segregation, (ii) mass balance and (iii) book and claim.

Segregation

In the segregation chain of custody, the product must be continuously tracked at each stage. For instance, it must be tracked through the production, transport, and consumption stages. All buyers and sellers are required to be connected to the same network or grid. There is also a need to separate certified products from the conventional ones. This approach can be applied to green hydrogen, but only when the gas is trackable at all steps within the supply chain. Of critical importance, in this model, green hydrogen is not allowed to be mixed with the other types of hydrogen, such as brown, black, etc. Therefore, the segregation chain of custody is highly restrictive.

Mass Balance

The mass balance methodology is sometimes considered as an improvement to segregation. In this model, both the sellers and buyers are not required to operate on the same network or grid. Both certified and non-certified products can be mixed, but they both must be tracked. With the mass balance chain of custody, it is possible to conduct green hydrogen blending into natural gas. It is also possible to inject different types of hydrogen (i.e., brown, grey, etc.) into the same gas network. The quantity of certified green hydrogen must be always monitored, in terms of whatever volume is entering the gas grid, and exiting it.

Book and claim

The third chain of custody option is the book and claim model. Basically, the product (renewable electricity or green hydrogen gas) is dealt separately from the trade of its corresponding GO. This means that the renewable electricity can be sold to a customer independently from the GO. However, producers of the goods and consumers (or buyers) are required to be physically connected. The aim is to allow the flow of energy across the grid. For instance, it is only possible to operate the renewable electricity GOs in a book-and-claim approach. On a national electrical grid network, it is not possible to define if an electron is green or brown or black. As such, a particular batch of electricity can be sold as green while the rest is sold as brown or black, and a GO is sold when a batch of renewable electricity is consumed. Using this model, it is possible to envisage that green hydrogen molecules will be sold separately from the GO. In this case, there would not need to be any traceability required from green hydrogen.

The system for managing and trading renewable energy GOs in Europe uses the book-and-claim approach. A hydrogen GO scheme is probably best to follow this method as it dissociates both the green hydrogen gas produced and its associated GOs. Alternatively, the use of the mass - balance approach is also appropriate and already being used by the biomethane GO schemes. Note that a GO is valid for a given period (two years from its date of issue). If it is not sold within that period, its validity is cancelled.

3.4. Challenges in Gaurantees of Origin (GO)

There is a multitude of challenges facing the green hydrogen GO. The most common are:

- Accounting boundaries for emissions
- Administering a GO scheme
- Initial market entry level
- Risks of misleading customers
- Future carbon price

3.4.1. Accounting for the different hydrogen supply chain boundaries for GHG

Accounting for the losses and emissions along the hydrogen supply chain is a very difficult and complex task. For instance, the emissions of GHG can happen at any of the different phase of the hydrogen production, compression, storage, and dispensing. Similarly, losses of hydrogen can occur anywhere at the production, compression, and transportation/distribution stage. The rationale is that there are many different production, transportation, distribution and consumption methods, and GHG emissions will differ from location to location and from the source of hydrogen.

There are other challenges with accounting. For instance, some GO systems do not account for emissions caused during the design, construction, commissioning, and decommissioning phases. Similarly, GHG associated with the transport of the feedstock is accounted for in many cases, while these may be neglected from one GO system to another one.

Hydrogen purity is also a cause for disagreement. Fuel cells require 99.999 percent purity, or what is known in the industry as Five-Nines. Other technologies do not require such purity, as applied for ICE engines and CCGT. The higher the purity, the more cleaning process is needed, and the more GHG. The compression delivery to a refueling station (or other such applications) sites is also the cause for the disparity between GO systems.

A good example is the difference between the TÜV-SÜD, and the EU CertifHy GO scheme. In the TÜV-SÜD, the compression for delivering hydrogen to a site is 20 MPa and the purity Five- Nines. In the EU CertifHy scheme, the pressure for delivery is 3MPa and the purity is Two-Nines (99 percent). This illustrates the complexity between different GO programs and the near impossibility of trading GOs between them, though TÜV-SÜD and CertifHy are both available in Europe.

To add to the complexity, most of the hydrogen GO schemes do not consider liquid hydrogen within their frameworks, though this storage mode is investigated for inter-country transportation of hydrogen and for marine fuel applications.

Different pressures, different purities, not considering a mode of storage and its energy requirements (e.g., liquid), etc. all add to the complexity of trading hydrogen GO and certificates.

All in all, the above means that for the exact same hydrogen supply, dissimilar GHG emissions will be considered for each process and stage. Added to this, different carbon accounting standards will be used under the exact same conditions. An international green hydrogen standard, approved by all countries involved in green hydrogen is therefore needed, if GOs are to be of value in accelerating green hydrogen development. Such will state the different GHGs assessed, what are their associated global warming likelihood, and, of importance, what is the carbon accounting method used. The GO can then be aligned to the approved standard and issues facing the green hydrogen industry completely waived.

3.4.2. Administering a GO scheme

Administering a GO scheme could come at a prohibitive price if all the different steps in the hydrogen supply chain are accounted for. Any extra expenses, added complexity, too much detailed requested and too many administrative requirements could discourage investors and developers and slow down the green hydrogen deployment. Currently, it is very challenging to find the best and most optimal methodology for a green hydrogen GO scheme because there are so many different pathways, different approaches, different country preferences and a lack of a common standard view, but also simply because some of the approaches are not yet fully understood or realized on the ground.

No matter what, administering and participating in a GO scheme will bring several extra operating expenditure costs in addition to the capital-intensive infrastructure costs of a hydrogen project. The extra costs range from validated data capture in the field, auditing the sites and data and hardware, trading fees including transaction fees and entry fees, etc. The more detailed the scheme is, the higher the cost of administration.

3.4.3. Initial market entry level

Green hydrogen is still a small market that needs developing, and currently, there are only a handful of small projects around the world, though this is gaining pace. One of the potential initial barriers to entry is associated with the minimum contract size for market trading. Ensuring a lower trading market entry for green hydrogen GOs would allow easier access to new hydrogen developer. When demand for green hydrogen will increase, and large-scale green hydrogen schemes are developed, the minimum market entry value can be increased. Currently, even a 1 MWh green hydrogen system is deemed large, and as such any GO scheme should factor in this criterion before launching the scheme.

3.4.4. Risks of misleading customers

There are many different pathways to produce hydrogen, and some pathways produce "low- carbon GHG hydrogen". Selling low-carbon GHG hydrogen instead of green hydrogen from renewable may lead to mistrust in the GO system by buyers. Customers who want to support the transition may feel that they are paying more for green hydrogen but getting a lower quality GHG credential for a higher price. There is a need to ensure that customers who pay higher prices are not misled in the quality of the green hydrogen and its origin (CCS, electrolyser, biomass, etc.). Transparency in terms of GHG per feedstock should be clearly stated to avoid such mistrust.

3.4.5. Carbon price and hydrogen viability

Hydrogen technologies can contribute substantially to the trading of certified CO2 emission reductions. Natural gas reforming and CCS are good examples where carbon storage could be included in CO2 international trading. The current cost of carbon is, however, low and is not contributing to green hydrogen's financial viability. The Hydrogen Council has considered an increase in the price of carbon trading from $30 per ton CO2-equivalent in 2020 to $50 per ton CO2 equivalent in 2030. Using this increase in the carbon price, the council described that hydrogen will become financially viable within the next decade. In summary, GOs for hydrogen are still at the infancy stage. However, the process of establishing GOs will accelerate as the number of projects around the world is growing rapidly.

4. Country Readiness Assessment for Green Hydrogen Ecosystem

A total of 41 governments, accounting for nearly 80 percent of global energy-related CO_2 emissions, have now adopted hydrogen strategies.[19] There is different low-carbon hydrogen uptake across regions due to varying opportunities and country priorities. Hydrogen's versatility makes it relevant in many countries, but its applications and supply chain development should be tailored to each specific context.

According to International Solar Alliance's Blueprint for Ecosystem Readiness Assessment for Green Hydrogen[20], a Subset of 33 ISA member countries was shortlisted for the green hydrogen readiness assessment. This was based on key parameters such as high RE potential, relevant policy framework in place, and hydrogen demand. The selected ISA member countries also accounted for the majority share of the total global hydrogen demand of 94 MTPA in 2021.

To assess the country readiness, a combination of eight key parameters were taken – strategic intent, relevant infrastructure experience, ease of doing business, existing RE installation and potential, hydrogen demand and project outlook, proximity to ports etc. A weighted average score was calculated for each country. Countries were assessed and placed into four broad categories based on their level of readiness for adopting GH. The categories were **Frontrunners, followed by Progressives, Prospectives and Potentials**.

Frontrunners	Progressives	Prospectives	Potentials
• USA	• Italy	• UAE	• Trinidad & Tobago
• Australia	• India	• Brazil	• Indonesia
• France	• Egypt	• Poland	• Somalia
• Spain	• Netherlands	• Morocco	• Qatar
• Germany	• Saudi Arabia	• Iran	• Nigeria
• Japan	• Republic of Korea	• Peru	• Bangladesh
• Chile	• Oman	• Mexico	
• United Kingdom	• Argentina	• Namibia	
	• Algeria	• Sudan	
	• South Africa		

Figure 9: Categorization of Countries Based on Readiness Framework

Source: ISA Blueprint for Ecosystem Readiness Assessment for Green Hydrogen 2022

19 *IEA - Global Hydrogen Review 2023*

20 *ISA Blueprint for Ecosystem Readiness Assessment for Green Hydrogen 2022*

Frontrunners

Perform well on multiple parameters and are more likely than other countries to have a structured policy mechanism for GH in place, with clear roadmaps, attainable targets, and an alignment among stakeholders. These countries would also have a moderate-to-strong installed base of renewable energy solutions, which is also indicative of the technical capabilities among the industry players required to deploy, operationalize, and maintain such solutions. With these enabling conditions in place, the Frontrunners are well positioned to scale up.

Progressives

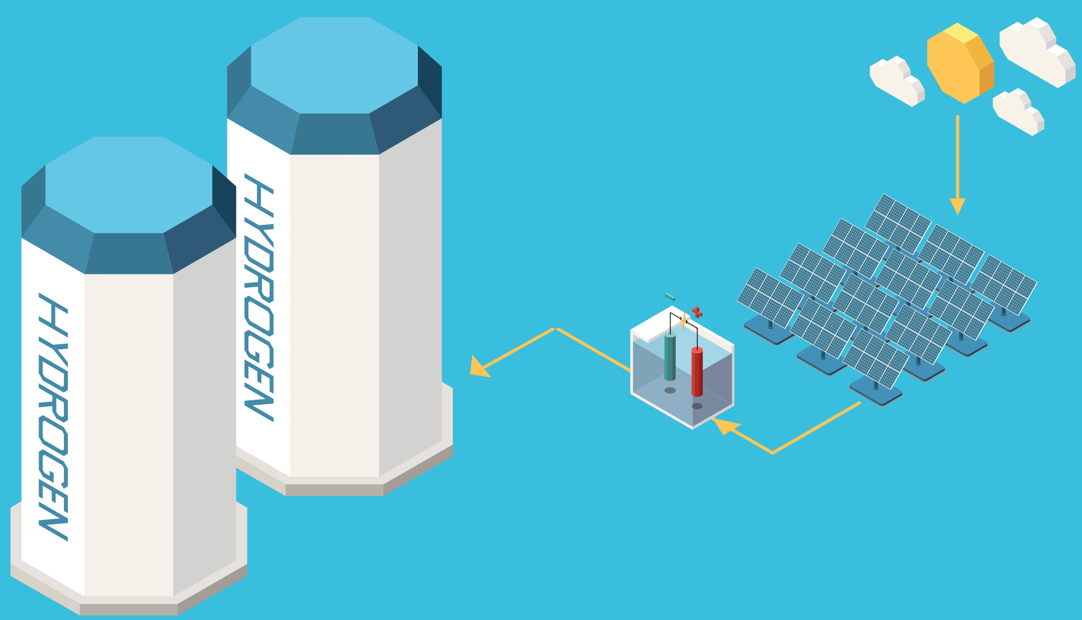
Perform well on some of the parameters but may be lacking on a few other parameters. Except for certain parameters inherently derived from the climate and the geography of the country, such as the level of renewable energy potential available in these countries and the distance to coast, the score on most other parameters could be improved with concerted effort. Gaps in GH policy framework can be swiftly addressed to have an impact on the country's readiness level. For developed countries falling in this category, plugging these policy gaps could be easier as compared to developing countries that have less expertise and affordable financial resources.

Prospectives

Countries score well on only a few parameters. For instance, most of the countries falling within this category have excellent renewable energy generation potential which is offset by the low levels of actual renewable energy deployment. Many of these countries have exhibited some strategic intent towards adopting GH, either with a stated vision to develop GH ecosystem or with a nascent strategy or a roadmap. Many of these countries also have announced net zero targets.

Potentials

Countries demonstrate strong developing trends which are expected to increase their energy consumption as they grow or have the potential to become a major GH export hub based on the renewable energy potential. As with Prospectives, Potentials need to focus on pushing RE portfolios and policy frameworks which will facilitate development of fuel handling and transportation infrastructure and promoting GH among industrial and commercial consumers.



Plenty of public support for low-carbon hydrogen development continues to be seen in developed regions like Europe and the US, however the momentum is also growing in Latin America, the Caribbean, Africa and the Middle East.

Low-carbon hydrogen projects in Latin America and the Caribbean will be seen first in the hard-to-abate industries like steel, oil refining, fertilisers, petrochemicals, cement, mining etc. and mobility sectors. Ammonia, a crucial feedstock for the agriculture sector and fertilisers industry, holds a great potential for decarbonisation. Latin America's industrial and oil refining sectors required more than 4 Mt of hydrogen in 2019 (around 5 percent of global demand), mainly to produce ammonia, methanol, steel and refined oil products.[21] The release of the 2020 Chilean National Green Hydrogen Strategy led to an accelerated regional interest in the hydrogen industry. In Chile, demand for green hydrogen will likely come from domestic adoption in the industrial sector, long-range transportation and exports.

Brazil, for instance, currently imports 80 percent of the ammonia used for making fertilisers, most of which is produced using fossil fuels. Many countries in Latin America and the Caribbean aim to explore their potential to export low-carbon hydrogen and its derivatives like green ammonia in the short term (Chile, Brazil). In terms of cost competitiveness, renewable hydrogen will be competitive in producing countries with existing incentives for renewable energy from the government. Countries in Europe and Asia are some of the more likely candidates to become importers of Latin America's green hydrogen. **Chile** has already signed a green hydrogen agreement with EU ports, and companies from Belgium and France, among other countries, are investing in Chile's green hydrogen production.

Considering the huge potential volume of demand for low-carbon hydrogen in Asia-Pacific, export can be the priority end-use, which could support cost reduction and in turn increase internal use. **India** could also consider low-carbon hydrogen export to its neighbors, after meeting its internal demand. Use of green chemicals like green hydrogen and green ammonia in India can improve the country's air quality indices and support the country's burgeoning population sustainably. India possesses tremendous solar and wind resources.

India can aim to become self-sufficient by substituting imports of fossil fuels with locally made clean fuels like green hydrogen. The Asia-Pacific region with its future big demand centres is at the forefront of the development of a global low-carbon hydrogen market, alongside Europe. Specific areas for action priorities in the region relate to supporting hydrogen-related technology development; and facilitating the development of the supply chain for hydrogen use in the mobility sector, through direct investment, incentives, and subsidies.

This section dwells deeper into three potential green hydrogen economies – **Chile, India, and Brazil**. With excellent RE potential, infrastructural capabilities, strategic intent, and hydrogen demand, all three countries are attractively positioned to not just act as major exporters, but also focus on domestic consumption of low carbon hydrogen. The three countries are members of the International Solar Alliance. In addition, two of the countries are G20 members. India assumed the presidency of the G20 in 2023 and will be releasing it to Brazil in 2024.

4.1. Republic of India

India is a mixed middle-income developing social market economy with notable state participation in strategic sectors. With a GDP of USD 3.18 trillion[22] , the country is the world's fifth-largest economy by nominal GDP and the third largest by purchasing power parity. **India has a strong manufacturing base with solid foundations in the core industrial sectors.** India is fast becoming a global manufacturing destination and has the potential to export goods worth USD 1 trillion by 2030[23]. The country ranks second globally in, coal, cement, steel production, food, and agricultural production, third in electricity generation and oil consumption, and fourth in automobile production.

21 *IEA – Hydrogen in Latin America 2019*

22 *With a GDP of USD 3.18 trillion22 , the country is the world's fifth-largest economy by nominal GDP and the third largest by purchasing power parity. (Trak.in, 2022)*

23 *India – A 1 trillion manufacturing export market by 2030 (Mint, 2022)*

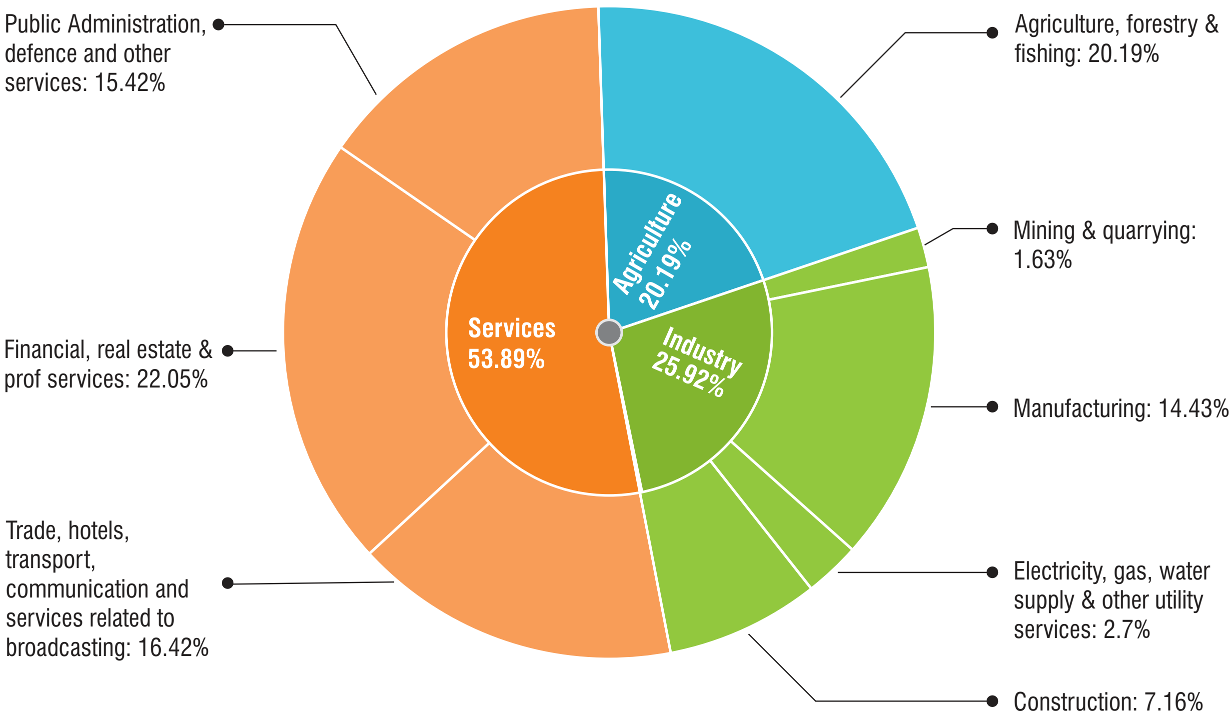


Figure 10: India's GDP by Economic Sector During 2021

Source: Ministry of Statistics and Programme Implementation 2021

Over the recent decades, India has grown from its status as a country with severe power shortages to one with surplus with infrastructure, policy, and regulatory reforms in the sector. Given the economy's growth potential and the large population, **growth in energy demand in India is expected to be significantly higher than all other countries, with demand rising 3 percent annually**.[24] Despite the country's historical dependence on fossil fuels - particularly coal - 60 percent of the growth in energy demand is expected to be met through renewable energy sources owing to the increasing policy push for the sector.

The Nationally Determined Contributions (NDCs) pledged by India to the United Nations Framework Convention on Climate Change (UNFCCC) specifies its target of achieving 50 percent share in the installed electric power generation capacity from renewable energy, by 2030, and a reduction of emissions intensity of its gross domestic product by a factor of 45 percent vis-à-vis 2005 level by the same year.[25]

India's power sector is largely diversified

Sources of power generation range from conventional sources such as coal, lignite, natural gas, oil, hydro and nuclear power, to viable non-conventional sources such as wind, solar, biomass, and domestic waste. As of February 2023, the total installed power generation capacity in India stood close to 412 GW, of which about 236 GW capacity is based on fossil fuels, while 168 GW of capacity is based on renewable energy sources, including hydro power.[26] At COP27, India submitted its Long-term Strategy for Low Carbon Development (LTS) which provides a breakdown of initiatives by sector and aligns its targets with the country's updated NDC targets. The LTS details India's plans to continue developing coal in the long-term, while also ramping up renewable energy solutions significantly. The Draft National Electricity Plan projects 26 GW of

24 IEA World Energy Outlook 2022

25 india's intended nationally determined contribution: working towards climate justice (unfcc, 2022)

26 India's renewable energy capacity reaches 168.96 GW till Feb 2023: Minister R K Singh (The Economic Times, 2023) coal-based power generation capacity to be added by 2026-27, meanwhile renewable energy capacity is expected to be quadrupled to 500 GW by the year 2030.

