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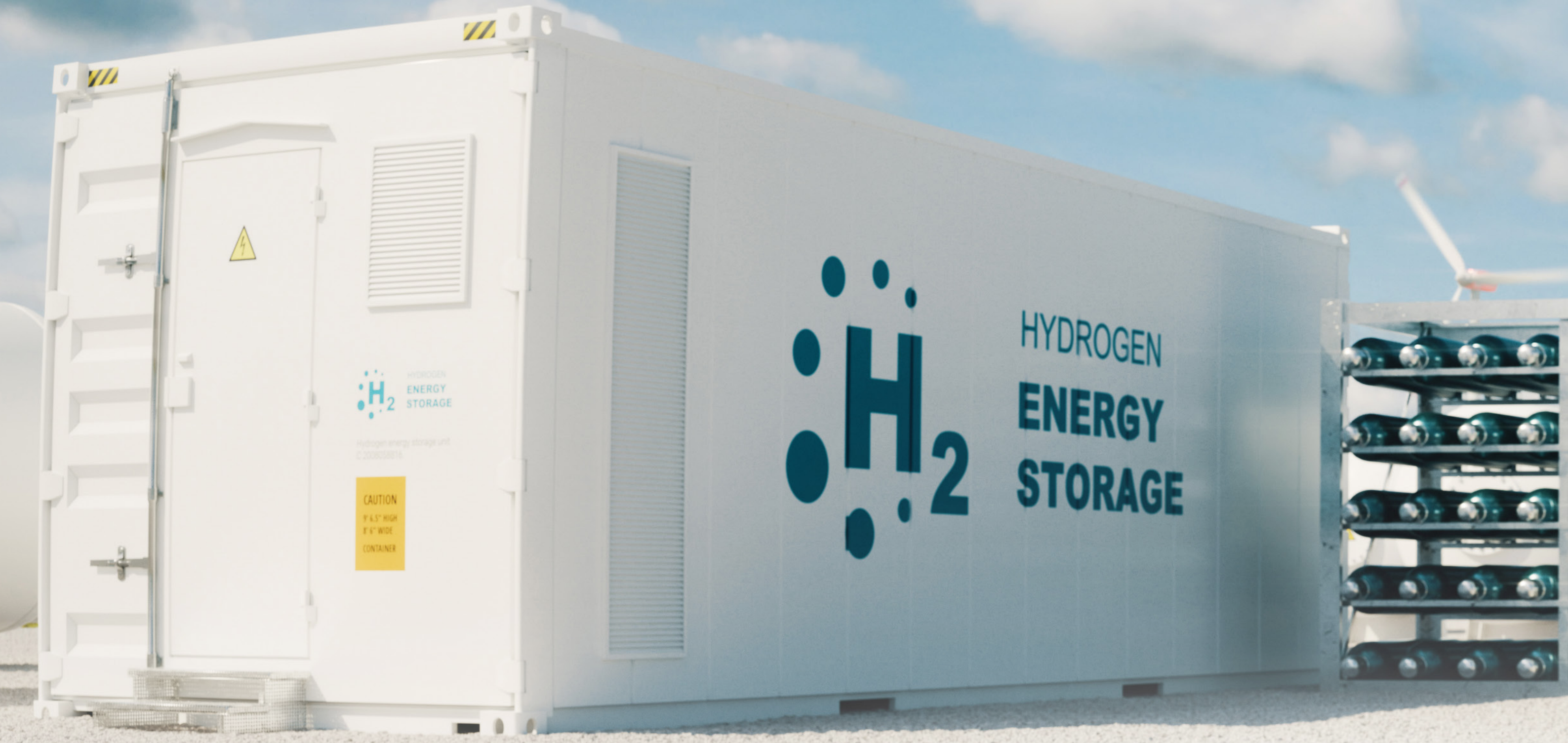
नवीकरणीय ऊर्जा मंत्रालय
MINISTRY OF
NEW AND
RENEWABLE ENERGY

G20
भारत 2023 INDIA

ACCELERATING THE PRODUCTION AND USE OF **GREEN HYDROGEN**



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AUTHORS

Anuraag Nallapaneni, Program Manager, Hydrogen, WRI India
Dr. Guncha Munjal, Program Manager, Hydrogen, WRI India
Pawan Mulukutla, Director, Integrated Transport, Electric Mobility, and Hydrogen, WRI India
Jatin Saxena, Junior Program Associate, Hydrogen, WRI India

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PREFACE

The G20 leadership has highlighted how low-carbon hydrogen could be a key pillar to drive cross-sectoral decarbonization and abate GHG emissions, mitigate climate change, and promote economic development and growth. Currently hydrogen is predominantly produced through steam methane reformation (SMR) of natural gas and coal gasification both of which are highly GHG intensive. Nations across the globe have started to incorporate low-carbon hydrogen strategies and road maps for mitigating emissions from hydrogen production, as well as drive green hydrogen adoption in new sectors.

However, for the world to meet net zero carbon emissions by 2050, the rate of deployment of green hydrogen needs to accelerate. Significant challenges across regulations, technology, and supply chains would have to be addressed through a global collaborative approach in order to achieve scale and reduce costs for green hydrogen. As a leading forum for international cooperation, the G20 nations can steer this development of the global green hydrogen ecosystem.

This study seeks to identify priority areas for collaboration to accelerate green hydrogen adoption through the establishment of supply chains, harmonizing a methodology for classification of hydrogen, and enhancing collaborative research and innovation for green and low-carbon technologies. The recommendations provided in this publication are aimed at policymakers and legislators across the G20 nations, highlighting contribution opportunities for stakeholders to accelerate the deployment of large-scale and cost-effective green and low-carbon hydrogen across the world. The report draws upon the expertise and experience of green hydrogen technology development and research across its value chain and seeks to provide project proponents, policymakers, institutions, investors, and industries across the world with a holistic understanding of the technology gaps that need to be addressed for an accelerated deployment of green hydrogen.

The development of a global green hydrogen economy is a complex and challenging task; however, the potential benefits are significant. This publication aimed at establishing a harmonized hydrogen standard, enabling supply chains, and enhancing cooperation and collaboration across critical facets of the green hydrogen value chain, I hope will be a valuable resource for the G20 policymakers and stakeholders as they work toward developing mechanisms for accelerating the global adoption of green hydrogen.