The industrial sector was the biggest consumer of energy at 56.22 percent of total consumption. The transport sector accounted for 8.82 percent of total consumption and the residential, agriculture, commercial, public and other sectors together contributed to around 34.96 percent of the overall consumption.[27]

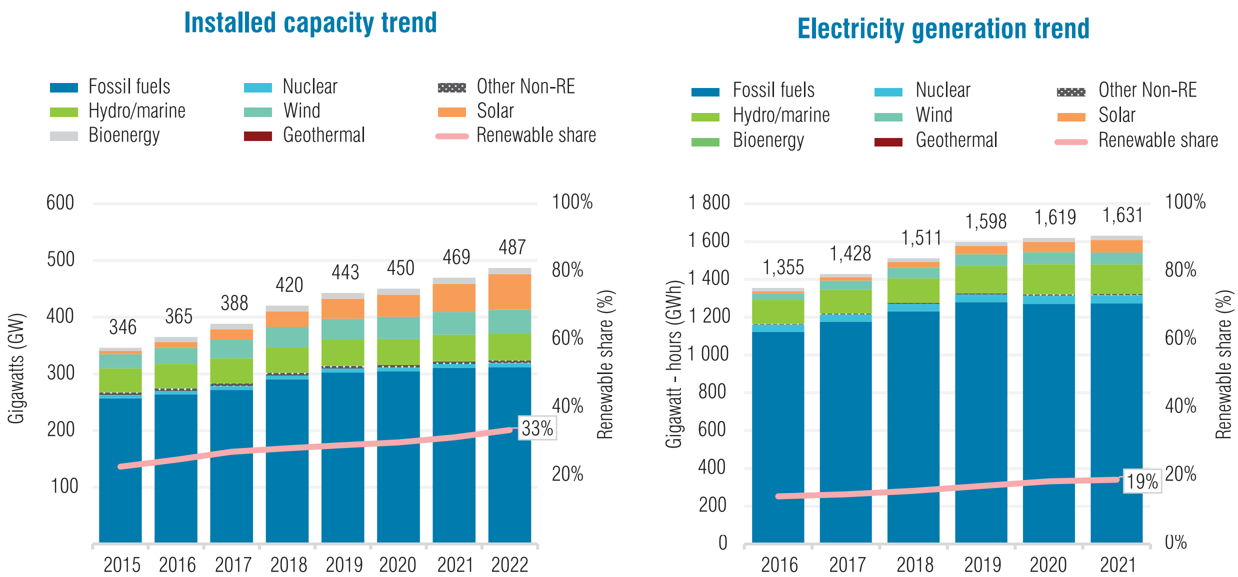


Figure 11: L-R: India Installed Capacity Trend; Electricity Generation

Source: followed by IRENA IRENA Country Profile - India, 2021

India's geographical location, climatic conditions, and abundance of renewable energy resources makes it a favorable location for producing green hydrogen at low prices by 2050.

India ranks fourth globally in total renewable energy installed capacity (including large hydro), fourth in wind power capacity & fourth in solar power capacity[28]. **The installed solar energy capacity has increased by 24.4 times in the last 9 years and stands at 67.07 GW as of July 2023**. This rapid growth in India's renewable energy sector justifies its rank as the third most attractive global destination for renewable energy investment.[29]

Solar energy potential in India is more-or-less uniformly distributed across the geographical span of the country, with pockets of slightly higher solar irradiation concentrated in the western region of the country and certain parts in the northern mountainous regions of the country. As a result, solar PV plants located in **most parts of the country yield more than 4 kWh per kWp on an average sunny day**. The climatic conditions in most parts of the country receiving more than 300 sunny days every year also contributes to the high levels of solar energy potential in the country. The National Institute of Solar Energy has assessed the **country's solar potential of about 748 GW** assuming around 3 percent of wasteland area to be covered by solar PV modules.

27 People's Archive of Rural India - Energy Statistics India 2022

28 REN21 Renewables Global Status Report 2022

29 India is 4th globally for total renewable power capacity additions (Invest India, 2023)

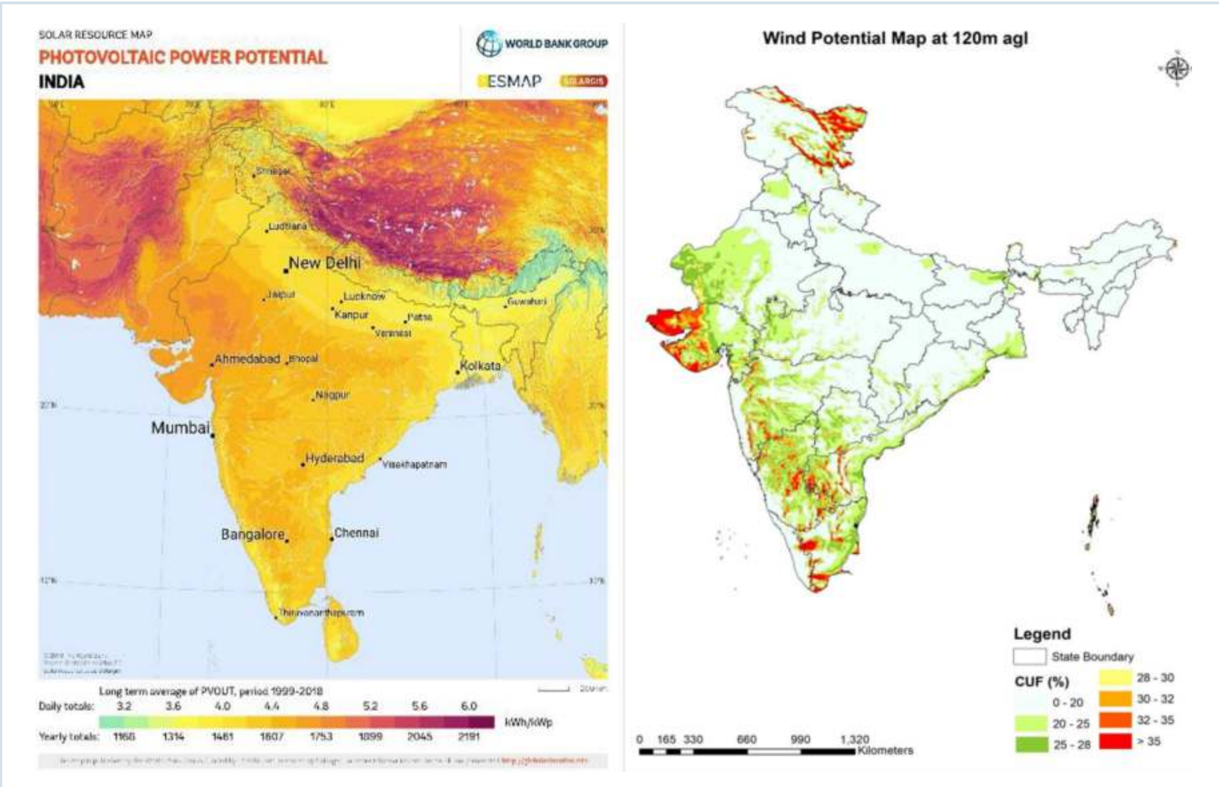


Figure 12: L-R: Solar Potential and Wind Potential in India

Source: Global Solar Atlas, 2023; National Institute of Wind Enery, 2022

On the other hand, wind energy potential in India is severely limited to certain pockets in the southern and southwestern parts of the country. The National Institute of Wind Energy estimates a total wind energy potential in India of **302 GW at a hub height of 100 m above ground, which more than doubles to over 695 GW at a hub height of 120m**[30]. Additionally, India also has a potential of **174 GW of offshore wind resources** along certain parts of the western and southern coast of the country.

The geographically dispersed renewable energy hotspots in India are well connected with an integrated transmission network that allow for cross-country transmission of power as well trading of power with neighboring countries. The high voltage **transmission network capacity in the country stands at more than 460,000 ckm of transmission lines and more than 1.15 million MVA of transformation capacity**. Additionally, India has also been establishing Green Energy Corridors for evacuation of the renewable energy in the resource rich states and its integration with the broader national transmission network.

India has established green hydrogen as a core pillar of its decarbonization and net zero strategy

India's National Hydrogen Mission launched in August 2021, acts as a policy enabler to attain its climate targets, and become a hub for green hydrogen and green ammonia production. The policy mechanism targets to reduce India's dependence on

30 *Ministry of new and renewable energy evaluation of wind energy in india twenty-seventh report*

fossil fuels and scale up its renewable energy capacity by setting up green hydrogen production facilities and bringing down the cost of green hydrogen. India's geographical location, climatic conditions, and abundance of renewable energy resources makes it a favorable location for producing green hydrogen at low prices by 2050.

A. Policy framework

India's National Green Hydrogen Mission (NGHM) sets out a roadmap for using hydrogen to meet its climate targets and make India a green hydrogen hub. The aim of this mission is to enable India to become a global hub for production, usage and export of green hydrogen and its derivatives. The National Hydrogen Mission lays down the following expected outcomes for green hydrogen in the country by the year 2030:

- Green hydrogen production capacity in the country to reach at least 5 MMT per annum
- Renewable energy capacity addition of ~125 GW
- Total investment of over USD 100 billion
- Creation of over 600,000 full time jobs
- Emission mitigation to the tune of 50 MMT of CO2 equivalent

Under the Mission, India proposes to adopt a phased approach towards its implementation. **The first phase focuses on creation of demand and building adequate supply** by increasing the domestic electrolyser manufacturing capacity through incentives aimed at indigenization of the value chain. On the demand side, the first phase is expected to stimulate green hydrogen usage in key end-use segments and initiate pilot projects in other hard-to-abate segments.

The **second phase to be undertaken towards the end of the decade is expected to scale up utilization of green hydrogen and enhance R&D activity** in the sector, to help increase penetration across all potential sectors leading to deep decarbonisation of the economy.

The Mission proposes two distinct financial incentive mechanisms, targeted at domestic manufacturing of electrolysers, and at production of green hydrogen. In addition, the Mission also provides for enabling mechanisms, including enhancement of ease of doing business, infrastructure and supply chain, regulations and standards, skill development and public awareness in the sector.

B. Regulatory framework

The National Hydrogen Mission sets the aim to harmonize regulations and standards with internationally accepted norms to ensure inter-operability of technologies, and incorporation of global best practices. The Mission also aims to notify necessary regulatory provisions, regulatory amendments and standards that will permit operation of hydrogen-fueled vehicles and other applications within a period of 12 months.

C. Partnerships

India has signed many agreements on hydrogen cooperation with countries across the globe including Germany, France, Netherlands, the United States and Denmark. For instance, India and France have announced the adoption of a "**Roadmap on the Development of Green Hydrogen**" under which the countries are expected to collaborate on:

- establishing a regulatory framework for the entire green hydrogen value chain
- carbon-content certification methods with knowledge sharing and skill development programmes between certification bodies
- R&D through cooperation between their relevant research institutions
- industrial partnerships between French and Indian energy industries

Germany signed an agreement on hydrogen cooperation with India. The cooperation agreement aims to establish a task force to promote the creation of a close network between the government, industry, and research institutes of both countries. Furthermore, a roadmap with specific joint measures to support the market ramp-up of green hydrogen will be developed. Additionally, the task force will work on exchanging know-how on hydrogen regulation, norming, safety procedures and sustainability criteria.

In addition, the United States Department of Energy (DOE), India's Ministry of New and Renewable Energy (MNRE) and the US India Strategic Partnership Forum (USISPF) have jointly launched a US-India Hydrogen Task Force. This is under the US-India Strategic Clean Energy Partnership (SCEP). This Task Force represents industry and government stake holders to assess technology status, study innovative policy options, and make recommendations. The focus will be on strengthening cooperation on hydrogen between industry and institutions from both countries. Another hydrogen centered association gaining momentum is the India H2 Alliance.

To increase its collaboration on green hydrogen and a 'Green Hydrogen Corridor', the **Netherlands** is also working together with MNRE and NITI Aayog. The country is also working with India to help meet its plans to have e-vehicles on the roads.

D. Market development

The Green Hydrogen Mission demarcates the sectors and the market development approach. The highest priority is accorded to those sectors where green hydrogen would support replacement of fossil fuels and fossil fuel-based feedstocks. These include:

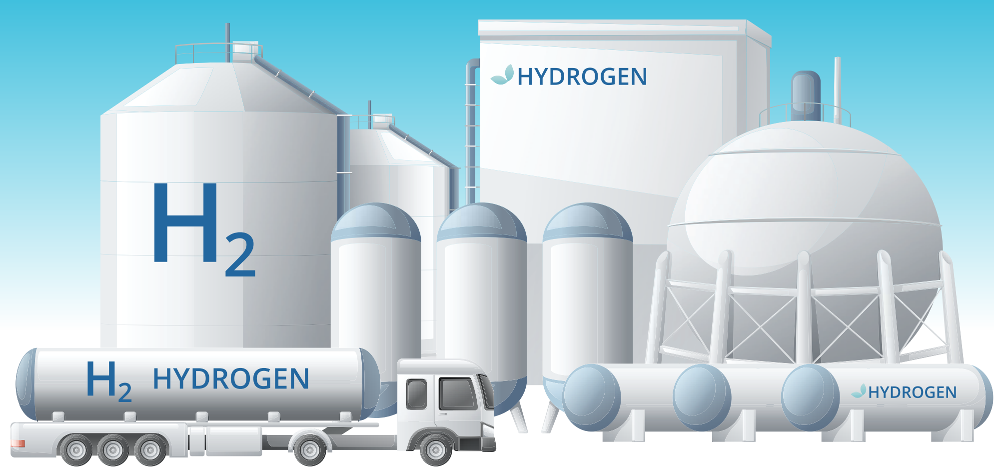
- replacement of fossil fuel derived hydrogen with green hydrogen in ammonia production and petroleum refining
- blending of green hydrogen in City Gas Distribution (CGD) systems
- production of steel with green hydrogen

GAIL has started hydrogen blending as a pilot project to establish the techno-commercial feasibility of blending hydrogen in City Gas Distribution (CGD) network.

While natural gas has lower carbon intensity when compared to other fossil fuels, it is still a fossil fuel that releases a considerable amount of carbon in the atmosphere when burned.

By blending it with lower emission alternatives like biogas, and zero-emission fuels like hydrogen, the net amount of carbon that is being released from the natural gas blend will be lesser than if an equivalent amount of just pure natural gas is used.

These blending methods, much similar to India's plans to blend ethanol with fuel, will not only reduce emissions but also reduce energy costs, depending on the difference between the cost of natural gas and the hydrogen being produced.

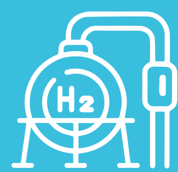


This is expected to be followed by use of green hydrogen-derived synthetic fuels, including green ammonia and green methanol, to replace fossil fuels in various sectors including mobility and shipping. It is also proposing to undertake pilot projects in potential sectors like railways, aviation etc. Pilot projects are being proposed as the key mechanism for identifying operational issues and gaps in terms of technology readiness, regulations, implementation methodologies, infrastructure, and supply chains in the nascent sectors.

E. Infrastructure

The Green Hydrogen Mission identifies various infrastructure initiatives for development of green hydrogen ecosystem in the country. The Mission proposes to identify and develop regions capable of supporting large scale production or utilization of hydrogen as Green Hydrogen Hubs (with trunk infrastructure allowing for pooling of resources and achievement of scale). Green hydrogen mobility corridors will be set up by setting up refueling infrastructure and hydrogen supply arrangements to connect the proposed Hubs. Additionally, infrastructure at major ports is expected to be developed as Green Hydrogen Hubs would be attracted to coastal zones in the vicinity of such ports.

Introduction of the National Green Hydrogen Mission has sparked interest for green hydrogen among the corporate sector in India



Provisions of India's National Hydrogen Mission, combined with enabling factors present in the country ranging from a vast renewable energy resource base, large demand potential and the availability of infrastructure has gained the attention of various corporate entities in the country. Companies from both the private and the public sector in India have announced plans for investing in the emerging green hydrogen sector and scaling it up in the long term. Some of the notable investment announcements include:

- **NPTC Ltd**. has commenced production of green hydrogen and its blending with natural gas supplied to its Kawas township by using power from 1 MW floating solar project
- **Oil India Limited (OIL)** has commissioned the country's first green hydrogen pilot plant with an installed capacity of 10 kilograms per day at its Jorhat Pump Station
- **Adani Group's** partnership with France's **Total Energies SE** plans to invest USD 50 billion over 10 years to develop a hydrogen ecosystem and develop a production capacity of 1 million ton per annum before 2030, with technology support from Cavendish Renewable Technology (CRT), Australia
- **Reliance Industries** proposes to transition to green hydrogen from grey by 2025 and reduce green hydrogen production costs to under USD 1 per kg by 2030. The group has partnered with Danish technology firm Stiesdal for development and manufacturing of electrolysers
- **IOCL** targets to replace five percent of hydrogen produced at its refineries with green hydrogen by 2027-28, and 10 percent by 2029-30
- A joint venture of **ONGC** and **Greenko** Group plans to spend up to USD 6.2 billion on renewable energy and green hydrogen projects in India with an intention to export
- **GAIL India** has initiated a project to set up a green hydrogen plan at its Vijaipur Complex with a capacity of 4.3 tonnes per day (approx. 10 MW)
- **Hindustan Petroleum Corporation Ltd (HPCL)** has set a green hydrogen production target of 24,000 tonnes a year. The company is expected to commission a 370-tonne capacity per annum green hydrogen plant at its Visakhapatnam refinery
- **Bharat Petroleum Corporation Ltd. (BPCL)** has proposed to set up a 5 MW electrolyser system to include green hydrogen in its city gas distribution networks in a phased manner

Sector attractiveness for potential hydrogen consumption in the country

Hydrogen demand in India for the year 2021 and 2022 is estimated to be 8.5 million tonnes and 9.1 million tonnes, respectively. This demand from the legacy sectors is expected to increase to 11 million tonnes by 2030.[31]The legacy consumers of hydrogen include the ammonia production process in the fertilizer industry and the desulfurization process used in fuel refineries. These two industries currently account for over 80 percent of the hydrogen consumption, primarily derived using natural gas through steam methane reforming (SMR).

The other major consumer of hydrogen in India is the steel industry based on direct reduction of iron ore (DRI). DRI steel production accounts for around 35 percent of the total steel produced in India, which is derived from more than 300 DRI steel mills located in various parts of the country. Most of the DRI units in India utilize hydrogen in the form syngas obtained from coal gasification. The large dependence on coal is due to the relatively good availability and low pricing of Indian coal compared to natural gas.

Development of a green hydrogen ecosystem would not only cater to the replacement of fossil fuel-derived hydrogen demand from these sectors, but also kick-start innovation and uptake in other potential sectors, such as:

31 India's Green Hydrogen Policy: Unprecedented growth needed to achieve 2030 targets (The Economic time, 2022)

- Blending with natural gas in its gaseous form and with liquid fuels in the form of green methanol
- Long-haul heavy-duty mobility, including trucks, railways, and shipping
- Storage and export of green hydrogen

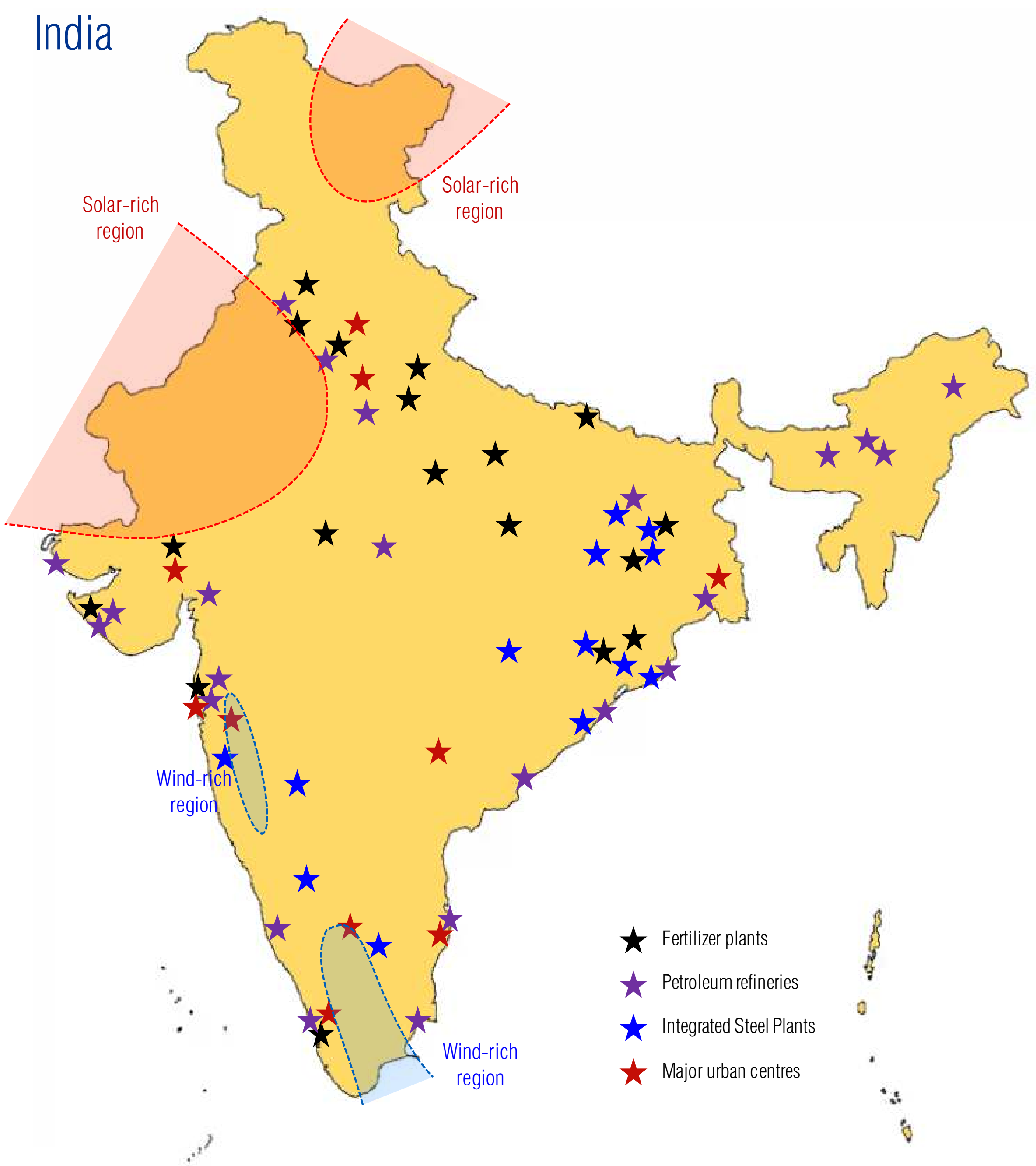


Figure 13: Potential Industries and RE Rich Regions in India*

** The country outline maps in this study are for illustrative purposes and may not precisely represent geographical boundaries.*

Fertilizer

India's fertilizer industry is of strategic importance for ensuring the country's food security, and for supporting the agricultural sector which employs close to two-thirds of the population. Fertilizers are a commodity the price of which directly controls with the food prices and inflation in the country, and as a result, India has been trying to achieve self- sufficiency in fertilizer supply over the decades. Fertilizer production in India has witnessed a surge over the years, from having an annual production of 22.23 MMT in 1990-91 to 43.66 MMT in 2021-22.[32]

Currently, **India is the world's second largest consumer and third largest manufacturer of fertilizers**. The industry produced diammonium phosphate (DAP) and complex fertilizers, such as ammonium nitrate, ammonium phosphate, nitro-phosphate-potash, and muriate of potash (MOP), however urea is the biggest produce of the industry with an annual production of more than 24.6 million tonnes.