Mr. Madhav Pai,
CEO, WRI India

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ACRONYMS AND ABBREVIATIONS

AEM	ANION EXCHANGE MEMBRANE
ALK	ALKALINE
BNEF	BLOOMBERG NEW ENERGY FINANCE
BOP	BALANCE OF PLANT
BP	BRITISH PETROLEUM
CEM	CLEAN ENERGY MINISTERIAL
CFGH	COLLABORATION FRAMEWORK ON GREEN HYDROGEN
CFRP	CARBON FIBER-REINFORCED PLASTIC
CMS	CARBON MANAGEMENT SERVICE
CNRS	FRENCH NATIONAL CENTER FOR SCIENTIFIC RESEARCH
COP	CONFERENCE OF PARTIES
CO_2	CARBON DIOXIDE
CSIR-CMERI	COUNCIL OF SCIENTIFIC & INDUSTRIAL RESEARCH-CENTRAL MECHANICAL ENGINEERING RESEARCH INSTITUTE
CSIRO	COUNCIL OF SCIENTIFIC AND INDUSTRIAL RESEARCH
DNV	DET NORSKE VERITAS
DOE	U.S. DEPARTMENT OF ENERGY
EC	EUROPEAN COMMISSION
EU	EUROPEAN UNION
FRP	FIBER-REINFORCED POLYMERS
GDP	GROSS DOMESTIC PRODUCT
GH2	GREEN HYDROGEN ORGANISATION
GHG	GREENHOUSE GASES
GMBH	TÜV SÜD INDUSTRIE SERVICE
GW	GIGAWATT
H2PA	HYDROGEN PRODUCTION ANALYSIS
H2TR	HYDROGEN TRADE RULES
IEA-AMF	INTERNATIONAL ENERGY AGENCY ADVANCED MOTOR FUELS
IEA-TCP	INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME
IPFS	INTERNATIONAL PATENT FAMILIES
IPHE	INTERNATIONAL PARTNERSHIP FOR HYDROGEN AND FUEL CELLS
IREDA	INDIAN RENEWABLE ENERGY DEVELOPMENT AGENCY
IRENA	INTERNATIONAL RENEWABLE ENERGY AGENCY
ISCC	INTERNATIONAL SUSTAINABLITY AND CARBON CERTIFICATION
JRC GECO	JOINT RESEARCH CENTRE GLOBAL ENERGY AND CLIMATE OUTLOOK
LCA	LIFE-CYCLE ANALYSIS
LSCF	LANTHANUM STRONTIUM COBALT FERRITE
LSM	LANTHANUM STRONTIUM MANGANITE
LOHC	LIQUID ORGANIC HYDROGEN CARRIERS
LPG	LIQUIFIED PETROLEUM GAS
MNRE	MINISTRY OF NEW AND RENEWABLE ENERGY
MTPA	MILLION TONNES PER ANNUM
MW	MEGAWATT
PEM	PROTON EXCHANGE MEMBRANE
PEMFCS	POLYMER ELECTROLYTE MEMBRANE FUEL CELLS
PFA	PERFLUOROALKOXY ALKANE
PGM	PLATINUM GROUP METALS
PP	POLYPROPYLENE
PTFE	POLYTETRAFLUOROETHYLENE
PVC-C	CHLORINATED POLYVINYL CHLORIDE
R&D	RESEARCH AND DEVELOPMENT
R&I	RESEARCH AND INNOVATION
RE	RENEWABLE ENERGY
RECS	RENEWABLE ENERGY CERTIFICATES
RED II	RENEWABLE ENERGY DIRECTIVE
SDG	SUSTAINABLE DEVELOPMENT GOAL
SMR	STEAM METHANE REFORMING
SOEC	SOLID OXIDE ELECTROLYZER CELL
TÜV SÜD	TECHNISCHER ÜBERWACHUNGSVEREIN
UNIDO	UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANISATION
WBG	WORLD BANK GROUP
YSZ	YTTRIA-STABILIZED ZIRCONIA

1. EXECUTIVE SUMMARY

To tackle climate change and accelerate the green transition to meet net zero targets, many countries including G20 nations have already set bold decarbonization and renewable energy targets. Low-carbon hydrogen, including green hydrogen derived from renewable sources, has emerged as a potential solution to support this transition with a potential to decarbonize hard-to-abate sectors such as heavy industry, buildings, and transportation while also catalyzing renewable-based energy technologies. Multiple G20 nations, including the European Union, India, Australia, Japan, and the United States, have already announced national hydrogen strategies or road maps to ensure widespread availability and affordability of low-carbon hydrogen and green hydrogen.

By promoting the use of green hydrogen, G20 countries can significantly reduce emissions, enhance energy security, and lead global efforts to combat climate change. But realizing the full potential of green hydrogen requires substantial scaling of production, reducing costs, and establishing a robust infrastructure, including renewable energy capacities and supportive legislation and regulations.

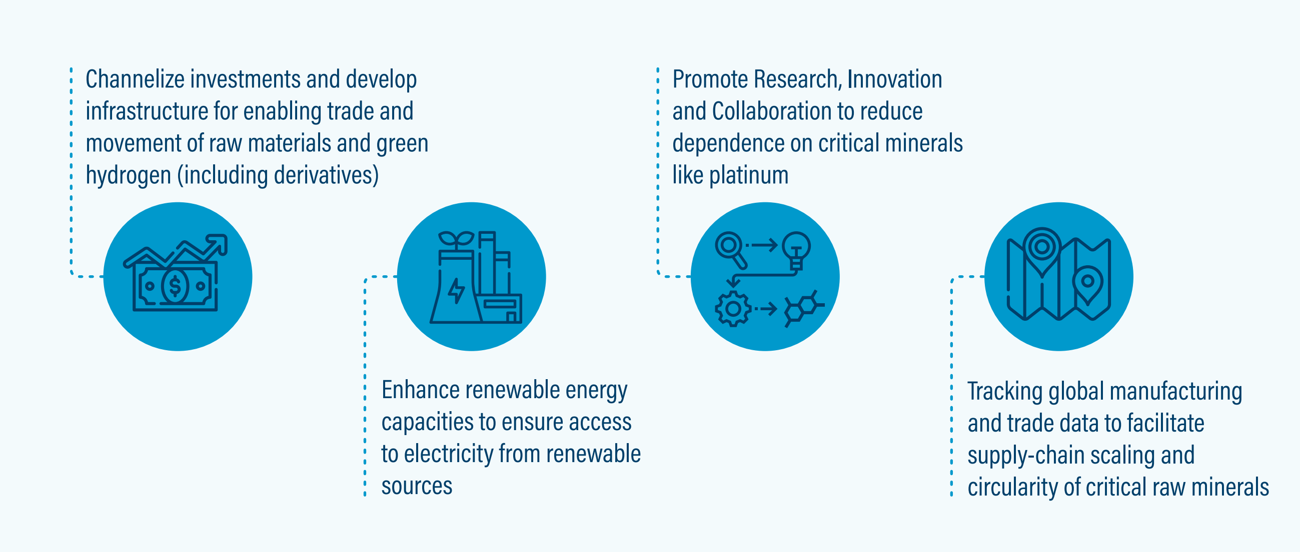
To realize these objectives would necessitate closer alignment and deeper engagement among G20 nations on several critical fronts, such as establishing international supply chains required for production and trade of green hydrogen and its derivatives and achieving a consensus on a framework for classification of hydrogen produced from various sources. G20 nations must also strengthen and harness collaborative research to advance green hydrogen technologies and facilitate knowledge sharing and technology transfers to accelerate global adoption of green hydrogen and advance the collective goal of a sustainable and decarbonized future.

The primary objective of this report, published under India's G20 presidency, is to elaborate on three key aspects on which the G20 nations should focus for establishing and accelerating the production and applications of green hydrogen. The methodology employed for this report involved a systematic approach to collect and analyze relevant literature for identifying and summarizing best practices and recommendations for development of a green hydrogen ecosystem. The key focus areas under consideration for this report include enabling supply chains for green hydrogen production and trade, establishing a standardized framework for classification of hydrogen, and deepening collaborative research and innovation (R&I) for advancing and promoting green hydrogen technologies. These three focus areas were chosen due to their vital importance and the necessity of simultaneous focus on all of them for a successful realization of a global hydrogen economy.

1. Creating resilient supply chains for accelerating green hydrogen adoption

It is estimated that by 2030, nearly one-third of the global hydrogen supply will be produced from low-carbon sources. Scenario studies predict that by 2050, around 85 percent of the world's hydrogen supply could come from low-carbon pathways with electrolysis alone accounting for approximately 60 percent. To meet the demand for green hydrogen under the assessed scenarios, an installed electrolyzer capacity of around 5,000 GW is

Figure ES-1 | **RECOMMENDATIONS FOR ENABLING SUPPLY CHAINS FOR GREEN HYDROGEN ADOPTION**



Channelize investments and develop infrastructure for enabling trade and movement of raw materials and green hydrogen (including derivatives)

Enhance renewable energy capacities to ensure access to electricity from renewable sources

Promote Research, Innovation and Collaboration to reduce dependence on critical minerals like platinum

Tracking global manufacturing and trade data to facilitate supply-chain scaling and circularity of critical raw minerals