India has 33 large urea plants manufacturing urea, 21 units producing DAP and complex fertilizers and 2 units manufacturing ammonium sulphate as a by-product. Most of the large urea plants are in areas connected with natural gas pipelines or with access to coal supplies which are required to produce hydrogen through steam methane reforming (SMR). The hydrogen thus produced is combined with nitrogen to produce ammonia which forms a key ingredient of the urea production process.

Petroleum refining

India is expected to be one of the largest contributors to non-OECD petroleum consumption growth globally. India consumed a total of 222.30 million tonnes of petroleum products in 2022-23, 10.2 percent higher year on year (YoY).[33] Despite the country's dependence on oil producing nations for most of its crude oil supply, India has developed a self-reliance in the petroleum refining sector.

The country's oil refining capacity stands at 248.9 million metric tonnes per annum and the capacity is utilized to it full extent. This makes **India the second-largest refiner in Asia, and the fourth largest in the world** after the United States, People's Republic of China, and Russia. **This refining capacity is spread across 23 refineries** - 18 operated by the public sector, 3 by the private sector, and 2 operated by public-private joint ventures. India plans to almost double its oil refining capacity to 450-500 million tonnes in the next 10 years to meet the rising domestic fuel demand as well as cater to export market.[34]

The refineries are strategically spread across the country's geography and relate to demand centres with cross-country pipelines. Most of the larger Indian refineries are located along the coast to best leverage crude oil imports. The oil producing region in the eastern part of the country also hosts few older low-capacity refineries.

Steel

India is the world's second-largest producer of crude steel. India is the world's second-largest producer of crude steel, with an output of 125.32 MT of crude steel and finished steel production of 121.29 MT in FY23.[35], respectively. With the large steel production capacity and its massive output, India is a net exporter of finished steel with close to 13.5 million tonnes of steel being exported. Steel industry aims to enhance steel production to 300 MTPA by 2030.

At present, Electric Furnace is the predominant technology used for the production of steel in India, which includes Induction Furnaces (IF) and Electric Arc Furnaces (EAF). Slightly less half of the steel produced in the country is produced in conventional integrated steel plants consisting of BF-BOFs (blast furnace – basic oxygen furnace) and SR-BOFs (smelter reduction – basic oxygen furnace), which remains the preferred technology across the globe.

India's steel production capacity is spread primarily across the southern and eastern parts of the country where most of the

32 Hydrogen Application in Indian Fertilizer Industry: An Introduction (WRI, 2022)

33 India's petroleum use at record high in FY23 on surging fuel demand (The Indian Express, 2023)

34 India plans to nearly double oil refining capacity by 2030: Dharmendra Pradhan (The Indian Express, 2023)

35 IBEF - Iron and Steel Industry in India, 2022

more than 50 EAFs, close to 1,000 IFs, and more than 1,200 rolling mills[36] which act as secondary steel producers. India also has more than 300 Direct Reduced Iron (DRI) units that produce close to 40 percent of the global supply of DRI steel, making India its largest producer.

Transportation

India's transport sector accounts for less than a fifth of India's final energy use resulting in almost 11 percent of India's energy sector related carbon dioxide emissions.[37] Although these numbers are small, India's accelerating economic growth and increasing purchasing power in the county is expected to significantly increase emissions from this sector.

The transport sector in India is diverse, with both road, rail, and air playing an important role. However, over the recent decades, with the large-scale investment in road infrastructure, such as expressways, highways and rural roads, the share of the road sector has far outstripped all other means of transport put together. Roadways also feature as the dominant means of transport for freight movement in the country. Even though air transport holds a very small share of the pie, the sector has grown tremendously over the past few decades with a multifold increase in passenger numbers and cargo movements.

Going forward, the continued dominance of trucks for long-distance goods movement and the increasing passenger movement through air is expected to continue which puts significant burden centralized on most of the large urban hubs in the country. As a result, these urban hubs are expected to emerge as large demand centres for green hydrogen directed at the transport segment of the country.

Possible arrangements for green hydrogen production, transportation, and supply in India

Considering the geographic spread of the renewable energy potential alongside the possible demand centres in the country, it is expected that following arrangements for green hydrogen production, transportation and consumption would emerge in India:

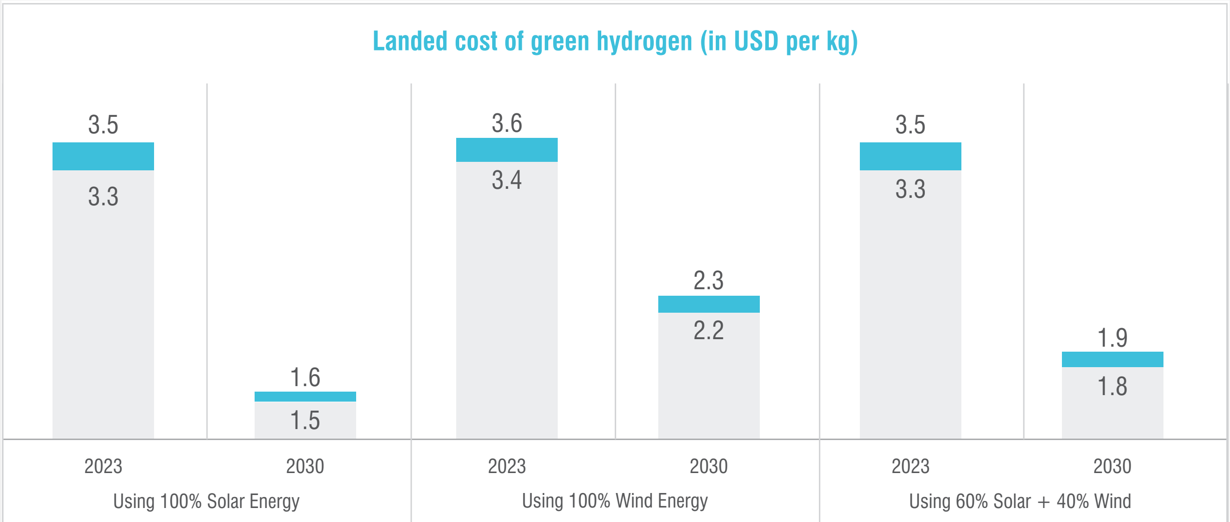
- Hydrogen would be produced close to the demand centres using energy sourced from solar and wind energy plants located in the renewable energy resource-rich parts of the country. This co-located green hydrogen production arrangement provides a large degree of flexibility because of the excellent transmission infrastructure present in the country.
- Hydrogen is centrally produced close to the renewable energy resource-rich areas and transported overland to demand centres using fleets of trucks and pipelines. Trucks carrying compressed green hydrogen in tanks or cascades would be able to serve shorter and leaner supply routes, whereas pipelines would be ideal for serving larger consumers with steady demand for the gas.
- Given the strong port infrastructure lining the peninsular coast of India, green ammonia could be produced close to the major ports using renewable energy delivered over transmission lines. With such an arrangement, the green ammonia thus produced is available to be readily exported to international markets.

Given these observations, the following scenarios for the production, transportation and supply of green hydrogen could be explored in India:[38]

36 Ministry of Steel
37 CEEW - India Transport Energy Outlook 2022
38 KPMG Analysis 2023

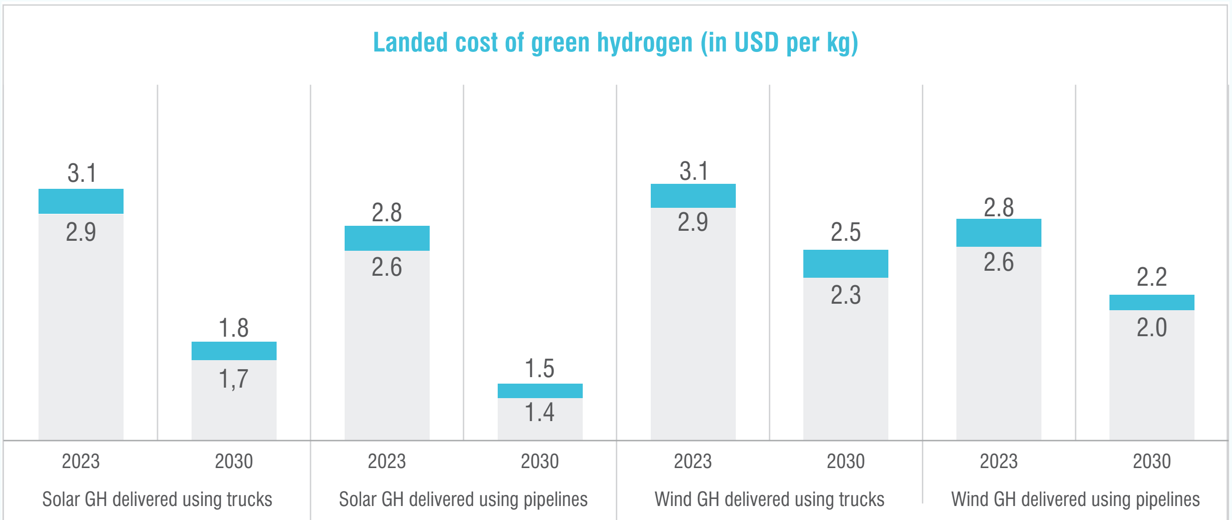
Scenario 1: Co-located Green Hydrogen Production

Hydrogen produced close to the demand centres using renewable electricity delivered through high-voltage transmission links



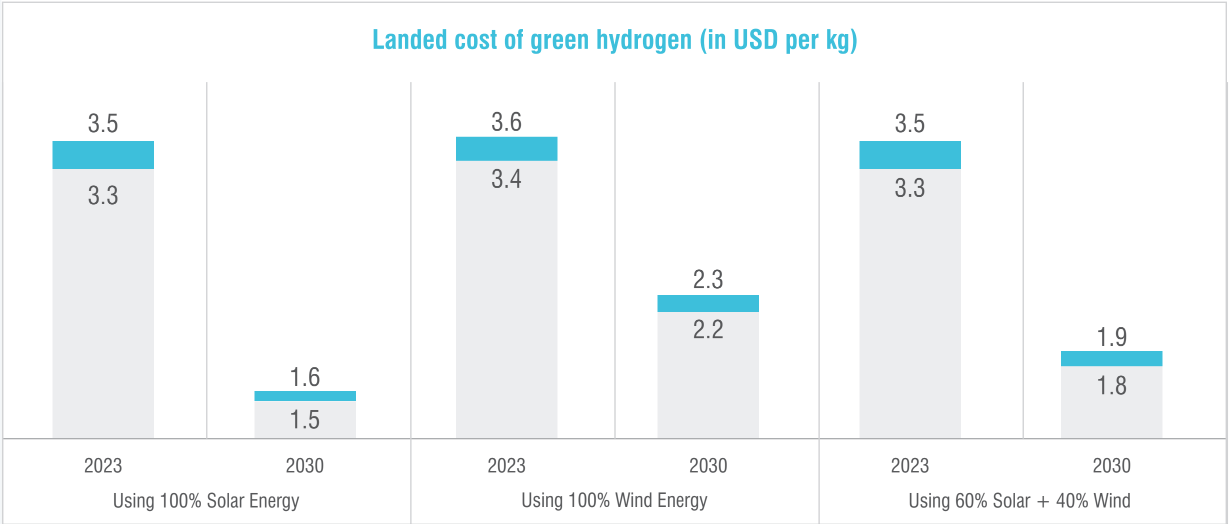
Scenario 2: Centralised Green Hydrogen Production

Production of green hydrogen close to the renewable electricity plants and transported to demand centres. It is assumed that trucks would deliver over shorter distances (up to 750 km) and pipelines would be used to deliver green hydrogen over longer distances (more than 1,000 km)



Scenario 3: Centralised Green Ammonia Production for export purposes

Green ammonia produced at an export terminal located close to a major port using renewable energy delivered through high voltage transmission lines. Landed cost also includes the cost of cracking at the destination to produce green hydrogen



The key findings resulting from above three scenarios include the following:

- **Prices for green hydrogen are expected to drop significantly** over the course of the decade, making it a much more economic source of energy. The drop in prices of green hydrogen produced using solar energy is much sharper than that of wind energy, making it a preferred technology to produce green hydrogen.
- Despite the fall in prices over the decade, **the landed cost of green hydrogen exported from India may not be competitive in the international markets**. This combined with the extremely large potential available in the domestic market and a strong infrastructure base point towards the development of India to become a self-sustaining player in the global green hydrogen landscape.

Way forward

India being a fast-developing nation with a surging energy demand, offers a large potential for high density energy carriers like green hydrogen and its derivatives, especially as the country traverses on its trajectory of decarbonization and net zero emissions by the year 2070. The green hydrogen produced in the country would be key to decarbonizing the large, energy intensive sectors, such as fertilizers, steel and cement, which would in-turn help downstream sectors like agriculture and food processing, and infrastructure segments to decarbonize.

Table 2: Recommendations for India

Drivers		Recommendation
1	**Policy and Regulatory Framework**	• With the Green Hydrogen Mission already launched, India can be at the forefront of developments in the sector. For this, the country must ensure that it puts in place policy and regulatory mechanisms, such as: • **Hydrogen utilization and blending standards** customized to the country's end-use industries • **Quality standards for key components** in the value chain, such as electrolysers, compressors, storage solutions, etc.
2	**Capacity Building and Innovation**	• Ensure that stakeholder training is taken up at a scale like the scale of deployment, and that the depth and breadth of training goes hand-in-hand with the R&D efforts in the country's green hydrogen sector
3	**Financing**	• Collaborate with Multilateral **Development Banks to develop attractive capital and risk financing mechanisms** to support green hydrogen projects • Develop **robust corporate governance regulations to ensure foreign investment** in hydrogen production remains secure
4	**Technology**	• Foster cooperation with countries and multi-national organizations to **support technology development in India and transfer of technology to the country** in future • Leverage **Technology Collaboration Programmes** to facilitate international R&D and information exchange

4.2. Republic of Chile

Chile is a developing country with a high-income economy situated along the western seaboard of South America. It is one of South America's most stable and prosperous nations, leading the region in human development, competitiveness, and globalization. The country's USD 317 billion[39] economy is supported by copper mining which makes up ~15 percent of Chile's GDP and 60 percent of its exports. [40]Overall, Chile produces a third of the world's copper. Apart from the mining activity, Chile's economy is supported by manufacturing and services industry which contribute about 9 percent and 55 percent, respectively to the country's GDP.[41]

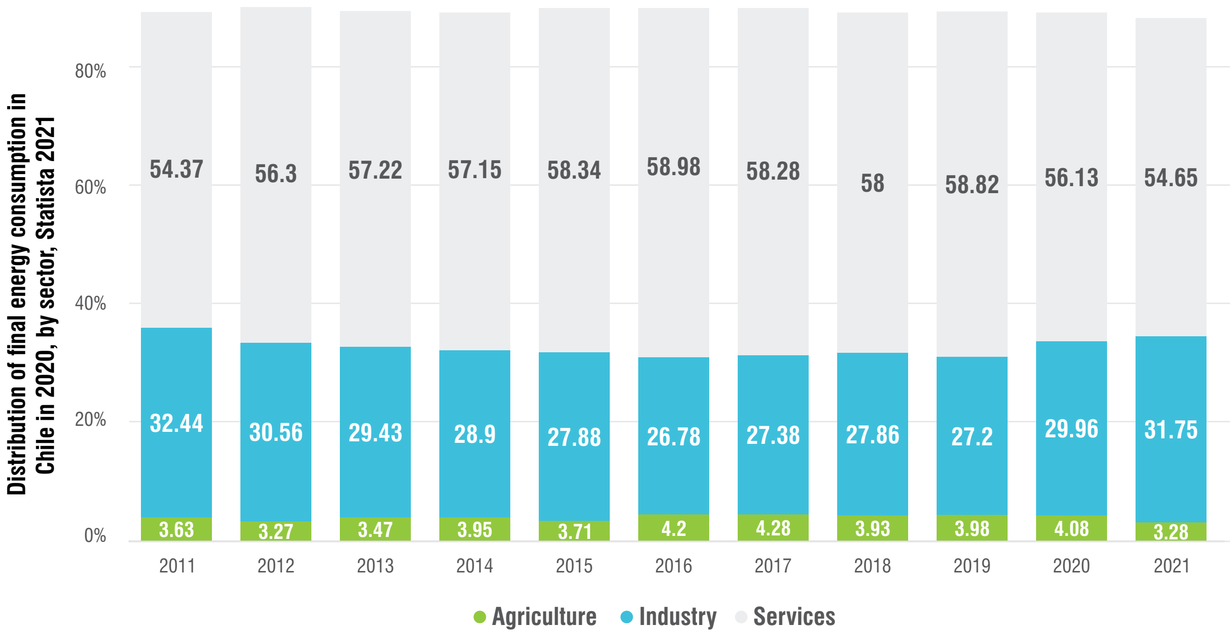


Figure 14: Chilean GDP by Economic Sector During 2021

Source: Chile: Distribution of gross domestic product (GDP) across economic sectors, Statista 2021

Energy sector in Chile has begun the transition from fossil fuels to clean energy in recent years

The energy sector in Chile is largely driven by fossil fuels, including oil, gas and coal, however, a remarkable renewable energy (RE) potential has led to an increase in its share in the installed generation capacity. The industrial and mining sector in Chile was the largest consumer of energy in 2020, accounting for 40 percent of the South American country's final energy consumption. Transportation sector accounted for another 33 percent of Chile's energy consumption in the same year. This was followed by electricity, representing 24 percent of the country's energy consumption.[42]

Coupled with abundant presence of RE, such as solar, hydro, wind and biomass in Chile, the high energy dependence on foreign fuel imports has pushed the country to adopt greener options. Almost all the fossil fuel - coal, oil, and natural gas

39 Chile - Country Commercial Guide, International Trade Administration 2022
40 Chile - Country Commercial Guide, International Trade Administration 2022
41 Share of economic sectors in the GDP in Chile 2021, Statista 2021
42 World Bank (2021)

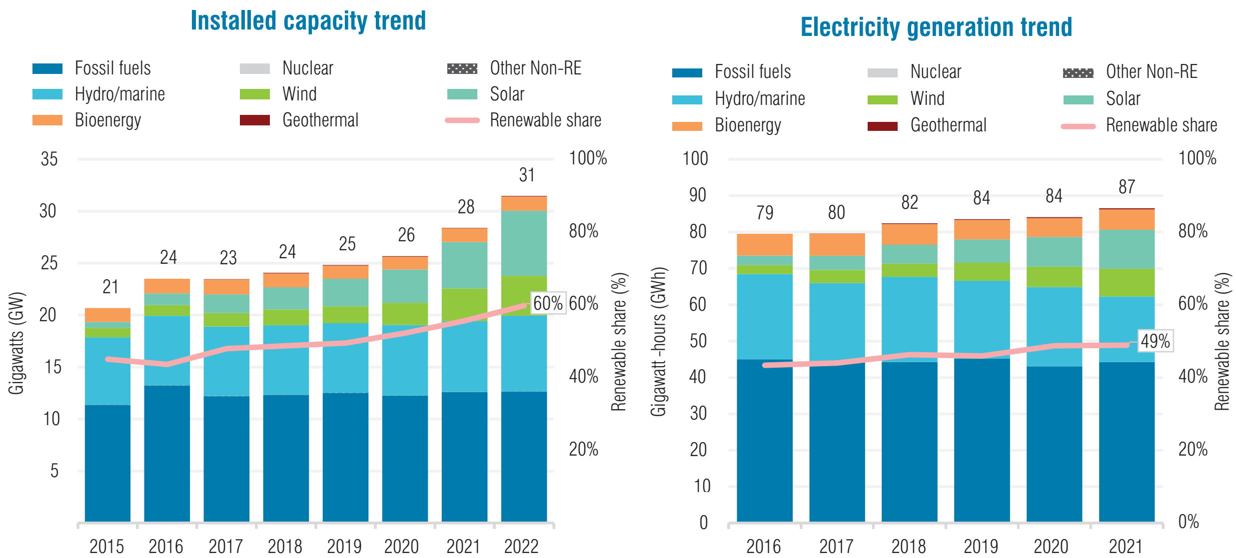


Figure 15: L-R: Chile Installed Capacity Trend; Electricity Generation

Source: IRENA Country Profile - Chile, 2023

(CONG) - consumed in Chile is imported. But the full spectrum of RE resources is there: Biomass, Geothermal, Solar, Hydro, Ocean, and Wind (BiGSHOW).

The high potential for tapping into RE has encouraged the government to decarbonize the power sector by phasing out its coal-fired power plants by 2040. Moreover, it has set highly ambitious goals within its National Energy Policy 2050, aiming to meet 60 percent of national electricity generation from clean energy sources by 2035 and 70 percent by 2050. National legislation encourages investment in generating capacity across the electricity sector. In addition, the expanded role of the state in energy planning has helped to boost project development, especially in electricity transmission. The country's entire population has access to electricity and clean cooking solutions, and since 2017, the country also has a single interconnected national electricity system.