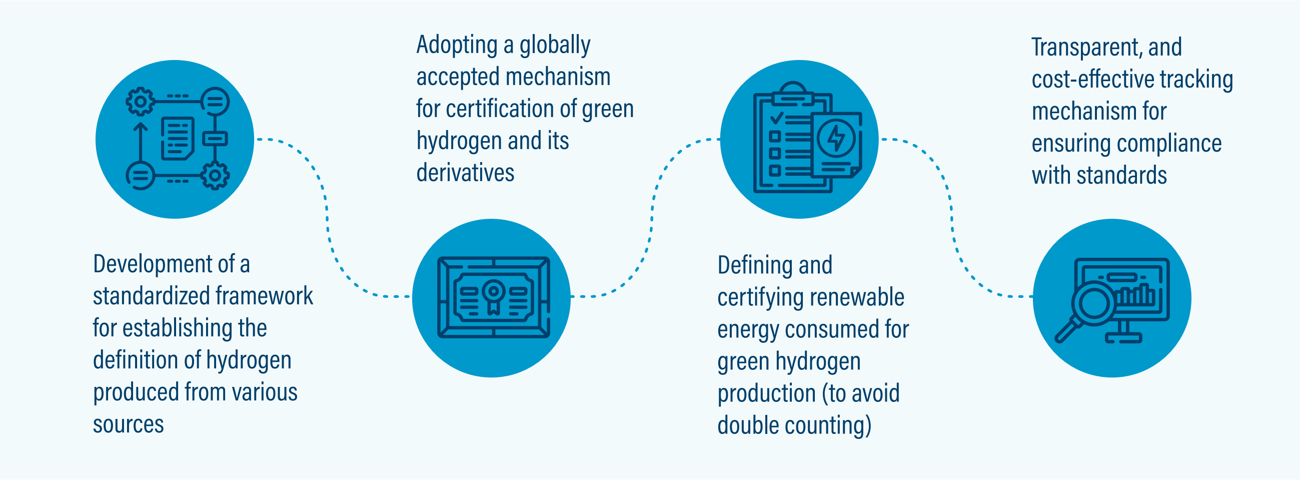
Source: WRI Authors.

required. This necessitates the development of a robust supply chain for electrolyzers, renewable energy generation, fuel cells, and all associated infrastructure along the hydrogen value chain, which can be accomplished through measures highlighted in Figure ES 1.

2. Harmonizing a framework for green hydrogen standard and certification

With G20 nations leading global GDP and trade, gaining consensus on a framework for classification of hydrogen from various sources would significantly accelerate its production and adoption globally. A standardized framework for classification of hydrogen with global consensus would provide assurance of quality, enable interoperability across geographies, and generate market certainty that would attract investment, encourage innovation, and facilitate international trade. The following recommendations have been made to establish a global consensus for the methodology for classifying hydrogen (Figure ES-2).

Figure ES-2 | **RECOMMENDATIONS FOR HARMONIZING A STANDARD FOR THE CLASSIFICATION OF HYDROGEN**



Development of a standardized framework for establishing the definition of hydrogen produced from various sources

Adopting a globally accepted mechanism for certification of green hydrogen and its derivatives

Defining and certifying renewable energy consumed for green hydrogen production (to avoid double counting)

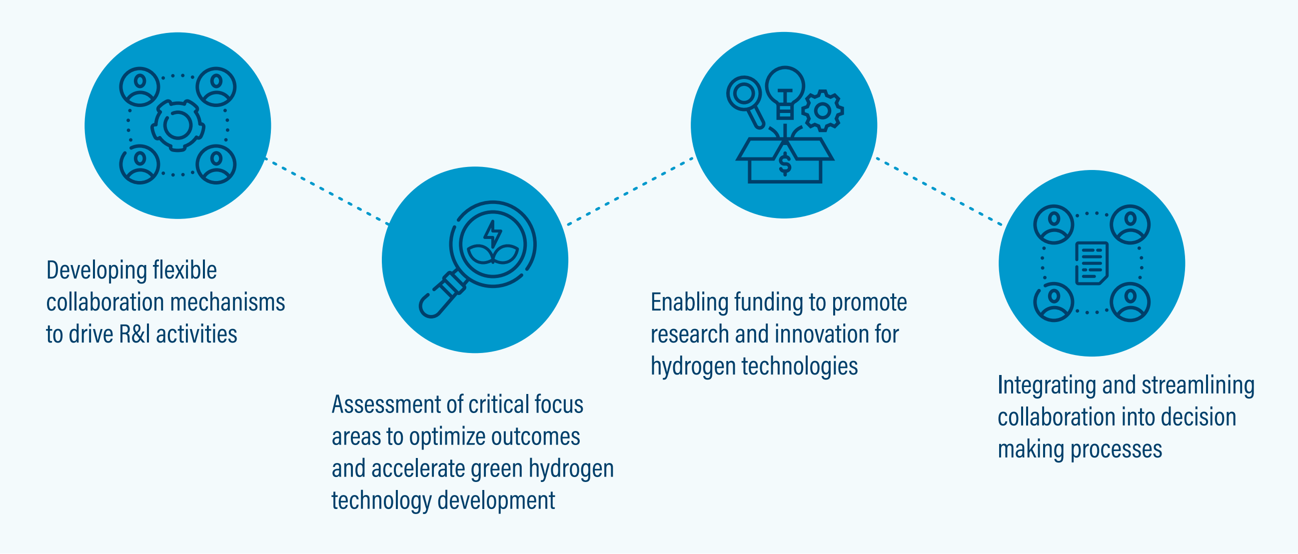
Transparent, and cost-effective tracking mechanism for ensuring compliance with standards

Source: WRI Authors.

3. Enhance collaborative research and innovation through ongoing multilateral initiatives to accelerate green hydrogen technology development: To commercialize and scale the production of green hydrogen it is essential to have continued innovation, research, and development for improving efficiencies and reducing costs of green hydrogen technologies. This would require collaborative and joint research partnerships to facilitate technology transfers, knowledge sharing, and project funding among the G20 nations. To align on cooperation on research and innovation, the following recommendations have been made (Figure ES-3).

Given the nascency and complexity of the green hydrogen ecosystem, it is essential that strong and influential multilateral engagement platforms like the G20 be leveraged to drive consensus on critical factors of the hydrogen economy. This publication is aimed at steering the G20 nations toward strategic cooperation on green hydrogen in the identified focus areas mentioned earlier. Intergovernmental cooperation among the participating nations would be critical to achieve scale and standardization and to enable global trade of green hydrogen to meet global climate targets and achieve net zero goals.

Figure ES-3 | **RECOMMENDATIONS FOR ACCLERATING COLLABORATIVE RESEARCH AND INNOVATION FOR DEVELOPING HYDROGEN TECHNOLOGIES**



Source: WRI Authors.

2. BACKGROUND

The global energy ecosystem is heading into a historic transition toward renewable and cleaner sources of energy. G20 members account for 80 percent of the global primary energy consumption and 75–80 percent of global greenhouse gas emissions (G20 Information Center 2021). At the same time, the G20 nations represent about 67 percent of the world's population, 75 percent of global trade, and 85 percent of the global GDP (G20 India 2023), accounting for the largest share of global wealth with the potential to shape the green transition. Thus, enhancing the efficiencies of energy systems and electrification of these economies with ever larger share of renewables are at the core of the energy transition efforts. However, for a comprehensive and decisive energy transition, clean and secure energy needs to be ensured across all sectors, including those that are intricately dependent on conventional energy streams for technical and cost reasons.

2.1 ROLE OF HYDROGEN

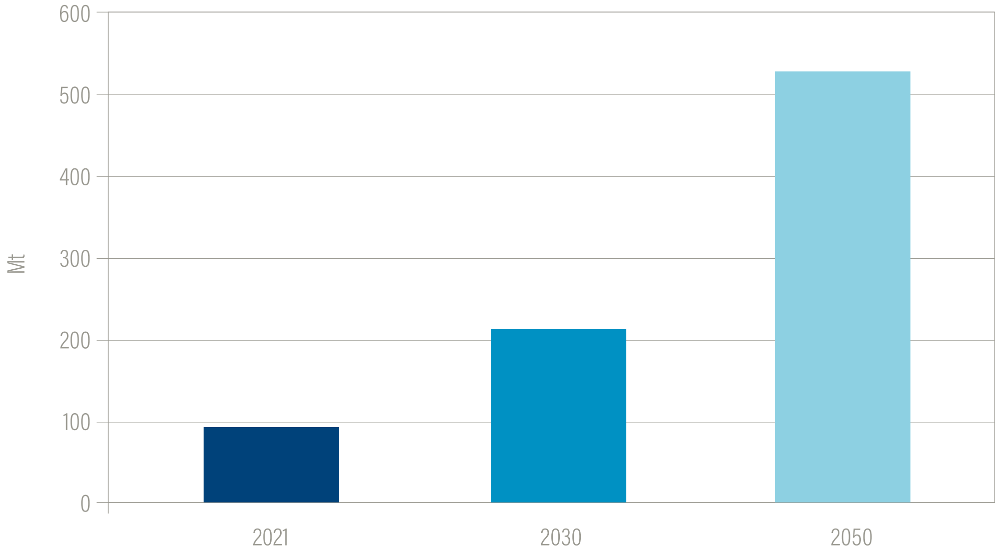
Green hydrogen, (i.e., hydrogen produced from renewable sources) has emerged as a promising clean energy carrier that holds the potential for deep decarbonization of a variety of hard to abate industrial sectors and long-haul heavy mobility, while also enabling diversification of energy supply chains. A range of sectors, where it is difficult to reduce emissions, can be decarbonized with green hydrogen. These include iron and steel, chemicals, and long-haul transport. Hydrogen's cross-sectoral decarbonization capabilities have led to several countries, including India and 16 other G20 countries, announcing their national hydrogen strategies (IEA 2022a).