Strong push towards clean energy transition

Thriving on its geographical and climatic potential, Chile plans to become the leading low-cost exporter of green hydrogen in the world by 2040. The country has the potential to produce over 1800 GW of renewable energy.[43]They also quote some onshore wind power potential (190 GW) and little (but not negligible) hydroelectric potential (6 GW).[44] The northern 1/3rd and central 1/3rd of the land area has good - excellent solar resources and the southern 1/3rd, though with not good solar but has excellent wind. In addition, since 2017 there is a national electricity grid, so solar in the central and north regions are complemented by wind in the south. With this, Chile aims to become a key supplier of the emerging energy sources with capacity to meet a substantial part of the global demand for green hydrogen, alongside a large domestic demand driven by the country's mining sector.

Ministry of Energy, Chile projects that the country could produce up to 160 megatons per year of green hydrogen and become the leading low-cost exporter by 2040, when the local market will be worth an estimated USD 33 billion, including USD 24 billion in exports.

A. Policy framework

Chile's frontrunner role is underlined by the governments pledge to net-zero by 2050, highlighting shutting two thirds of coal plants by 2025. This goal is supported by a **Just Transition Strategy**, currently being developed by the government. It also includes a focus on green hydrogen and electric mobility, in line with the respective **National Hydrogen Strategy** (2020)

43 *Chile Country Profile (GH2 Organization, 2023)*

44 *Lessons from Chile, the spearhead in the hydrogen revolution (Hydrogen Central, 2021)*

and the **Electromobility Strategy** (2022). The former aims for 5 GW of electrolysis capacity by 2025, while the latter lays out a goal of 100 percent electric vehicle sales by 2035.

Chile's Ministry of Energy presented a National Strategy for Green Hydrogen with three main objectives:

- To have **5 GW of electrolysis** capacity under development by 2025
- To produce the **cheapest green hydrogen** in the world by 2030
- To be among the world's three **largest hydrogen exporters** by 2040

The Chilean government has set a target of producing 1 million tonnes of green hydrogen and attaining a target price of USD 1.5 per kg by the year 2030. The Ministry projects that Chile could produce up to 1.6 million tonnes per year of green hydrogen and become the leading low-cost exporter by 2040, when the local market will be worth an estimated USD 33 billion (including USD $24 billion in exports).

In 2022, Chile's Ministry of Energy published an update to its Long-Term Energy Policy (Planificación Energética de Largo Plazo, first published in 2015), which re-emphasizes the pledge to net-zero, laying out a clear decarbonisation pathway that addresses all sectors of the national economy.

B. Regulatory framework

The Chilean policy for green hydrogen also provides for modifications to **standards and safety** regulations to include hydrogen as an energy carrier and allows for bylaws to be emitted to regulate safety issues along the value chain. To achieve the hydrogen targets, the government, through its ministries, mainly the Energy, Mining and Transport Ministries, has set out a regulatory roadmap, anticipating a series of regulations, such as, Hydrogen Facilities General Regulation, Multi-Fuel Service Stations Regulation, Technical, Construction and Security Requirements for GH2 (gaseous state hydrogen) Powered Vehicles Regulation, and Hydrogen Systems for Mining Operations Regulation.

To establish a **certification mechanism** in Chile, World Bank commissioned a study of the guidelines for setting up of a green hydrogen certification scheme compatible with international and national markets' conditions.[45]Interactive workshops were carried out to highlight industry's requirements for the certification mechanism, including a clear set of rules from the beginning, ease of verification by third parties, compliance with national and international standards, and a governance mechanism involving the private and the public sector, as well as external auditors. The certification scheme shall comply with the national emission reduction targets of Chile on one hand while also providing credibility and trust in international markets.

C. Partnerships

The Chilean policy for green hydrogen embraces the principles of Public–private partnerships to promote green hydrogen trade. The policy structure intends to set up a Public-Private Agreement for Hydrogen in Mining and Transportation, alongside key public and private stakeholders, to define specific barriers and actions to accelerate the adoption of hydrogen in these sectors.

D. Market development

Exercising the policy, Chile is also gathering support from global partners. A task force has been established by the Chilean Ministry of Energy under **German-Chilean partnership** to support developers in permitting and piloting for green hydrogen projects and its derivatives. The World Bank Group is supporting Chile in putting in place several components of its **National Green Hydrogen Strategy**, including guidelines to set up a green hydrogen certification scheme compatible with international and national markets' conditions, and addressing the safety standards in mining. The World Bank is also working on the development of a **financial instrument** that will reduce the levelized cost of green hydrogen production in Chile, so that the country rapidly and successfully enters the global market.

45 *Consultancy Services for Technical Assistance Activity: Recommendations for Green Hydrogen Certification Scheme in Chile (World Bank, 2020)*

E. Infrastructure

Chile also boasts an infrastructure that could be repurposed for green hydrogen production, particularly the mining sector in the Atacama Desert. Chile's best solar resources are in the Atacama Desert region and more broadly in the northern 1/3rd of the country, as mentioned above. Mining operations are some of the "anchor" customers for some of these big solar projects. Given a **status as an exporter of commodities**, such as copper, Chile has a well-established infrastructure base to position itself as one of the largest exporters of green hydrogen over the next few years.

Chile has established a competitive renewable energy market with a dramatic increase in solar and wind capacity since 2015

Chile has a unique opportunity to develop a competitive green hydrogen industry that forms an energy source for local use and exportation and promotes a sustainable economy around it. Stretching from Atacama Desert in the north to Patagonian south, Chile draws on abundant RE.

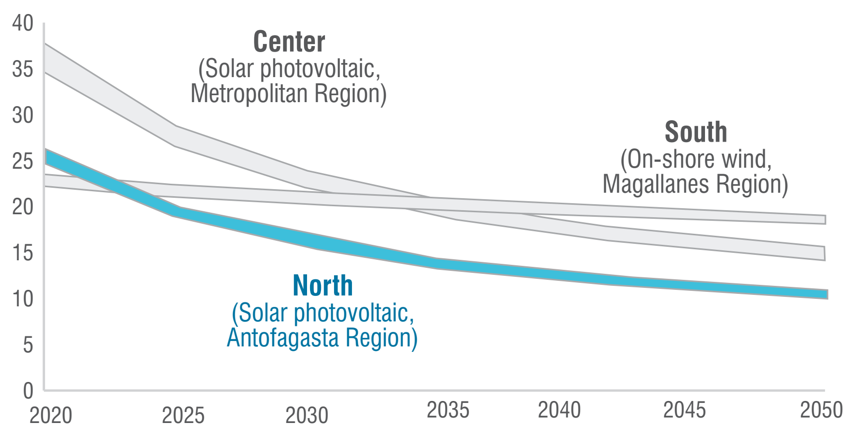


Figure 16: Declining Levelized Cost of Renewable Electricity (USD/MWh)

Source: Chile's Green Hydrogen Strategy and investment opportunities (Ministries of Energy and Mining, 2021)

With high solar radiation and onshore winds, Chile's geography provides both renewable energy opportunities and challenges. The country's greatest solar resource lies in its far north in the Atacama Desert, which has a potential of 9 kWh per m^2 a day, the highest in the world. Chile also has an extensive coastline providing numerous onshore wind sites with good wind speeds, the best is found in the remote Patagonian region in the country's far south.

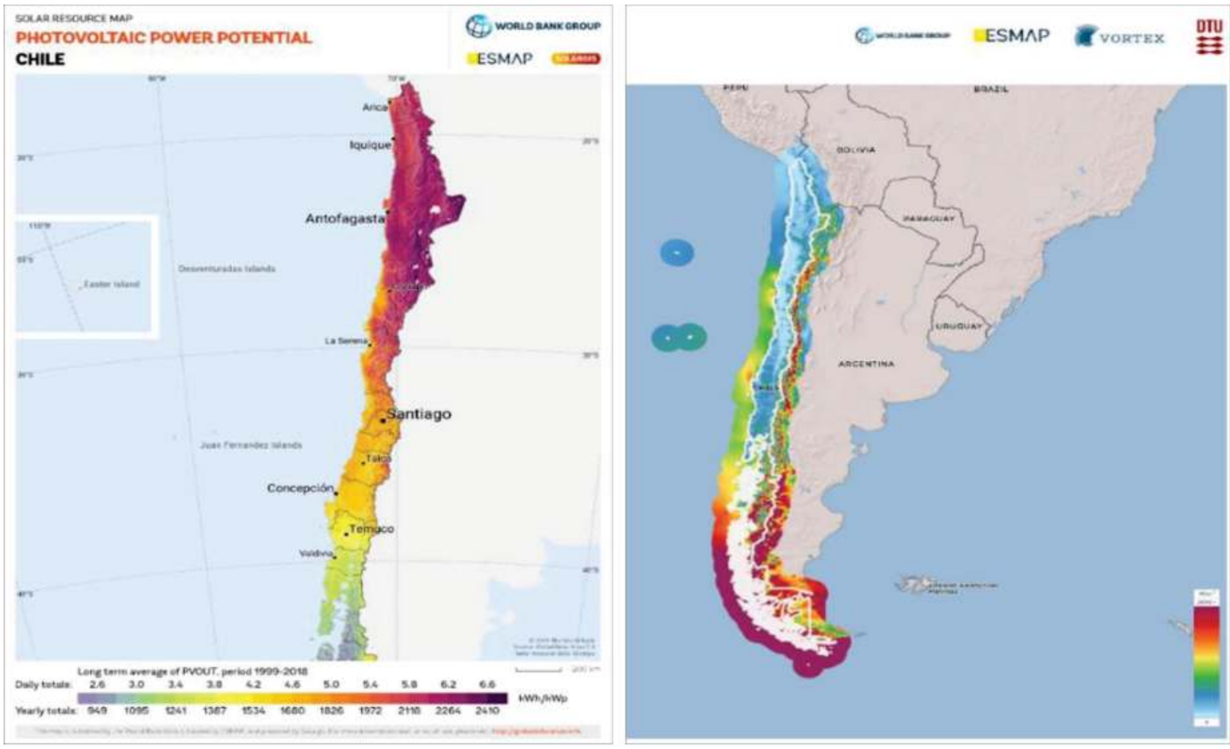


Figure 17: L-R: Solar and Wind Potential in Chile

Source: Solargis, 2018; Chile Wind Map (Vortex, 2021)

Solar generation in the north is perfectly positioned to supply energy to the country's mining operations. Transmission capacity has been the key to unlocking the renewable potential of the north. In addition, the new interconnections have reduced grid congestion and allowed renewable electricity to flow south.

As of 2021, Chile has 29.5GW of installed electricity generation capacity already in operation. The energy matrix breaks down into the following - solar 18 percent, coal 16 percent, diesel 14 percent, wind 13 percent, natural gas 13 percent, hydroelectric dams 12 percent, and run-of-the-river hydroelectric 11 percent. Biomass, geothermal energy, and other technologies make up the remaining amount.

Rich RE environment and presence of a pan-country transmission network makes renewable energy widely available across the length and breadth of the country. This in turn comforts site selection for green hydrogen projects for investors and developers. A mobile green hydrogen pilot plant was opened in Antofagasta to validate the feasibility of producing green hydrogen with solar photovoltaic energy.

Early interest from global players has given pace to green hydrogen development in Chile

With these enabling factors in place, the Chilean development agency has selected and approved six hydrogen projects with a cumulative electrolysers capacity of 396 MW to be supported by public sector funds totaling USD 50 million from companies such as:

Table 3: Hydrogen Projects in Chile

S. No.	Project	Developer	Funds (USD/ Million)	Electrolysis capacity (MW)	Project description
1	**Faro del Sur**	Enel Green Power Chile	16.9	240	Production of some 25,000 tonnes of H2/ year via wind-powered electrolysis. Off-taker is e-fuels producer and exporter HIF Chile
2	**HyPro Aconcagua**	Linde	2.4	v20	3,000 tonnes/year of green H2 to replace some of the grey hydrogen at ENAP's oil refinery in Aconcagua
3	**HyEx - Produccion Hidrogeno Verde**	Engie	9.5	26	Pilot plant to produce 3,200 tonnes/year. Off-taker Enaex to convert green H2 to ammonia
4	**Antofagasta Mining Energy Renewable (AMER)**	Air Liquide	11.8	80	Green H2 to be combined with captured CO2 to produce 60,000 tonnes of e-methanol per year
5	**Quintero Bay Green Hydrogen**	GNL Quintero	5.7	10	Green H2 plant to produce some 430 tonnes/ year. Output to be sold to industrial companies in Quintero Bay area
6	**H2V CAP**	CAP	3.6	20	Green H2 plant to produce 1,550 tonnes/year for green steel making

The Chilean government picked the above mentioned six projects and expects to attract around USD 1 billion worth of investments and bring the country close to 400 MW of electrolysis capacity.

Current potential for hydrogen consumption is Likely to be driven by heavy duty mobility applications

As of 2019, Chile had a hydrogen demand of 0.2 Mt per annum.[46] The country has only a few heavy industries that are conventional consumers of hydrogen, such as **steel, chemicals, petroleum refineries, and fertilizer manufacturing**. As reflected in the figure below, **mining** and **metals** industry in Chile is being promoted as the primary beneficiaries of green hydrogen development plans and policies, with heavy duty trucking and mining haul trucks making up for most of the hydrogen demand in future. The energy transition can drive the broader economic transition. The traditional mining industry - digging giant holes in the ground - can be replaced in part by "mining" RE resources which are inherently sustainable. This has led to Chile experiencing a remarkable clean energy transformation over the past few years. The significant RE potential, favorable business climate and effective policy framework by the Chilean government have made the country an attractive market for energy transition and green growth.

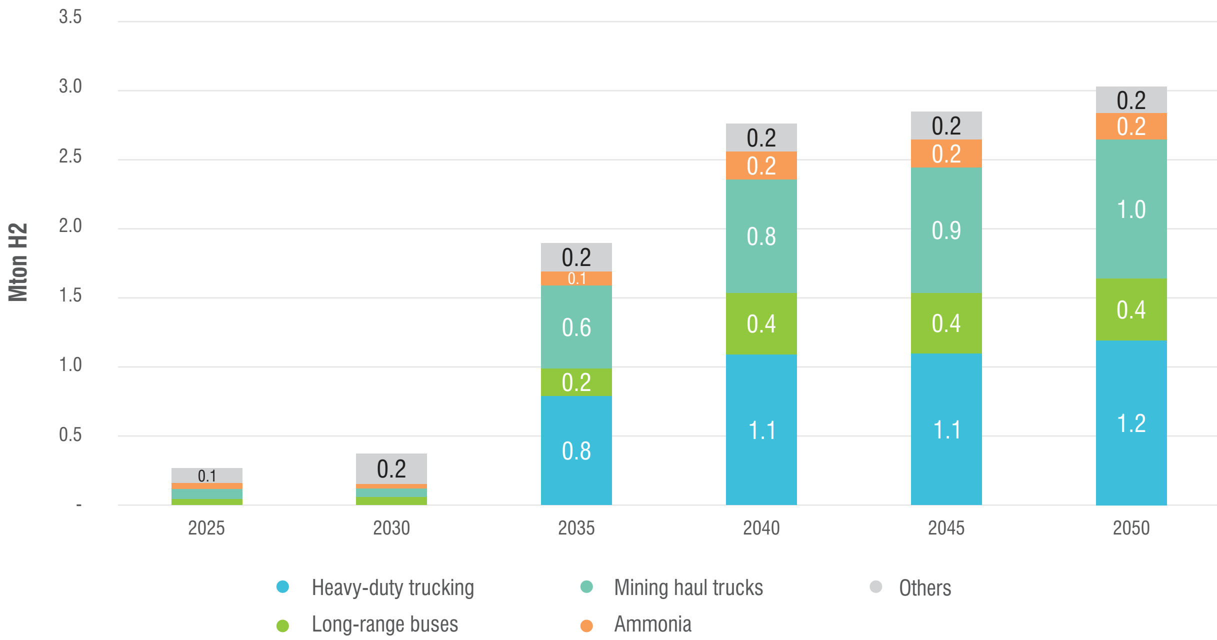


Figure 18: Hydrogen Consumption in Chile for Different Applications

Source: Chile's Green Hydrogen Strategy and investment opportunities (Ministries of Energy and Mining, 2021)

46 *IEA – Hydrogen in Latin America 2019*

Mining sector is an essential part of Chile and is the backbone to its development. Thanks to its comparative advantages, such as the high concentration of copper deposits, Chile is positioned as a competitive producer of minerals, such as copper and lithium. Mining companies in the region are looking up to hydrogen to slash operational costs by eliminating the expensive import of diesel.

Refineries in the country have taken steps to include green hydrogen in their chemical process. Chile's massive mining industry is in the frontline, **developing pilot projects chiefly in the sphere of industrial transport**, such as excavators and haul trucks. Plans for hydrogen deployment in the processing phase are also on the drawing board. And now the **country's air transport sector has also entered the arena. Public transport sector in Chile has also been identified as a target for green hydrogen intervention**.

Fertilizer or urea producing facilities are an ideal consumer segment for green hydrogen, however, Chile does not have any major fertilizer or urea plants. Based on products manufactured by the chemical industry and the noticeable lack of large organic chemical production units, there is limited scope for green hydrogen to be used in the industry.

Additionally, as green hydrogen production ramps up, opportunities could open in the manufacturing industry sectors, such as low-emission explosives, fuel for metallurgical processes, backup power generation and personnel transport among other things.

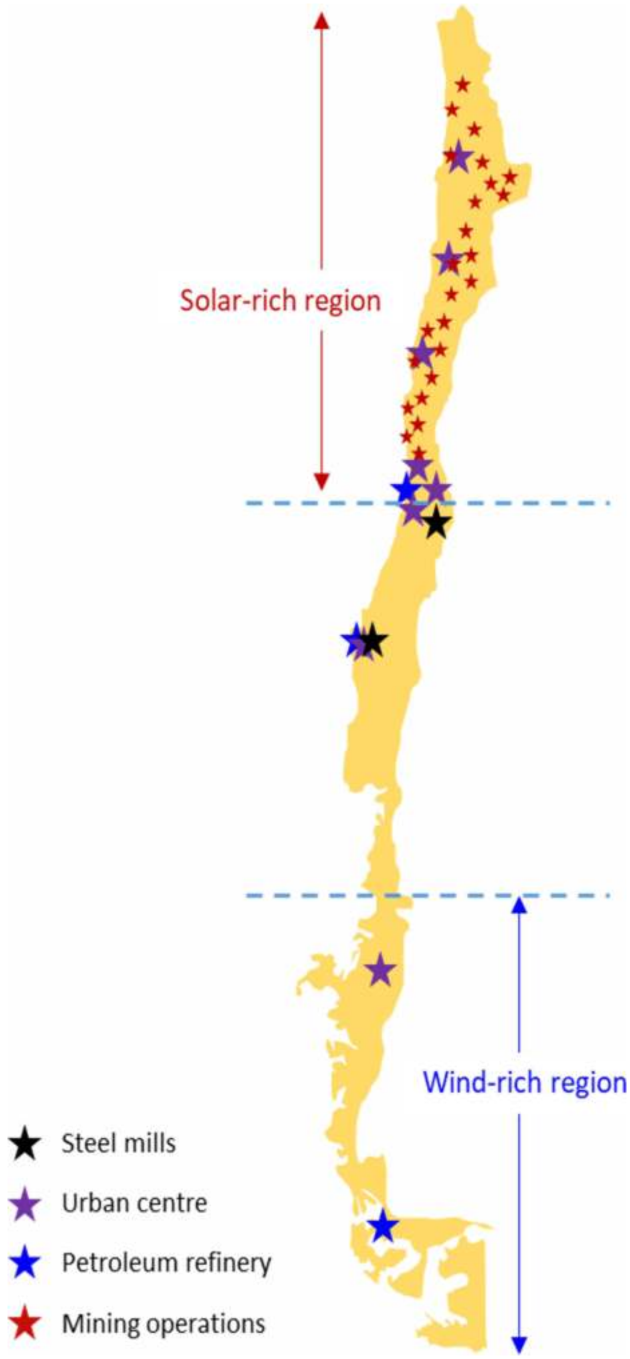


Figure 19: Potential Industries and RE Rich Regions in Chile*

** The country outline maps in this study are for illustrative purposes and may not precisely represent geographical boundaries.*

Mining

Chile is renowned as a country rich in minerals. Copper production is 5,730 tons per year (2020), representing 28 percent of world copper production. In addition, Chile has the largest lithium deposits, with 44 percent of the world's lithium reserves, which is a key component for the development of renewable energy production and the electromobility industry. The mining boom is the result of the huge increase in private foreign capital investment. Between 1974 and 2012, the country saw over USD 30 billion of foreign investment in the sector. Accordingly, approximately 60 percent of everything that Chile exports is related to mining products, and the sector currently represents about six percent of tax revenues.

Chile's mining project pipeline remains large but lacks certainty in future. At present, projects are being developed at a more moderate pace relative to previous years, by both state owned andprivate sector companies. The underlying reasons for the change of pace is the socio- environmental opposition to large infrastructure projects and the prevalent uncertainty brought by the tax, labor and energy sector reforms introduced by the current administration.

Mining companies are looking up to renewable sources of energy to reduce their carbon footprint. **The industry aims to curb carbon emissions by fueling haul trucks with green hydrogen. Longer distances between mines and processing plants lead to higher emissions. The green hydrogen truck market is expected to reach USD 1.6 billion by 2050 and account for 30 percent of domestic demand for fuel, according to the 2050 national mining policy**.

A modular skid-based prototype vehicle has been proposed to be subjected to field testing under live mining conditions with a 60kW fuel cell and 140kWh battery. This is expected to be followed by a proof-of-concept demonstration involving the conversion of a 2 MW diesel engine mining truck into a fully electric fuel cell and battery powered truck that is projected to consume between 800 and 1,000 kg of hydrogen per day.