The world currently produces around 94 million tonnes per annum (MTPA) of hydrogen. Most of this is consumed as feedstock for industrial applications, (particularly in fertilizer and chemical production iron and steel refining, and petroleum refining). The majority of this hydrogen is produced through the SMR of natural gas, coal gasification, where hydrogen is a by-product, resulting in over 900 Mt of CO_2 emissions as of 2021 (IEA 2023a).

Hydrogen consumption forecasted under various scenarios by 2030 is expected to significantly increase as has been indicated in various studies by BNEF, DNV, IEA, IRENA, JRC GECO, Shell, and BP (see Acronyms and Abbreviatons), and is estimated to be around 180 Mt, resulting in a modest growth of 5 percent annually (JRC 2022). Based on the scenario studies mentioned above, global hydrogen consumption is expected to be around 530 Mt by 2050 in a balanced case, with most scenarios predicting hydrogen consumption to be between 450 and 590 t (JRC 2022). See Figure 1.

According to IRENA's 1.5°C scenario, it is projected that the water electrolysis pathway will account for approximately two-thirds of overall hydrogen production by 2050. This scenario indicates the need for a substantial installed electrolyzer capacity of around 5,000 GW (IRENA 2023a). (An electrolyzer uses electrical current to split water molecules (H_2O) into constituent hydrogen (H_2) and oxygen (O_2). If all announced projects are realized, electrolyzer installed capacities are projected to reach 134–240 GW by 2030 (IEA

Figure 1 | **GLOBAL HYDROGEN DEMAND**



Source: IEA (2021d).

2022b). Therefore, ensuring a rapid increase in global electrolyzer manufacturing capacity emerges as a crucial objective to meet the possible demand for green hydrogen envisioned in these scenarios. This electrolyzer capacity requirement suggests that the establishment of robust supply chains to effectively support and expedite the advancement of both new and ongoing electrolyzer manufacturing projects, along with the ecosystem required for handling, storing, transporting, and trading the hydrogen, is important.

Along with strong commitments for hydrogen adoption across industrial, climate, and energy policies, access to low-cost renewable energy is also vital to produce green hydrogen. But, the uneven distribution of renewable resources throughout the world creates variable conditions that would divide countries into producers, exporters, and consumers. (Overland et al. 2022). As a result, the trade of hydrogen and its derivatives becomes an essential aspect of the global hydrogen economy. To ensure smooth trade and transactions, universally accepted standards and certifications for green hydrogen are essential to establish a common framework that guarantees safety and environmental sustainability throughout all phases, that is, production, storage, transportation, and utilization. By implementing common standards, countries can enable easy and open trade of green hydrogen, thereby facilitating seamless exchanges and helping accelerating global adoption of the hydrogen economy.