Steel

Despite being a mining hub, Chile has limited steel production capacity. Demand for steel in the country is primarily dependent on imports. Domestic steel production capacity is held by two producers CAP and Gerdau AZA, with the former being the only integrated production facility in the country and the latter being a secondary steel mill.

The CAP Acero steel plant located in Huachipato, Talcahuano is Chile's only integrated steel plant. The plant has a capacity of about 1.5 million tonnes of crude steel per annum. However, the Gerdau AZA plant has an annual production capacity of 520,000 tonnes of crude steel.

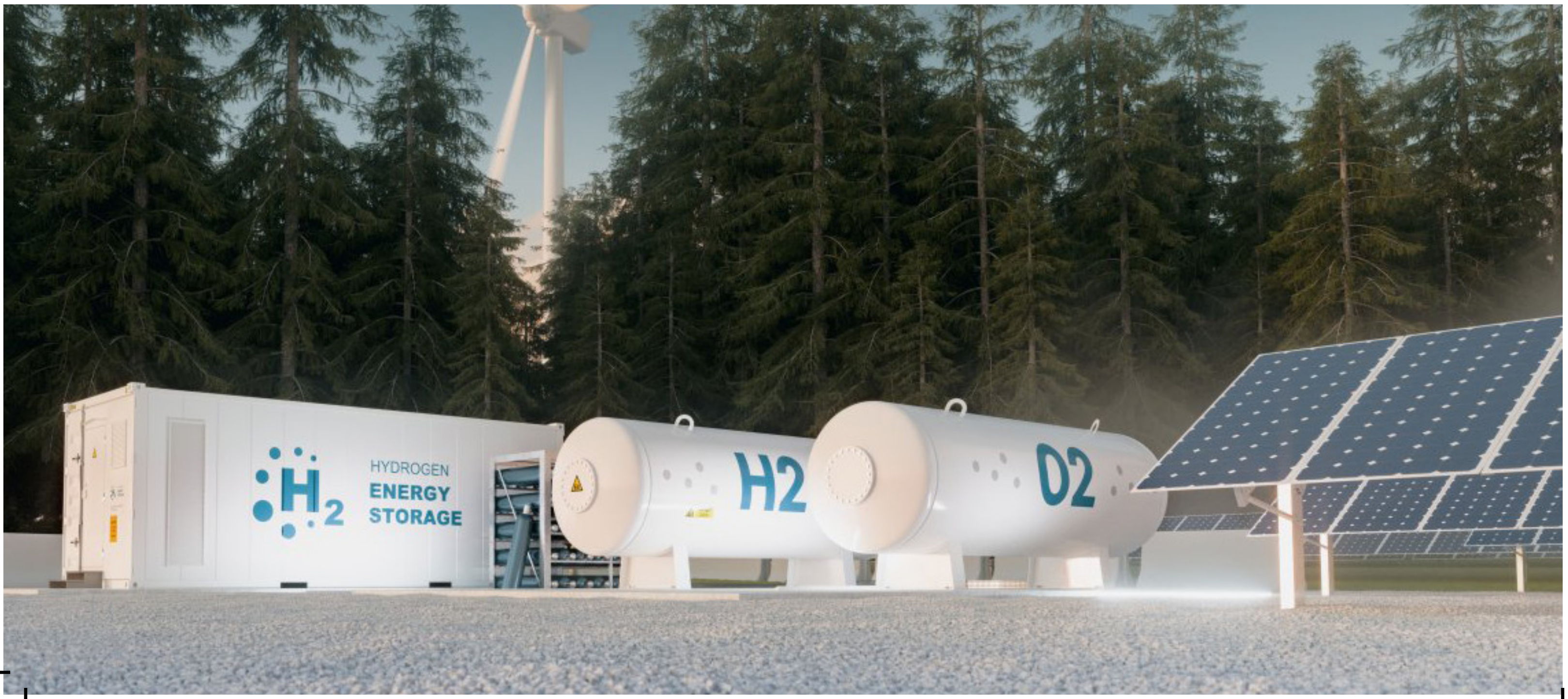
CAP recently closed a USD 3.6 million financing agreement with development agency Corfo for the H2V CAP green hydrogen project. The steel plant will build a 12 MW, USD 25 million pilot plant to produce about 1,500 tonnes of green hydrogen per annum. Operations under the project are expected to commence in 2025 and help explore alternatives to produce green steel by 2027.

Petroleum refining

The Chilean economy relies heavily on oil and gas consumption with growth in oil demand being driven by the transport sector, followed by the industrial and buildings. Since the refining capacity in Chile is not enough to meet domestic oil product demand, the country imports a substantial share of its refined products – Chile is a net importer of crude oil, gas, and coal - and depends on its regional neighbors, such as Brazil, Colombia, Argentina, and Ecuador.

Currently, USA is the main source of oil products for Chile, particularly for diesel, supplying more than 95 percent in the past five years. Due to the long distance the fuel travels from its source to the tank, its carbon footprint gets amplified significantly. Chile has three petroleum refineries with a joint capacity of 238,000 barrels per day (bbl per day) which process all the crude oil imported into the country from Brazil and Ecuador. These are:

- Aconcagua refinery with a capacity of 104,000 bbl per day or 16,500 m^3 per day
- Biobío refinery with a capacity go 116,000 bbl per day or 18,500 m^3 per day
- Gregorio refinery with a capacity of 18,000 bbl per day or 2,800 m^3 per day

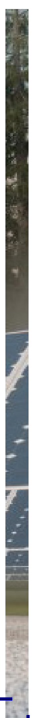


The two larger refineries in the country have taken steps to include green hydrogen in their chemical process. The 20 MW green hydrogen project proposed by Linde and selected to be subsidized by the Chilean government involves retrofitting the hydrotreater at the Aconcagua oil refinery to utilize green hydrogen. The project expects to generate and utilize 3,000 tons of green hydrogen per year. Meanwhile, the Bio-Bio refinery had initiated a project to substitute natural gas in the refinery process with green methanol derived from green hydrogen. The project will use green hydrogen derived from 3.4 MW of dedicated wind energy to produce green methanol at a rate of 350 metric tonnes per year.

Transportation

In Chile, 36 percent of the final energy consumption corresponds to the transport sector, and 99 percent of this corresponds to oil derivatives, making it responsible for about 24 percent of the total emissions of GHG emissions of the country. Transportation in Chile is a predominantly dependent on roadways, with railways playing a minor role and aviation mostly catering to the demand for long-distance and international passenger travel. As a result, petrol and diesel are the primary fuels used in the sector.

Chile's push for emission reduction in the transport sector has resulted in policies for fuels with low sulfur content, local emission regulations and green taxes on light and medium gas and diesel vehicles. Public transport sector in Chile has also been identified as a target for green hydrogen intervention with proposed plans for a pilot project deploying hydrogen-powered buses under Santiago's Red BRT system. Chile is also considering development of a separate pilot programme for a green hydrogen locomotive deployment in the country.



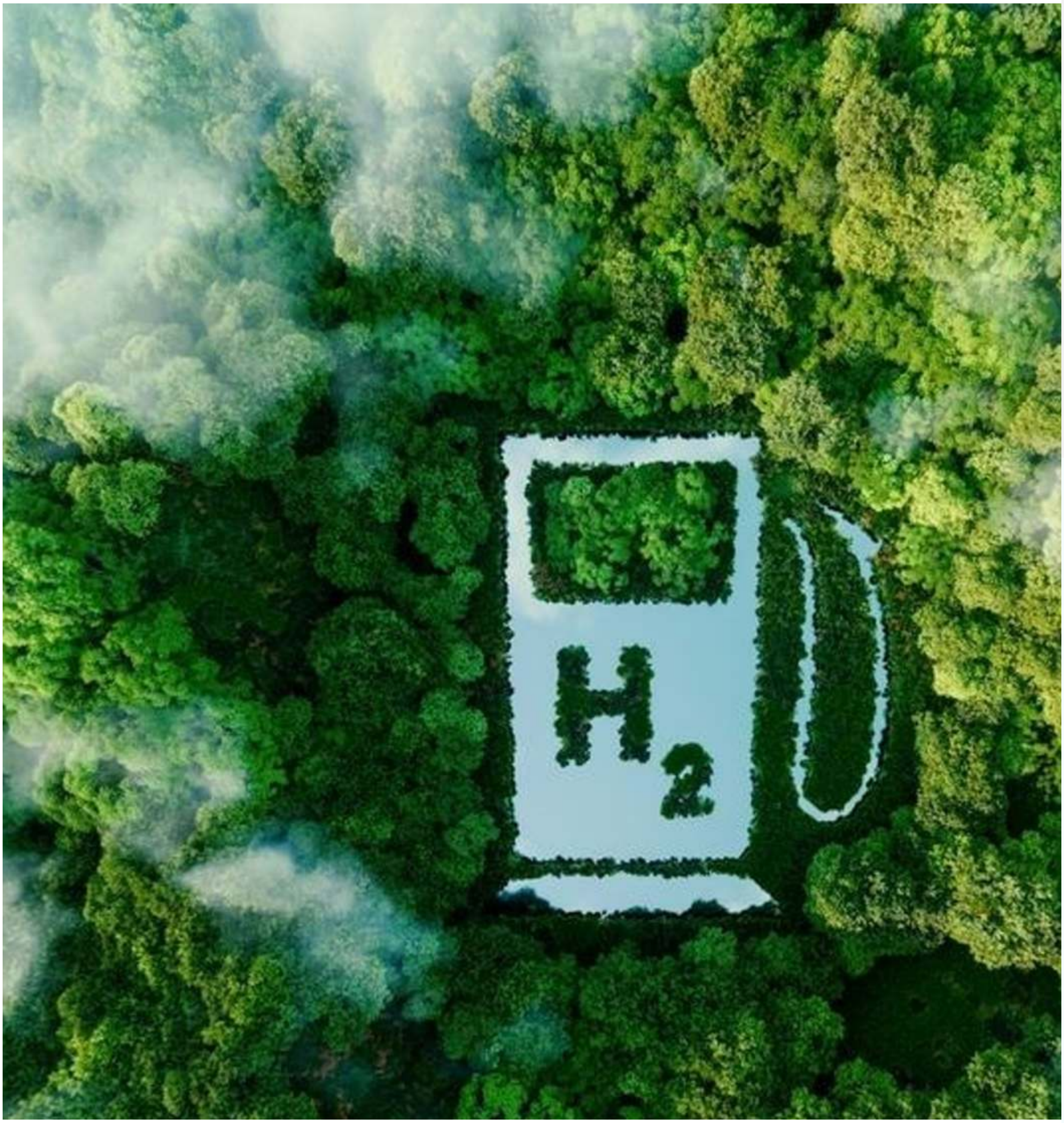
Possible arrangements for green hydrogen production, transportation, and supply in Chile

As seen in the section above, superimposing the major demand centres in Chile along with regions of high renewable energy potential, allows for the selection of the various modalities that could be implemented in setting up a green hydrogen economy in the country.

The high degree of overlap between the solar energy resources and potential demand centres in the northern part of the country makes it ideal for overland transportation of green hydrogen. Potential demand centres being scattered in the northern part of the country corresponding to the mining industry operations reflects the need for producing green hydrogen close to the demand centres.

There is an abundance of wind energy resources, but a lack of significant demand centres and transportation infrastructure in the southern parts of the country. Thus, there is a potential for building sea routes to transport the green hydrogen to demand centres within the country

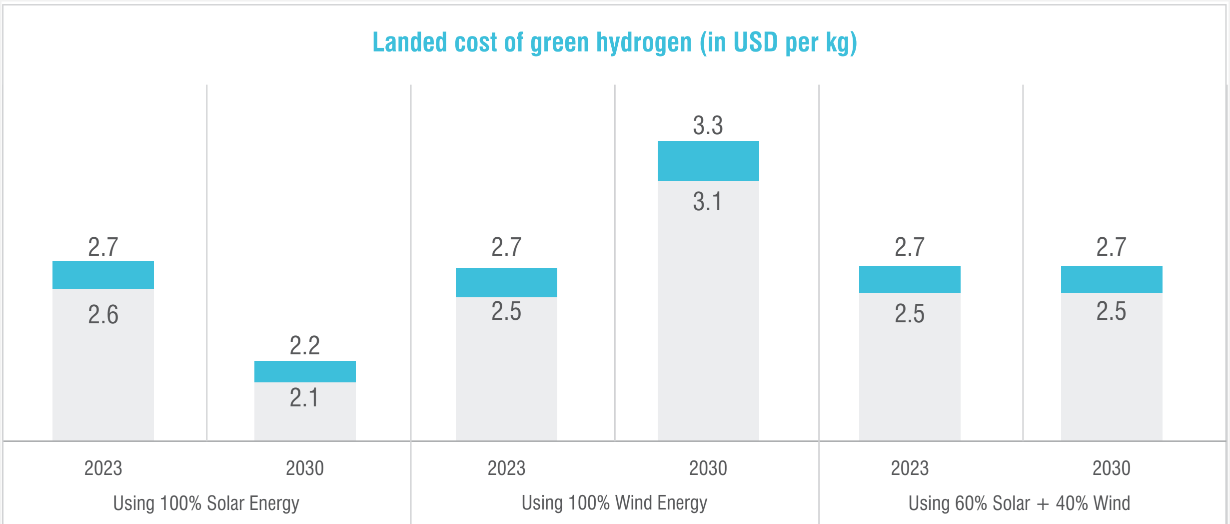
Given these observations, the following scenarios for the production, transportation and supply of green hydrogen could be explored in Chile:[47]



47 KPMG Analysis 2023

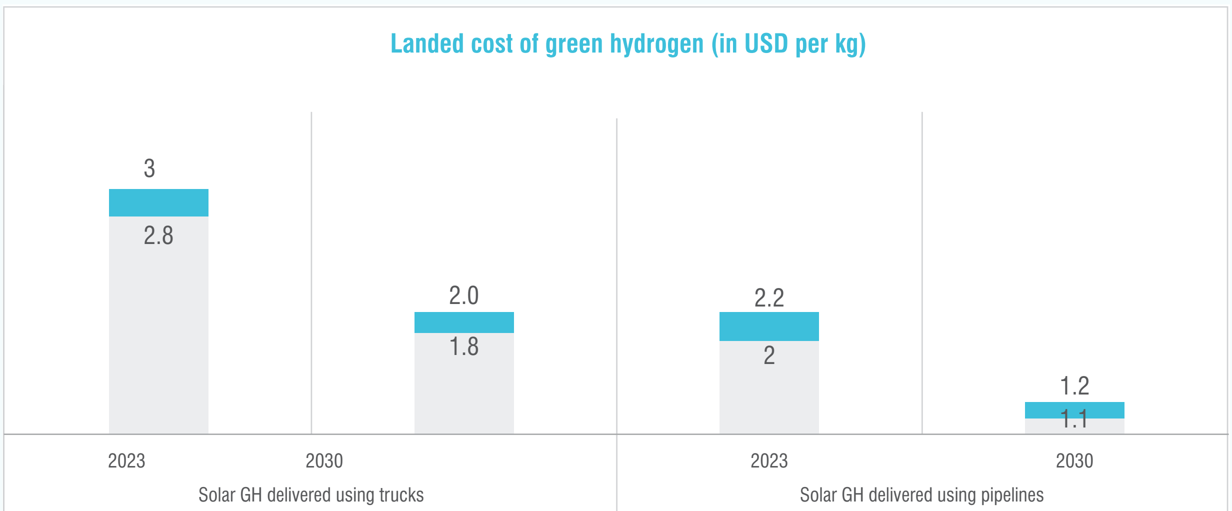
Scenario 1: Co-located Green Hydrogen Production

Hydrogen produced close to the demand centres using renewable electricity delivered through high-voltage transmission links



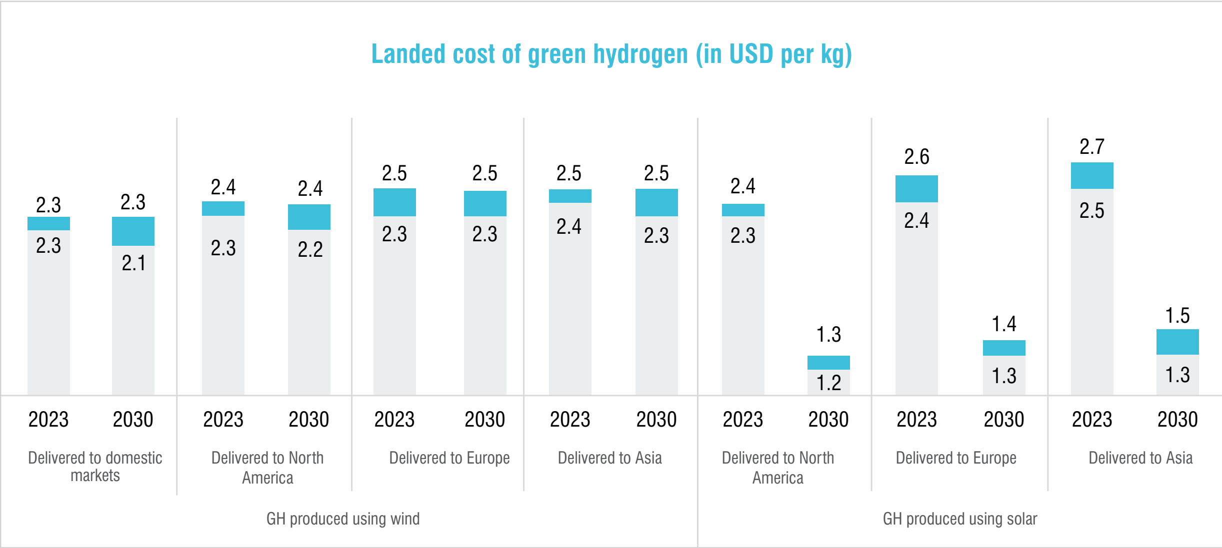
Scenario 2: Centralised Green Hydrogen Production

Production of green hydrogen close to the renewable electricity plants and transported to demand centres



Scenario 3: Centralised Green Ammonia Production

Green ammonia produced close to renewable electricity plants, transported, and cracked to produce green hydrogen close to the demand centres



The key findings resulting from this analysis include the following:

- **Green hydrogen produced using solar energy** is observed to be significantly cheaper than that produced using wind energy despite the high wind energy potential available in the country. The difference could be attributed to the expected fall in cost of solar PV technology vis-à-vis changes in the cost of wind energy equipment the technology for which has matured
- **Pipelines are economically superior over short to medium distances (up to 2,500 km), compared to trucks and ships**. Considering the hydrogen lost in the ammonia cracking process, ships are found to be cost effective for transportation only over longer distances (over 8,000 km)
- **Production of hydrogen close to the demand centres using renewable energy** delivered over transmission lines provides a large degree of flexibility. However, with the low cost of renewable energy, transmission charges and network losses could add significantly to the landed cost of hydrogen

As green hydrogen projects mature and become more familiar to industry and investors, long-term revenue agreements with reputable off takers provide another solution to attracting investment and lowering financing costs. In Chile, green hydrogen, and its derivative products (such as green ammonia or green methanol) present the mining industry and retailers with an alternative to fossil fuel-derived products. Based on the experience in other innovative energy projects, long-term offtake contract with a creditworthy off taker is key to demonstrating the demand necessary to support the development of a stable, domestic market for green hydrogen projects in Chile and the bankability of those projects. Government support, in the form of funding, guaranties and other credit enhancements, bolsters confidence with off takers that the project will have access to the financial resources necessary to realize the project and fulfil the offtake contract, which in turn improve the project's financeability and ultimate rate of return. Like the trajectory observed in the development of renewable generation in Chile, these structural elements work together to push and accelerate the development of a scalable industry with adequate access to investment.

Way forward

Chile has the potential to produce large volumes of green hydrogen at highly competitive prices, while the domestic demand levels are relatively low given the lack of energy intensive industries. This makes Chile an **excellent candidate for being a global export hub for green hydrogen and a supplier for consumer markets in Europe and Asia**. Chile must aggressively **seek cross-border support and collaborations to develop an export-oriented green hydrogen production environment, which could in-turn be leveraged to develop the domestic hydrogen demand**.

Table 4: Recommendations for Chile

	Drivers	Recommendation
1	**Policy and Regulatory Framework**	• Introduce measures like **duty exemptions and subsidies** to ease flow of capital equipment into the country and keep costs low • Implement **certification of origin systems** for green hydrogen benchmarked to the highest standards to ensure that Chile becomes a preferred supplier of green hydrogen in international markets • Introduction of **production-linked subsidies/incentives** • Establish a single-window facility to **assist with land-use planning and obtain permits** for green hydrogen projects • **Promote pilots of larger scale to ensure scalability**. • **Introduce schemes to establish hydrogen export hubs**.
2	**Capacity Building and Innovation**	• Invite developed countries that are expected to be net energy importers to **collaborate on studies and coordinate on policy initiatives** to help develop the green hydrogen industry in Chile

3	**Infrastructure**	• **Kick-off planning studies** to:
		  • ease the movement of hydrogen to domestic consumers through roadways and pipelines, or
		  • implement dedicated high voltage transmission lines and electrolyser farms near demand centres
		• Establish **Green Hydrogen Special Economic Zones** in the renewable energy rich regions with integrated port and water treatment infrastructure. Attractive concession structures at these zones could unlock massive foreign investments

4	**Financing**	• Collaborate with Multilateral Development Banks to **develop attractive capital and risk financing mechanisms** to support green hydrogen projects • Develop co-funded projects under the PPP structure to distribute risks and build investor confidence • Develop **robust corporate governance regulations to ensure foreign investment** in hydrogen production and energy-intensive downstream industries, such as cement or steel remain secure

5	**Technology**	• Foster cooperation with countries and multi-national organizations to **support technology development in Chile and transfer of technology to the country** over the long- term future • Leverage **Technology Collaboration Programmes** to facilitate international R&D and information exchange
6	**Partnerships**	• **Develop global long-term partnerships** with countries in the EU, US, Japan, South Korea for potential production and export of green hydrogen • **Tap into regional green hydrogen demand** from other countries **such as Brazil, Argentina**

4.3. Brazil

Brazil - a country in South America – is one of the largest countries in the world with an area of 8,515,770 Km2. Brazil is one of the largest energy producing countries in the world and the third– largest producer in the Western Hemisphere. In 2022, according to International Monetary Fund (IMF), Brazilian GDP was USD 1.894 trillion. The services sector is the largest sector in Brazil contributing almost 65 percent to its gross domestic product. Agriculture and industry also contribute a substantial amount to Brazil's economic growth.[48]

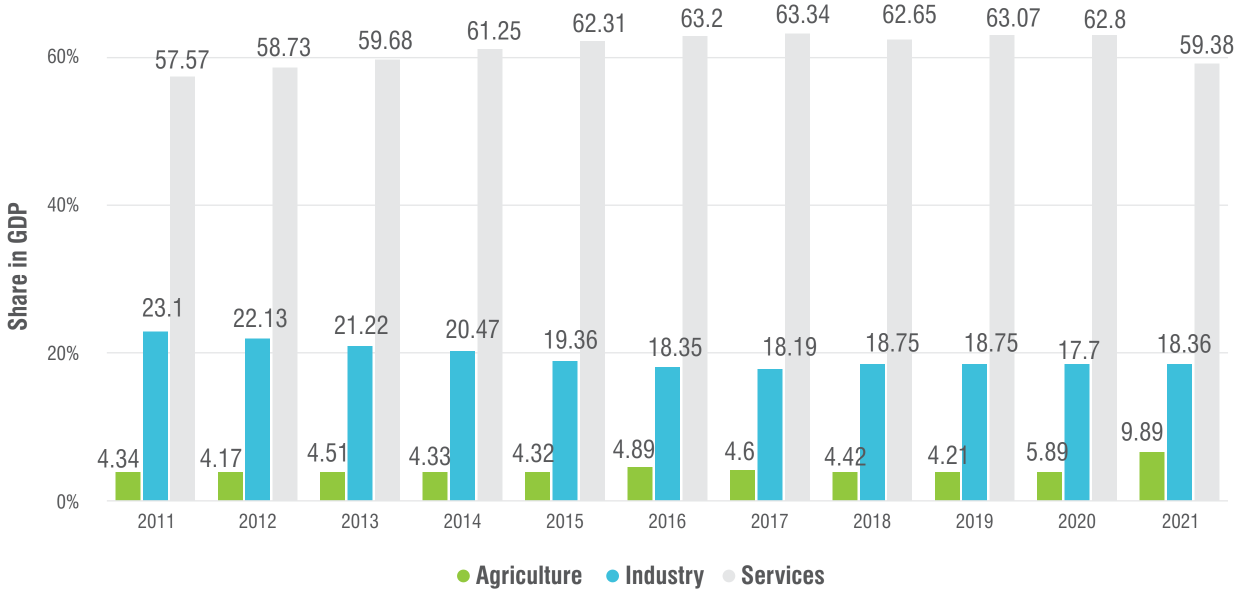


Figure 20: Share of Economic Sectors in the GDP

Source: Statista 2021

Thermals (coal, gas, oil and nuclear) represent 16 percent of the Brazilian electricity matrix.[49] According to the Ministry of Mines and Energy (MME), Brazil is expected to add 15 GW of centralized power generation capacity by 2025. Investments in utilized-scale power generation are estimated to reach $62 billion by 2029, while distributed generation should see investment of $10 billion in the same period. Looking at the country's energy profile, a **huge part of its renewables come from biofuels and hydro**.

48 Services, Value Added (%of GDP)- The World Bank 2021

49 Brazil- Country Commercial Guide (International Trade Administration, 2023)

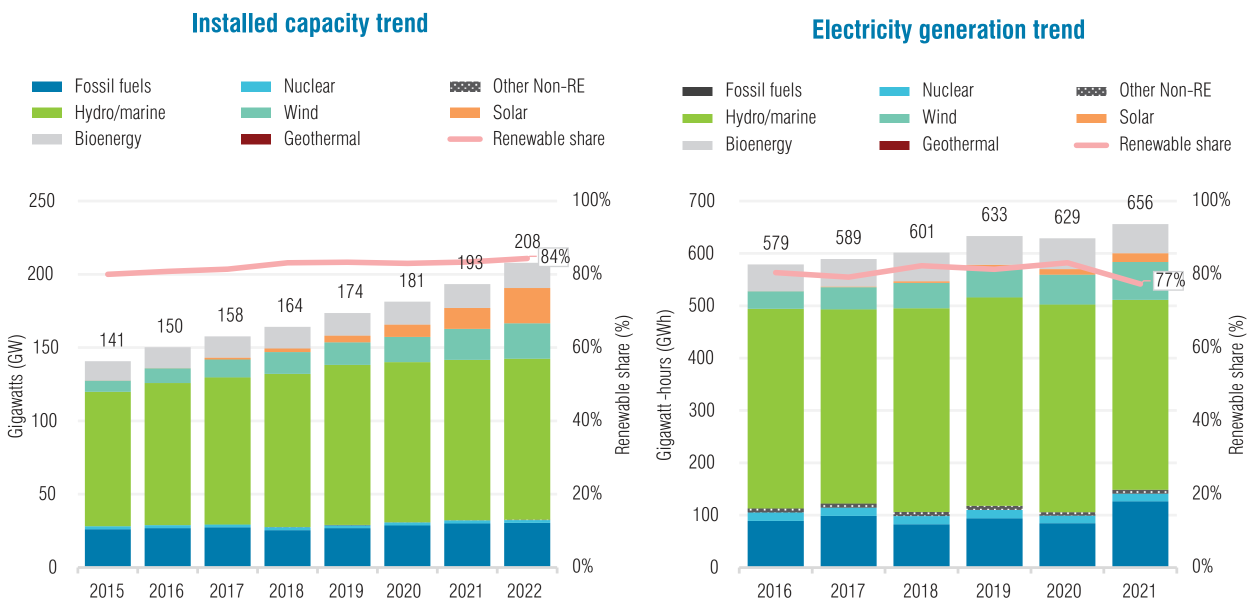


Figure 21: L-R: Brazil-Installed Capacity; Electricity Generation Trend

Source: IRENA Country profile- Brazil, 2023

Total primary energy demand has doubled in Brazil since 1990, led by strong growth in electricity consumption and in demand for transport fuels. Industrial production and transport accounted for approximately 63 percent of the country's energy consumption. As of 2019, the share of renewables in the transport sector and industries stood at 25 percent and 58 percent, respectively.[50]

Brazil presents numerous opportunities in several sectors of the economy. The Energy Outlook 2019 indicates that the country's energy consumption will grow by 65 percent by 2040. Renewable energy, which includes biofuels, will have the largest share in this growth. Bioenergy will be an essential part of advancing towards a low carbon future. As of 2022, large hydropower plants account for around 80 percent of domestic electricity generation, making the Brazilian electricity mix one of the cleanest in the world.

Brazil's energy policies align to the pressing need to mitigate climate change and energy challenges. As mentioned above, access to electricity across the country is almost universal and renewables meet almost 45 percent of primary energy demand. This makes Brazil's energy sector one of the least carbon-intensive in the world.[51]

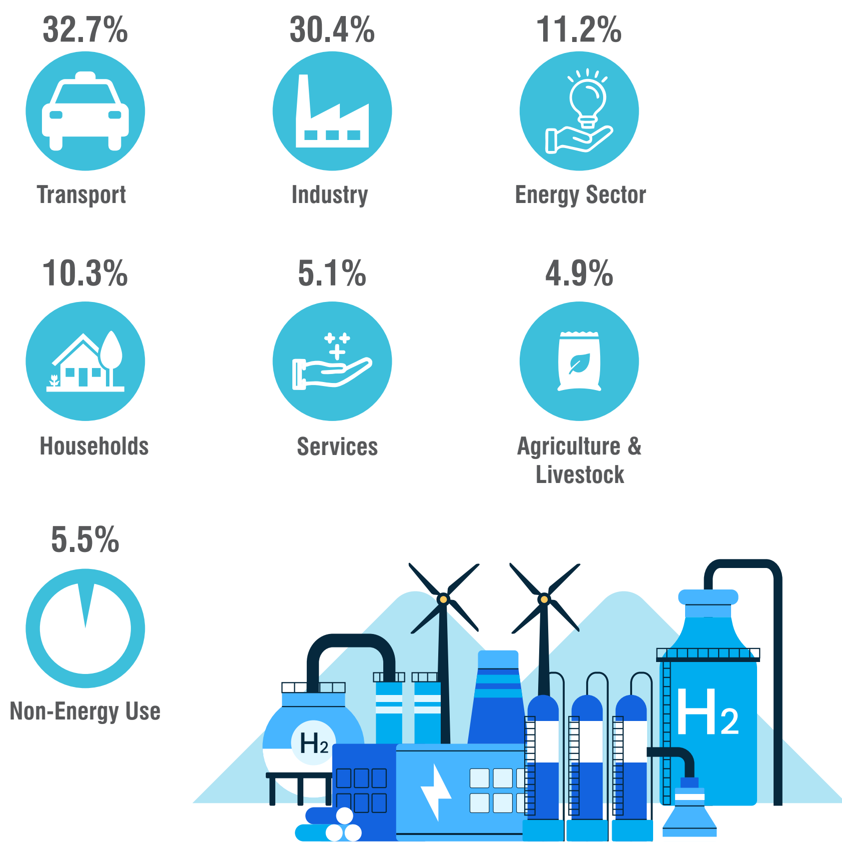


Figure 22: Energy consumption by sectors

Source: Generation trend (BEB,2020)

50 *BEB- Summary Report 2020*

51 *Brazil- Country profile (IEA,2022)*

Brazil's energy matrix is one of the cleanest in the world, with renewable energy accounting for over 80 percent of the country's electricity matrix.

Taking advantage of the great variety of sources for hydrogen production, Brazil's abundant natural energy resources beyond renewable energy, such as ethanol, natural gas, biogas biomass and even natural hydrogen reservoirs also contribute greatly for the country's potential to become a major hydrogen producer and exporter

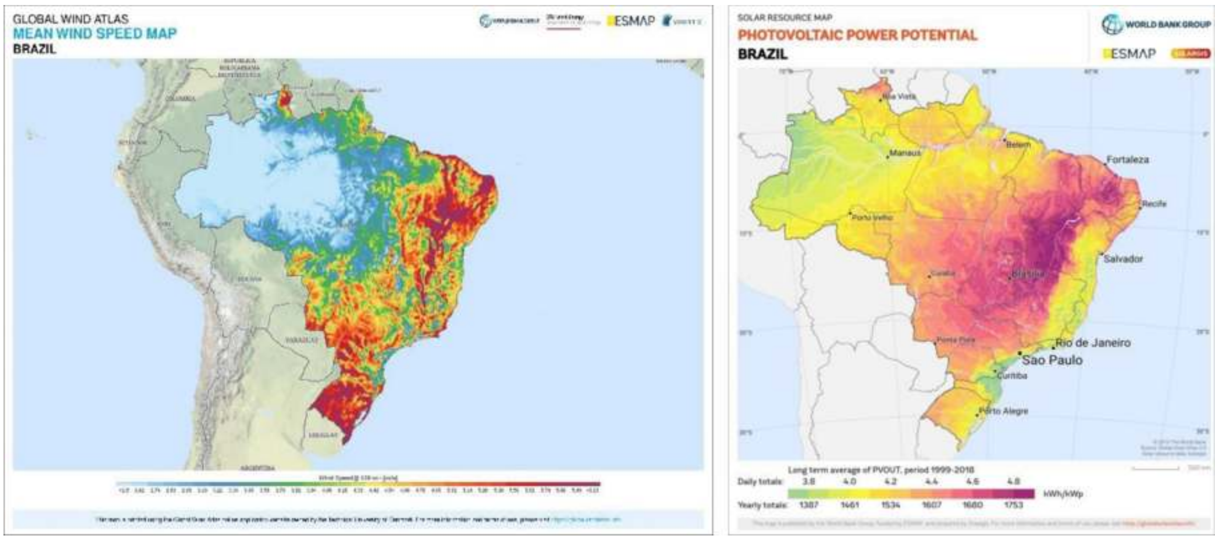


Figure 23: L-R: Wind Potential in Brazil; Solar Potential in Brazil

Source: Brazil Wind Map (Vortex, 2021); Brazil Solar Map (Global Solar Atlas, 2018)

The **Northeast region of Brazil** has reliable winds, with stable wind speed that also does not frequently change direction. It also has a high average solar irradiance, which means there is good potential to produce both wind and solar energy.

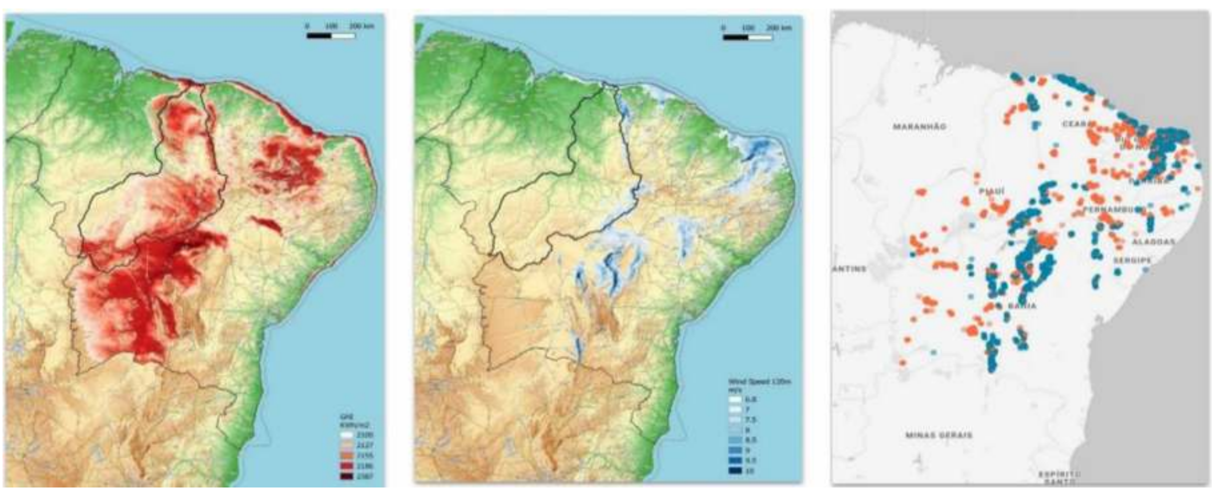


Figure 24: L-R: Solar potential in Northeast; Wind potential in Northeast; Projects across Northeast

Source: GH COP26

The neighboring state of **Rio Grande do Norte**, which is the national leader in wind energy production, can also generate electricity from the wind to supply to green hydrogen plants. Three companies have signed MOUs with this state to set up green hydrogen plants that will use energy supplied by future offshore wind farms.

Brazil's energy matrix contains 48 percent renewable sources, well above the world average. However, the country saw an increase of 9.5 percent in its greenhouse gas emissions, largely due to increased deforestation in the Amazon.[52] This explains the need and significance of hydrogen in the country.

In 2020 wind and solar accounted for 10 percent and 2 percent of Brazil's generating capacity respectively, but these numbers are expected to rise to 30 percent and 17 percent by 2040, largely driven by the falling RE prices. **The Levelized Cost of Energy for wind energy in the Northeast of Brazil was around USD 3.5 – 7.8/MWh and is expected to drop by around 27 percent by 2040. The LCOE for solar energy is around USD 8 - 9/MWh in the Southeast, and USD 7 - 9/MWh in the Northeast, and is estimated to fall by 46 percent by 2040.[53] Producing green hydrogen using power from offshore winds is a viable option that can give the country a competitive edge.**

Endowed with abundant wind and solar energy potential, an integrated, low-carbon power grid and geographic advantages to export to Europe and the east coast of North America, plus a significant domestic industry, Brazil has an opportunity to become one of the world leaders in the production of green hydrogen. In Brazil, wind and solar can be combined at the same location (such as at the countryside of the states of Ceará, Piauí and Bahia), thus optimizing hydrogen production projects.

The potential to expand variable renewable energy production in the country is huge considering the availability of cheap land with abundant wind and solar resources. Also, the existence of a flexible and integrated national grid allows the energy to be generated far from the hydrogen plant.

Green hydrogen will have a relevant role in achieving the Brazilian vision for energy transition and net zero economy

Brazil has great opportunities to harness its huge clean energy potential in order to foster a low carbon hydrogen industry, particularly in hard-to-abate sectors. The country, at COP26, announced a long-term objective to reach **net-zero emissions by 2050 and a 50 percent carbon emissions reduction plan coupled with a zero illegal deforestation target by 2030**. This is supported by an announced 2030 climate action plan and a hydrogen national strategy being developed. Moreover, Brazil has a significant domestic market potential for low carbon hydrogen, along with robust logistics for exporting it to international markets.

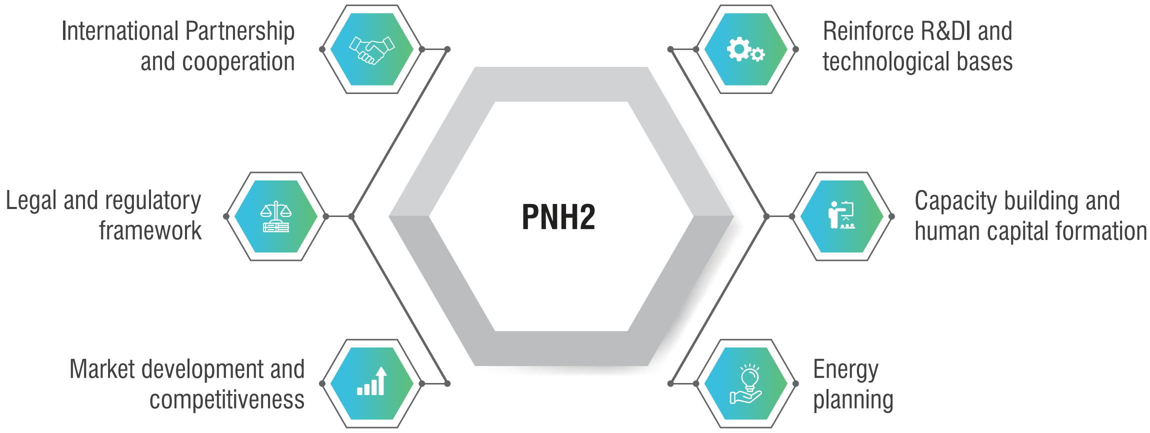


Figure 25: Elements of PNH2

52 Brazil's greenhouse gas emissions increased by 9.5% in 2020 largely due to increased deforestation in the Amazon (Reuters, 2020)

53 How Brazil can optimize its cost of energy (Mckinsey, 2021)

A. Policy framework

To become one of the key players in green hydrogen economy, Brazil must establish a competitive marketplace and an attractive business environment, overcoming challenges. Brazilian Government launched the **Guidelines for National H2 Program (PNH2) in August 2021** and related actions are under development and coordination of the Brazilian Ministry of Mines and Energy (MME). The PNH2 was developed to mobilize public and private sectors, as well as academia, together with international cooperation to accelerate the development of a comprehensive and competitive hydrogen market. The Program realizes six critical areas (Figure 17).

In addition, there are public policies for renewables in Brazil, which will contribute to boost low carbon hydrogen economy. Policies such as **tax reliefs or taxes differentials for renewables and/or in Export Processing Zone (EPZ) and infrastructure, green finance and specific funds to renewables and infrastructure investments**. There are also recent programmes under discussions, for instance, the Fuel for **the Future (Fuel Cell, Advanced biofuels, e-fuels, etc.) and carbon pricing**, which will reinforce existing programs.

In December 2020, the Ministry of Mines and Energy issued the Brazilian **National Energy Plan 2050**, outlining the directives for the long-term strategy for the Brazilian energy sector. The 2050 Energy Plan dedicated a chapter to hydrogen, listing it as a disruptive technology, capable of significantly changing the energy market. The Energy Plan also highlights that hydrogen may help solve energy challenges such as reduction of carbon emissions in hard-to-decarbonize sectors, storage of renewables, safety in the energy supply due to the flexibility and diversity in its use cases. The 2050 Energy Plan also listed fuel cells as a potential key technology for the decarbonisation of the transportation sector in Brazil going forward.

The main strategy to support low carbon hydrogen projects in Brazil will be to remove barriers and to reinforce market design, low carbon energy policies, R&D and Innovation, capacity building, skills and international cooperation, to ensure competitiveness in the domestic and global markets.

B. Regulatory support

Bill of Law No. 725/2022 aims to establish rules and incentives for hydrogen produced using renewable energy sources. It is currently under discussion in the Brazilian Senate. If the bill is signed into law, the National Petroleum Agency (ANP) would become responsible for regulating, authorizing and inspecting the activities of the hydrogen chain. The measure would be a significant regulatory step forward, considering the multiple sources involved in the production of hydrogen.

The Bill does not propose a guideline for green hydrogen certification, which could pose a challenge in practice. It may be necessary to develop a certification mechanism to guarantee not only the use of renewable energy in the production process but also throughout its supply chain.

C. Partnerships

Brazil has been engaged in international cooperation on low carbon hydrogen under the following programs:

- **German - Brazilian Energy Partnership** (the "H2 Brazil" in the "German – Brazilian Power- to-X Partnership Program")
- **US-Brazil** Energy Forum for World Commerce and Development
- **UK Brazil** Energy Program
- **India and Brazil** on Bio-energy Cooperation
- **BRICS** – Energy Research Cooperation Platform
- **Brazilian Energy Compact** on Hydrogen established at UN High-Level Dialogue on Energy

D. Market development

Brazil's National Institute of Clean Energies (INEL) announced the **establishment of a green hydrogen secretariat (SHV**) to accelerate the growth of green hydrogen production in the country. The secretariat aims to secure low-cost clean energy to produce green hydrogen. The purpose is also to coordinate with the main players in the market, as well as national and international authorities, clean energy associations, companies, entrepreneurs, and the public.

Country's first industrial-scale green hydrogen production plant, by Unigel, came up in 2022. The project includes three standard 20 MW electrolysers supplied by Thyssenkrupp Nucera, with a second phase expected to expand the project's capacity beyond 100 MW.

Shell's Brazilian subsidiary is also working on hydrogen projects, in collaboration with the port of Açu. The two are developing a pilot plant at the port, north of Rio de Janeiro, with an initial capacity of 10 MW. They aim to eventually develop a **100 MW green hydrogen production facility at the port**.

E. Infrastructure

The development of biogas and biomethane can support the hydrogen scaling-up process in the region and play an important role in country's clean energy transitions. Brazil's biomethane potential alone could represent 12 percent of the global total.[54] In addition, Brazil hosts the only commercial CCUS facility in Latin America - the Petrobras Santos Basin Pre-Salt Oil Field CCS project. This is the only offshore EOR project in operation in the world.

In additions, since Brazil produces most of the electricity from different types of renewables, there is a conducive environment for the construction of new renewable energy capacity. The mature wind and solar industries in Brazil have the resources to develop large projects given the acquired knowhow by the workforce and the established supply chain. Also, there is a solid regulatory framework for large renewable projects, allowing large projects to be developed in short timeframes.

Many initiatives are assisting in the development of large hydrogen projects in Brazil

Many initiatives are assisting in the development of large hydrogen projects in Brazil

- **Pecém Port** (Ceará State): Signed several individual MoUs for green hydrogen production involving companies as Fortescue, Qair, Enegix, EDP and White Martins
- **SUAPE Port** (Pernambuco State): MoU with Qair Company, to develop hybrid hydrogen projects (green and blue ones)
- **Açu Port** (Rio de Janeiro State): green hydrogen MoU with Fortescue
- **Raizen Group** announced a five-year contract with Yara to acquire biogas to green hydrogen and ammonia production
- **Unigel retrofit** of installations in Camaçari (Bahia State) at the end of 2022, enabling it to produce green ammonia.

Furthermore, there have been some significant **R&D and innovation projects** under development in Brazil:

- **Itaipu Technological Park (PTI)** is supporting building capacity at hydrogen for PECEM Port
- **Furnas (Electricity generation public enterprise)** is supporting a R&D and Innovation project aiming to produce green hydrogen from a hybrid scheme considering their hydropower plant and Solar PV facility
- Current studies of **Eletronuclear** (Nuclear generation public enterprise) aiming to produce high purity hydrogen from Angra I & II power plants.
- The **Ministry of Mines and Energy (MME), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and the National Service for Industrial Learning (Senai)** signed a cooperation agreement for the creation of the first Center of Excellence in Green Hydrogen, in the city of Natal (RN). In addition to five regional education and training hubs in the field of green hydrogen (H2V) in Brazil.

54 *Outlook for biogas and biomethane: Prospects for organic growth (IEA, 2019)*

Sector attractiveness for potential hydrogen consumption in the country

Total hydrogen demand in Latin America could see significant growth to 2030, with most additional demand coming from existing uses in **oil refining and industry**. In the Baseline case[55], total demand increases by 52 percent to reach 6.2 Mt. Practically all the additional 2.1 Mt of hydrogen demand comes from existing uses in **oil refining and industry**, while demand for transport and new applications in industry remains very limited. In the Accelerated case[56], total demand increases by 67 percent to reach 6.8 Mt. New **applications in industry and transport expand significantly** to meet more ambitious energy and climate targets, while hydrogen demand for oil refining grows less than in the Baseline case.

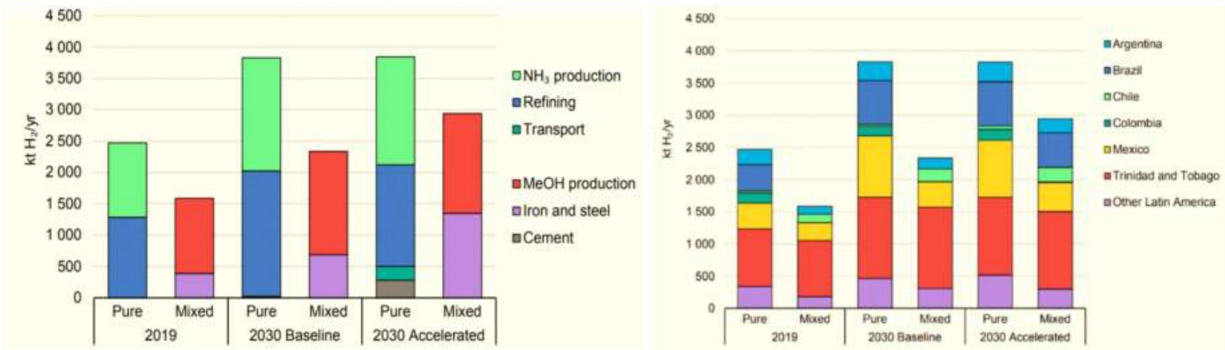


Figure 26: L-R: Hydrogen Demand in Latin America by Applications; Hydrogen Demand by Countries

Source: Global Hydrogen Review (IEA, 2021)

In 2019, six countries in Latin America, including Brazil, accounted for about 87 percent of the region's hydrogen demand. Brazil's hydrogen demand stood at about 400 kt in 2019. Oil refining accounted for 83 percent of total demand. The remaining volumes were used for ammonia-based fertilisers production.[57] It is estimated that the Levelized Cost of green Hydrogen produced in Brazil **would be around USD 1.50/ H2 kg in 2030. The cost is estimated to drop to approximately USD 1.25/kg**. Brazil has the potential to be competitive and fight for a share of the US and EU import markets, capturing **USD 1 to 2 billion by 2030**. By 2040, exports could reach USD 4-6 billion, or 2-4 million tonnes of green hydrogen. [58]The domestic market is the largest opportunity for Brazil, and by 2040 can reach USD 10-12 billion, driven mostly by **trucking, green steel, and other industrial energy uses**.

55 *The Baseline case describes how demand for hydrogen could evolve considering energy- and climate-related policies already in place in the countries of the region, and an uptake on demonstrated technologies following commercialization trends observed in other low-carbon energy technologies*

56 *The Accelerated case reflects an optimistic vision for the deployment of hydrogen end-use technologies to 2030, assuming that more ambitious energy- and climate-related policies are put in place and that the required techno-economic and infrastructure progress for the analyzed applications will be achieved by that year*

57 *Global CO2 emissions in 2019 (IEA, 2019)*

58 *Green Hydrogen: an opportunity to create sustainable wealth in Brazil and the world (Mckinsey, 2021)*

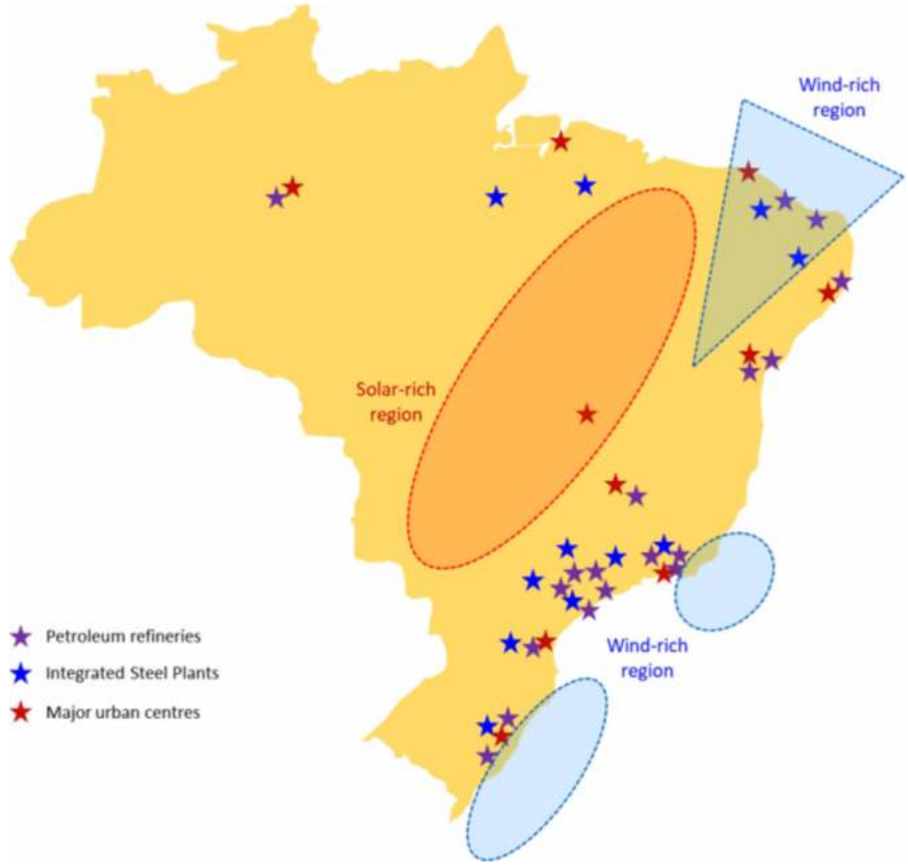


Figure 27: Potential Industries and RE Rich Regions in Brazil*

The world needs Brazil to decarbonize, not only because it is the seventh largest GHG emitter in the world, but also because it is uniquely positioned to become a powerhouse in support of the global transition. Brazil's emissions profile is quite different from the rest of the world. It emits close to 2.2 gigatons of carbon dioxide equivalent (GtCO2eq) every year, half of which comes from deforestation, a quarter from agriculture, a fifth from transportation and energy, and the remainder from industry and waste.[59]

Transport

Given the country's large export activity and dependency on road transportation, the Brazilian transportation sector is a large consumer of fossil fuels, being responsible for almost 80 percent of total diesel consumption in 2019. [60]In this scenario green ammonia or hydrogen could play a vital role in reducing the sector's greenhouse gas emissions by replacing oil used in trucks and maritime vessels, if it became sufficiently cheap.

Figure 28: Electric Hydrogen Hybrid Bus

59 The green hidden gem – Brazil's opportunity to become a sustainability powerhouse (Mckinsey, 2022)
60 Brazilian Energy Balance (Empresa de Pesquisa Energética, 2020)

** The country outline maps in this study are for illustrative purposes and may not precisely represent geographical boundaries.*

__The electric-hydrogen hybrid bus__ developed at Coppe's LabH2 was initially launched in 2010 (refer Figure 20). The hydrogen fuel cell bus had its second-generation launched during Rio+20, promoted by the United Nations (UN), in 2012, in Rio de Janeiro. The 3rd generation of Coppe buses, was developed in partnership with Furnas and Tracel, and transported athletes in Vila Olímpica during the Olympic Games in Rio de Janeiro. With the new configuration, the bus now has a range of 330 km and meets the requirements for urban vehicles in Rio de Janeiro. Currently, the 4th generation of buses is under development with a capacity to transport 100 people.

In Brazil, automakers and their suppliers are working on some sustainable, low-carbon emitting solutions like "**Hydrotreated Vegetable Oil" (HVO), using biomass and hydrogen to produce biodiesel**. HVO is also being a bet for German companies like Bosch, BASF, Mahle and Mercedes looking for the big truck and bus market in Brazil. **Moreover, companies in Rio de Janeiro have formed a partnership to produce hydrogen-powered buses next year**.

Agriculture

Brazil is a major exporter of agricultural produce and an importer of fertilizers. In 2019 the country imported USD 2.4 billion worth of nitrogen-based fertilizers, mostly in the form of urea.[61] **A cheaper hydrogen feedstock could enable a local production of competitive green fertilizers, replacing the need to import such products**. That substitution would be advantageous to the economy, especially if small-scale, distributed electrolysis technologies evolve, because they would avoid internal logistical difficulties that increase costs to farmers.

Green ammonia can be used as feedstock to produce fertilizers and explosives, with a much lower carbon footprint than using grey ammonia.

Steel

The Iron and Steel sector is the largest industrial source of greenhouse gas (GHG) emissions globally and the second-largest industrial energy consumer. Because of its intensive energy use and high carbon profile, governments and global corporations are focusing on the sector's rapid decarbonization. Brazil is the ninth-largest steel-producing country globally and the largest in Latin America. The country plans to achieve carbon neutrality by 2050. Although the emission intensity of the country's steel production is lower than the average of other major producers, such as People's Republic of China and India, [62]it is essential to take action to benefit and to compete in the decarbonized global market.

Brazil has the strategic resources (iron ore, expertise in the use of charcoal, and high potential for renewable energy) necessary for transforming the global steel industry. With low metal supply costs and abundant natural

61 https://www.scirp.org/journal/paperinformation.aspx?paperid=104496#ref16
62 Hasanbeigi and Springer, 2019

resources, it can increase its productivity and competitiveness and play a leading role in meeting the growing global demand for low-carbon products.[63] In addition, the country can contribute to the decarbonization of other countries by becoming a competitive exporter of low-carbon Direct Reduced Iron (DRI).

Hydrogen-based steel and sponge iron (DRI) production is seen as a great opportunity on the horizon until 2050.[64] A possible path to the sector's decarbonization is replacing coal with natural gas to serve as a bridge to hydrogen technologies in the future. Brazil has abundant potential for producing renewable hydrogen, with prospects of becoming a significant producer and exporter of hot briquetted iron (HBI) and green steel.

In Brazil, the companies are aiming to establish a greenfield project to produce green hydrogen. If realized, the hydrogen production facility will enable approximately 5 million tonnes of green steel through direct iron reduction, in a plant owned by H2 Green Steel, holding back approximately 9,5 million tonnes of CO_2 per year.[65] In addition, the parties are evaluating supplying green hydrogen to other off takers in hard-to-abate sectors. The companies are also looking into possibilities for a large scale, green hydrogen facility in the Nordics.

Hydro Havrand, Hydro's renewable hydrogen company, and H2 Green Steel have signed a Memorandum of Understanding (MoU) to jointly explore opportunities for large scale green hydrogen production facilities in Brazil and the Nordics.

Possible arrangements for green hydrogen production, transportation, and supply in Brazil

Superimposing the geographic spread of the renewable energy potential and the spread of the possible demand centres in the country, the following arrangements for green hydrogen production, transportation and consumption would emerge in Brazil:

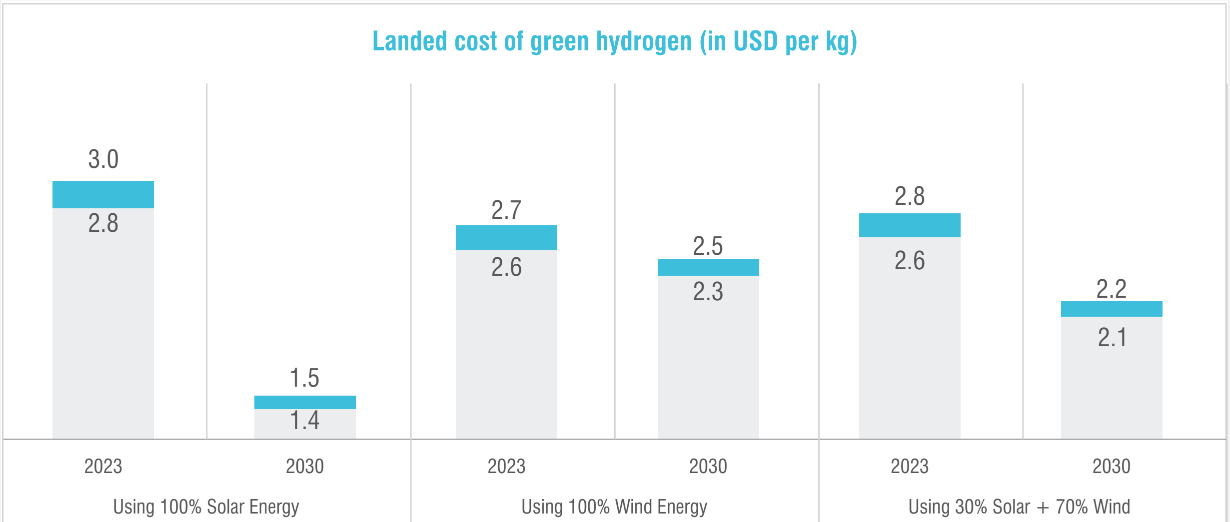
- Hydrogen would be produced close to the demand centres in a co-located manner using energy sourced from solar and wind energy plants located in the renewable energy resource- rich parts of the country
- Hydrogen is centrally produced close to the renewable energy resource-rich areas and transported overland to demand centres using fleets of trucks and pipelines.
- Green ammonia could be produced close to the major ports using renewable energy delivered over transmission lines. The green ammonia thus produced could be readily exported to international markets

Given these observations, the following scenarios for the production, transportation and supply of green hydrogen could be explored in Brazil[66] :

63 *Carvalho et al., 2015*
64 *Scoping Paper on the Brazilian Decarbonization – STEEL INDUSTRY - 2022*
65 *Scoping Paper on the Brazilian Decarbonization – STEEL INDUSTRY - 2022*
66 *KPMG Analysis*

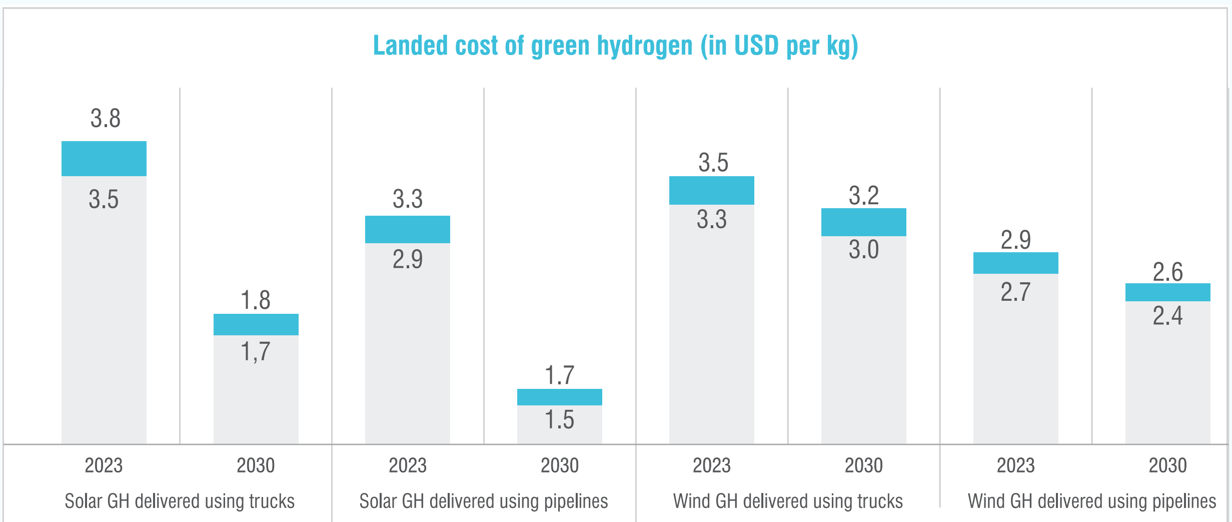
Scenario 1: Co-located Green Hydrogen Production

Hydrogen produced close to the demand centres using renewable electricity delivered through high-voltage transmission links



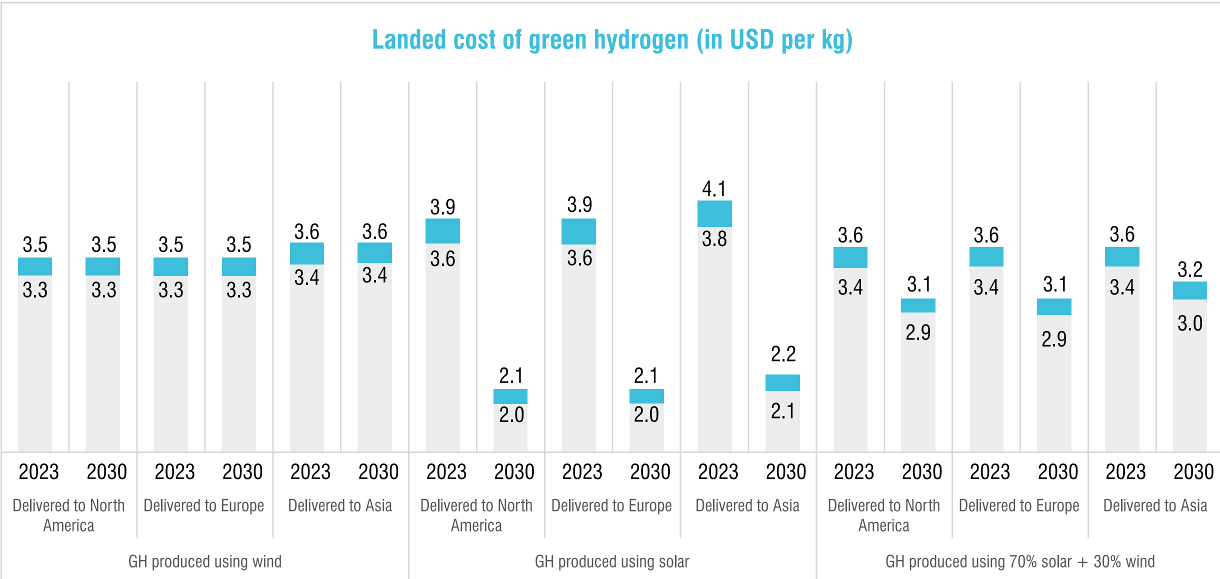
Scenario 2: Centralised Green Hydrogen Production

Production of green hydrogen close to the renewable electricity plants and transported to demand centres. It has been assumed that trucks would deliver over shorter distances (up to 1,500 km) and pipelines would be used to deliver green hydrogen over longer distances (more than 3,000 km)



Scenario 3: Centralised Green Ammonia Production for export purposes

Green ammonia produced at an export terminal located close to a major port using renewable energy delivered through high voltage transmission lines. Landed cost also includes the cost of cracking at the destination to produce green hydrogen



The key findings resulting from this analysis include the following:

- **A sharp drop in prices for green hydrogen produced using solar energy** is expected to be seen in Brazil which is in congruence with the expected fall in prices for solar energy technologies, and the fall in prices of green hydrogen needed to sustain an effective transition at scale around the world. Cost of green hydrogen produced using wind energy is also expected to fall over the decade, however the decline is expected to be much smaller than that for solar.
- Given the cost levels, the green hydrogen produced in Brazil might not be able to compete with other suppliers in the international markets or the South American regional markets in terms of costs. However, given the continent's proximity to the African continent, **export of green hydrogen from Brazil across the southern Atlantic for decarbonization of the African continent** provides an opportunity that could be tapped to move towards global decarbonization.

Way forward

Blessed with substantial wind and solar energy potential, an integrated, low-carbon power grid and geographic advantages, the country is **best-fit to export to Europe and the east coast of North America.** Along with a **significant domestic industry**, Brazil is positioned well to become one of the world leaders in the production of green hydrogen. However, there are certain area that must be addressed to allow green hydrogen to develop in Brazil across the value chain. To produce green hydrogen Brazil would need to accelerate the expansion of its power infrastructure. The expanding generation will require doubling or at least reinforcing the current transmission infrastructure.

Table 5: Recommendations for Brazil

	Drivers	Recommendation
1	**Policy and Regulatory Framework**	• Developing a **regulatory framework to attract private investment** • Participate in international discussions regarding **certification criteria** • Foster carbon pricing and implementation mechanism
2	**Capacity Building and Innovation**	• Define **strategy for talent development and skill building** • Invest in R&D and new use cases • Fosters **innovative technologies along the green hydrogen value** chain and support exchange programmes between Brazilian and foreign universities and research institution
3	**Infrastructure**	• **Planning and streamlining permitting and approval processes** for rapid infrastructure expansion • Start operations of **pilot hydrogen plants and respective transmission lines and pipelines**
4	**Financing**	• Collaborate with Multilateral **Development Banks to develop attractive capital and risk financing mechanisms** to support green hydrogen projects
5	**Technology**	• Foster cooperation with countries and multi-national organizations to **support technology development and transfer of technology to the country** over the long-term future • Leverage Technology Collaboration Programmes to facilitate international R&D and information exchange

5. Strengthening the Green Hydrogen Supply Chain

Hydrogen can be crucial in helping hard-to-abate sectors achieve their climate targets. Countries with the availability of critical resources and industry experience can help create, deploy, and scale the technology. Countries rich in minerals have the potential to turn this into an opportunity by taking advantage of their resources, geographic locations, access to abundant renewable energy, and highly developed infrastructure to develop and export green hydrogen and its derivatives.

As mentioned, green hydrogen is expected to play a significant role in decarbonizing hard-to-abate sectors such as heavy industries and long-haul transport. The demand for hydrogen reached over 94 MMTPA in 2021 and is expected to grow over 500 MMTPA by 2050.[67] From 2020 to 2021, the hydrogen production market was valued at USD130 billion and is estimated to grow up to 9.2 percent per year through 2030.[68] However, significant challenges must be resolved. The hydrogen value chain is both complex and capital-intensive, many segments are still in a nascent stage. There is a need to adapt to evolving technologies and regulations. Stakeholders will need to come together to grasp this opportunity and develop green hydrogen value chains across geographies. The development of a green hydrogen supply chain presents several challenges that must be addressed to ensure the scalability and sustainability of the market. The table explores a few of these challenges, followed by a pathway to strengthening the green hydrogen supply chain.

Table 6: Challenges in the Development of a Green Gydrogen Supply Chain

S.No.	Categories	Challenge
1	Cost	The cost of producing green hydrogen is still higher than that of grey or blue hydrogen. It is essential to reduce costs to make green hydrogen competitive. Additionally, the cost of renewable energy sources, such as solar and wind, required to produce green hydrogen, can vary significantly depending on geographic location, availability, and other factors.
2	Infrastructure	The development of green hydrogen infrastructure, such as pipelines and storage facilities, is still in its early stages and requires significant investment. Additionally, the transportation of green hydrogen is challenging due to its low energy density and the need for specialized equipment and safety measures.
3	Scale and demand	The scale-up of green hydrogen production and the creation of market demand are critical challenges. The current demand for green hydrogen is low, and the production capacity is limited, which can limit its scalability. However, several countries are setting ambitious targets for green hydrogen production and infrastructure development, which could drive demand and create a market for green hydrogen.
4	Supply chain complexity	The green hydrogen supply chain is complex, involving several stages, including the production of renewable energy, the electrolysis of water to produce hydrogen, transportation, storage, and distribution. Each stage of the supply chain presents unique challenges, such as the management of intermittency in renewable energy production, the efficiency of electrolysis, and the safety and efficiency of transportation and storage.

67 IEA – The future of hydrogen, 2019

68 Energy Transition Commission - Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy, 2021

5.	Lack of technical and	Hydrogen can be as safe as the fuels in use today, with proper handling and controls. However, the need to transport and store hydrogen entails hazards that need to be addressed. For green hydrogen to become widely accepted in applications where it is not already used, it will become increasingly important to develop and implement internationally agreed codes and standards covering the safe construction, maintenance and operation of hydrogen facilities and equipment, along the entire supply chain.

The development of the green hydrogen supply chain presents several challenges, as reflected above, but it also introduces opportunities, such as renewable energy integration, market development, innovation, and job creation. The development of the green hydrogen supply chain requires alliance across several sectors, including renewable energy, hydrogen production, transportation, and storage. Additionally, policies and regulations that support the development of the green hydrogen supply chain are essential to ensure its scalability and sustainability.

Strengthening the green hydrogen supply chain is crucial for the widespread adoption and utilization of this clean energy source. Green hydrogen, produced using renewable energy sources, has the potential to play a significant role in decarbonizing various sectors, such as transportation, industry, and power generation. Following are the broad areas that need to be focused on to strengthen the green hydrogen supply chain:

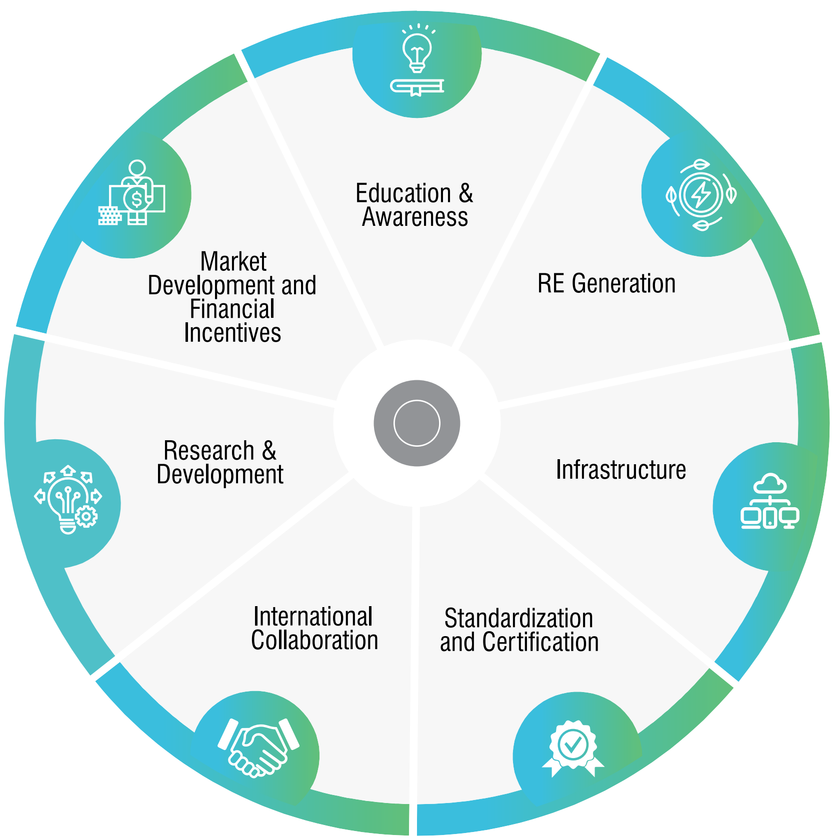


Figure 29: Broad Contours to Strengthen Green Hydrogen Supply chain

1. **Renewable Energy Generation:** The first step is to ensure an abundant and reliable supply of renewable energy, such as solar and wind power. Governments and stakeholders need to prioritize the expansion of renewable energy capacity to provide the necessary electricity for green hydrogen production.

The International Energy Agency (IEA) estimates the installed electrolysis capacity for producing hydrogen to rise over 130 GW in 2030.[69] Powering all these electrolysers to produce green hydrogen will require the production of about 600 terawatt (TW) hours of renewable energy, providing a huge new market for the renewable-power generation industry.

2. **Electrolysis Infrastructure:** To strengthen the supply chain, investments are needed in the development and scaling up of electrolysis infrastructure. This includes establishing electrolyser manufacturing facilities and optimizing the efficiency and cost-effectiveness of the technology.

   To meet the expected demand for green hydrogen, the cost of electrolysis must decline. Out of several existing electrolysers the most common are proton exchange membrane (PEM) electrolysers, which use stacks of solid polymer membranes between the anode and cathode, and alkaline electrolysis cells (AECs), which use a liquid alkaline solution as the electrolyte. The solid oxide electrolysis cells (SOECs), on the other hand, use a solid electrolyte to produce hydrogen from steam; the technology is less mature but offers the potential for efficiency levels of up to 80 percent.

   The cost to produce and operate electrolysers is high, owing largely to the inefficiency of current electrolyser technology. Increasing overall efficiency offers a major opportunity for manufacturers. For example, boosting the system efficiency of PEM electrolysers from 60 percent to 70 percent seems possible, primarily by improving the materials used in the stack.

69 IEA – Electrolysers Analysis 2022

At present, capital cost for electrolysers is high majorly because they require a large amount of high-cost materials, such as precious metals. This holds true, especially for PEM electrolyser stacks that mostly use a membrane with platinum on the cathode and iridium or ruthenium on the anode. Research and development are currently under progress to investigate the ways of reducing the amount of precious metal needed without compromising on performance. Another issue is that at present, only a small number of electrolysers are being produced.

Cutting down on the cost of materials and adding automation and standardization could reduce the required capex.

3. **Water Availability:** Access to clean water is essential for hydrogen production. Policies and strategies need to be in place to ensure sustainable water management, particularly in areas where water scarcity is a concern. Additionally, research and development efforts can focus on improving water electrolysis efficiency and exploring alternative sources of water, such as wastewater and seawater.

4. **Storage and Transportation:** Green hydrogen needs to be efficiently stored and transported from production sites to end-users. Developing robust storage solutions, such as high-pressure tanks, underground caverns, or chemical storage methods, can help address the intermittency of renewable energy sources and ensure a continuous supply of hydrogen. Moreover, investments in hydrogen pipelines, shipping infrastructure, and liquefaction technologies can facilitate the transportation of hydrogen over long distances.

5. **Standardization and Certification:** Establishing safety standards and regulations specific to hydrogen is crucial to building trust and confidence in the supply chain. Governments, industry associations, and relevant stakeholders need to collaborate to develop comprehensive safety guidelines, codes, and protocols for hydrogen production, storage, and transportation. Training programs and certifications for personnel involved in the green hydrogen sector can also enhance safe practices.

<table>
<tr><td rowspan="5">BARRIERS</td><td colspan="6">Sustainability Issues</td></tr>
<tr><td colspan="6">Technical Barriers</td></tr>
<tr><td colspan="4"></td><td>Unclear Future</td><td>Unfit Power System Structure</td></tr>
<tr><td>Sustainability of Grid Electricity</td><td>High Cost of Electrolysers</td><td>Unfit Power System Structure</td><td>Lack of Demand</td><td colspan="2">Lack of Standards</td></tr>
<tr><td>High Cost of Renewable Electricity</td><td>Unclear Future</td><td>Green Hydrogen Cost Gap</td><td>Unclear Future</td><td colspan="2">High Infrastructure Costs</td></tr>
<tr><td colspan="7">H2</td></tr>
<tr><td rowspan="8">POLICY OPTIONS</td><td rowspan="2">ELECTRICITY CONSUMPTION</td><td rowspan="2">ELECTROLYSIS</td><td colspan="2">GREEN HYDROGEN OFFTAKE</td><td colspan="2">INFRASTRUCTURE</td></tr>
<tr><td>PRICE</td><td>DEMAND</td><td>TRANSPORT</td><td>STORAGE</td></tr>
<tr><td>Sustainability Assurance Measures</td><td>Capacity Targets</td><td>Fiscal Incentives</td><td>Green Gas Targets</td><td colspan="2">Financing</td></tr>
<tr><td>Exemptions from Electricity Taxes and Levies</td><td>Manufacturing Capacity Support</td><td>Green Gas Premium</td><td>Virtual Blending</td><td colspan="2">Planning</td></tr>
<tr><td></td><td>Direct Financial Support</td><td>Auctions</td><td>International Agreements</td><td colspan="2">Creation of Standards</td></tr>
<tr><td></td><td>Fiscal Incentives</td><td>Ancillary Market Participation</td><td></td><td>Support for Green Trucks and Ships</td><td>Seasonal Storage Support</td></tr>
<tr><td colspan="6">Guarantees of Origin</td></tr>
<tr><td colspan="6">Research and Development</td></tr>
</table>

Figure 30: Barriers and Policy Options for the Supply of Green Hydrogen

Source: IRENA, 2021

6. **Market Development and Financial Incentives:** Encouraging market demand for green hydrogen is essential for the growth of the supply chain. Governments can implement policies and incentives to support the adoption of green hydrogen in various sectors, such as offering subsidies, tax breaks, or low-cost finance. Long-term contracts and offtake agreements can also provide stability and attract investments in green hydrogen infrastructure. Figure below illustrates examples of policy and incentives to address technical barriers such as lack of demand, high costs etc.

7. **International Collaboration:** Green hydrogen has the potential to become a global energy carrier, and international collaboration is vital for its development. Governments, industry players, and research institutions need to engage in knowledge sharing, joint research projects, and technology transfers to accelerate the deployment of green hydrogen technologies worldwide. This collaboration can also help address challenges related to standardization, certification, and harmonization of regulations. Collaboration between different industries, such as renewable energy, transportation, and manufacturing, is essential for the development of a robust green hydrogen supply chain. For example, partnerships between renewable energy companies and industrial manufacturers can facilitate the establishment of dedicated electrolysis facilities or the utilization of excess renewable energy for hydrogen production.

8. **Research and Development:** Continued investment in research and development is crucial to advance green hydrogen technologies and drive innovation. Funds need to be allocated to support research projects aimed at improving electrolysis efficiency, developing new catalysts, exploring advanced storage solutions, and reducing costs associated with production, storage, and transportation.

9. **Education and Awareness:** Increasing public awareness and understanding of green hydrogen's potential benefits is vital for its acceptance and adoption. Educational campaigns and awareness programs can help promote the advantages of green hydrogen, drive out misconceptions, and build public support for investments in the supply chain.

10. **Continuous Improvement:** The green hydrogen supply chain should be viewed as an evolving system that requires continuous improvement. Regular monitoring, data collection, and analysis can identify bottlenecks, inefficiencies, and opportunities for optimization. Feedback loops and lessons learned should be incorporated to drive ongoing enhancements and ensure that the supply chain remains resilient and adaptable.

Table 7: Summary: Way Forward for Strengthening the Green Hydrogen Supply Chain

S.No.	Areas to focus	Key recommendations
1	Renewable Energy Generation	• Need for abundant and reliable supply of renewable energy • Expand renewable energy capacity
2	Infrastructure	• Establish electrolysers manufacturing facilities • Ensure sustainable water management • Develop robust storage solutions • Initiate investments in hydrogen pipelines, shipping infrastructure, and liquefaction technologies to facilitate the transportation of hydrogen
3	Standardization and Certification	• Collaborate to develop comprehensive safety guidelines, codes, and protocols for hydrogen production, storage, and transportation
4	Market Development and Financial Incentives	• Create demand side measures • Offer subsidies, tax breaks, or low-cost finance
5	International Collaboration	• Engage in knowledge sharing, joint research projects, and technology transfers
6	Research and Development	• Boost investment to drive innovation and research and development
7	Education and Awareness	• Organise educational campaigns and awareness programs
8	Continuous Improvement	• Routine monitoring and evaluation

ANNEXURE 1:
Common assumptions for calculation of landed cost of green hydrogen

Parameter	Unit	Year 2023	Year 2030
Solar PV system - Installation and Operation[70]			
Solar PV CAPEX	USD million per MW	1.08	0.75
Levelised Solar PV OPEX	USD per MW per year	15,000	6,000
Useful life of asset	years	30	50
Wind energy solution - Installation and Operation[71]			
Wind energy CAPEX - Onshore	USD million per MW	1.335	1.2
Wind energy CAPEX - Fixed-base offshore	USD million per MW	3.551	2.8
Wind energy CAPEX - Floating offshore	USD million per MW	-	3.7
Levelised wind OPEX - Onshore	USD per MW per year	39,000	33,400
Levelised wind OPEX - Fixed-base offshore	USD per MW per year	90,000	70,500
Levelised wind OPEX - Floating offshore	USD per MW per year	-	85,500
Useful life of asset	years	30	30
Electrolysers for green hydrogen production - Installation and Operation[72]			
Electrolyser CAPEX	USD million per MW	0.9	0.7
Electrolyser OPEX	% of CAPEX per year	1.5	1.5
Useful life of asset	hours	95,000	95,000
Efficiency	%	64	69
Electrolysers for green ammonia production - Installation and Operation[73]			
Electrolyser CAPEX	USD per kg NH3	1.16	0.885
Electrolyser OPEX	% of CAPEX per year	1.5	1.5
Useful life of asset	years	25	25
Parameter	Unit	Year 2023	Year 2030
Design capacity	million kg per year	1,500	
Ammonia cracker for green hydrogen production from ammonia - installation and operation[74]			
Ammonia Cracker CAPEX	USD million	460	460
Ammonia Cracker OPEX	% of CAPEX per year	4	4
Useful life of asset	years	30	30

70 *2030 Solar Cost Targets (Office of Energy Efficiency & Renewable Energy, US Dept. of Energy, 2021)*
71 *NREL Expert Elicitation Survey, 2021*
72 *IEA-The Future of Hydrogen Assumptions Annex 2019*
73 *IEA-The Future of Hydrogen Assumptions Annex 2019*
74 *IEA-The Future of Hydrogen Assumptions Annex 2019*

Parameter	Unit	Year 2023	Year 2030
Design capacity	million kg NH3 per year	1,500	
Pipeline for green hydrogen transportation - Installation and Operation[75]			
Pipeline CAPEX	USD million per km	1.21	1.21
Useful life of asset	years	40	40
Capacity Utilisation Factor	%	75	75
Design capacity	million kg per year	340	340
Truck fleet for green hydrogen transportation – Procurement and Operation[76]			
Truck CAPEX	USD million per unit	0.185	0.185
Trailer CAPEX	USD million per unit	0.65	0.65
Truck OPEX	% of CAPEX per year	12	12
Trailer OPEX	% of CAPEX per year	2	2
Useful life of asset	years	12	12
Design capacity	kg	670	670
Design speed	km per hour	50	50
Capacity Utilisation Factor	%	75	75
Marine vessel fleet for green hydrogen transportation – Procurement and Operation[77]			
Vessel CAPEX	USD million per unit	85	85
Vessel OPEX	% of CAPEX per year	4	4
Vessel Capacity	million kg NH3	56.7	56.7
Useful life of asset	years	30	30
Vessel speed	km per hour	30	30
Fuel Consumption	kg H2 per km	22	22
Capacity Utilisation Factor	%	90	90

75 *IEA-The Future of Hydrogen Assumptions Annex 2019*
76 *IEA-The Future of Hydrogen Assumptions Annex 2019*
77 *IEA-The Future of Hydrogen Assumptions Annex 2019*

ANNEXURE 2: Country-specific assumptions for calculation of landed cost

Parameter	Unit	Chile	India	Brazil
Variables related to renewable energy generation				
Wind energy mix – onshore installations[78]	%	50	80	25
Wind energy mix – fixed-base offshore installations[79]	%	30	20	60
Wind energy mix – floating offshore installations[80]	%	20	0	15
Wind turbine average capacity utilization factor[81]	%	60	35	50
Average daily solar PV output[82]	MWh per MWp	6	4.5	4.75
Average number of sunny days[83]	days per year	360	300	280
Variables related to transmission of renewable energy				
Transmission and wheeling charges	USD per MWh	15[84]	6[85]	4.5
Transmission and wheeling losses	%	4	4	4
Variables related to domestic transportation of green hydrogen[86]				
Distance to market using pipelines	km	1,500	750	1,500
Distance to market using truck fleet	km	1,500	1,500	3,000
Distance to market using ammonia ships	km	2,500	-	-
Variables related to export of green hydrogen[87]				
Distance to North American markets (ex-Miami)	km	7,000 ^ / 10,000*	18,500	9,000
Distance to European markets (ex- Rotterdam)	km	13,500 ^ / 15,000*	15,000	10,000
Distance to Asian markets (ex- Singapore)	km	20,000 ^ / 17,000*	3,000	17,000

^ Distance from solar rich northern region of Chile
* Distance from wind-rich southern region of Chile

The ISA Programme – Solar for Green Hydrogen – will address these barriers in close collaboration with ISA membership and other stakeholders. This report builds upon the Readiness Assessment Framework introduced in ISA Consultation Draft (launched in COP27, Egypt) report and provides a deep-dive analysis on select countries.

78 *Assumed based on spread of resource potential in Global Wind Atlas*
79 *Assumed based on spread of resource potential in Global Wind Atlas*
80 *Assumed based on spread of resource potential in Global Wind Atlas*
81 *Selected from high resource potential areas represented in Global Wind Atlas*
82 *Selected from high resource potential areas represented in Global Wind Atlas*
83 *Estimate based on Weather data from Weather and Climate*
84 *Assumed based on data from National Energy Commission, Ministry of Energy, Government of Chile (CNE-CL)*
85 *Assumed based on data from Grid Controller of India Limited*
86 *Measured using Google Maps*
87 *Measured using Sea-Distances.org*

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