To expedite the development of the green hydrogen value chain, it is crucial to leverage existing multilateral collaboration and research platforms, considering the nascency of the green hydrogen ecosystem. It is imperative for G20 nations to align their green hydrogen R&I initiatives and reinforce ongoing global collaborations and innovations. A key approach to achieving this is the integration of output-oriented cross-border research initiatives on green hydrogen technologies within these platforms. By fostering synergy and coordination among international efforts, significant strides can be made in advancing green hydrogen technologies and accelerating its widespread adoption and deployment in the industry

2.2 ABOUT THE REPORT

The aim of the report is to elaborate on three key aspects on which the G20 nations can focus for establishing and accelerating the production and applications of green hydrogen: (1) developing robust supply chains to meet the projected consumption for green hydrogen technologies; (2) harmonizing a framework for green hydrogen standards and certification; and (3) enhancing collaborative research and innovation through ongoing multilateral initiatives to accelerate green hydrogen technology development.

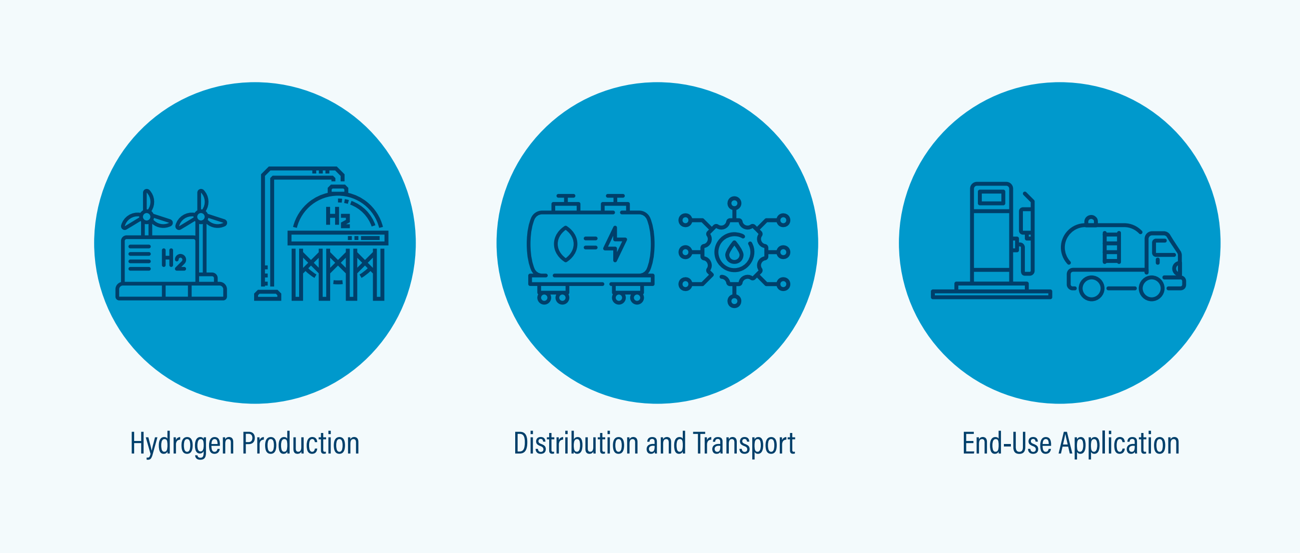
A comprehensive literature review was conducted to assess challenges across these identified themes and propose actions to mitigate them. The report discusses recommendations for the G20 nations to focus on for scaling the green hydrogen industry by overcoming challenges across the three key aspects.

3. ENABLING SUPPLY CHAINS FOR ACCELERATING GREEN HYDROGEN ADOPTION

The hydrogen value chain consists of production, transportation, and storage and end-use applications of green hydrogen (ABB 2020). As deployment of green hydrogen scales across the world, nations must also work toward developing supply chains to produce and manufacture the resources required for individual components in the green hydrogen value chain. Each segment of the hydrogen value chain will require raw materials as input for manufacturing as well as technology development and manufacturing expertise for niche components, such as electrolyzers and fuel cells.

The complete hydrogen value chain would have to consist of all three segments, which have been broadly categorized in Figure 2.

Figure 2 | **ILLUSTRATION OF GREEN HYDROGEN VALUE CHAIN**



Source: TÜV SÜD (2023).

While some of the raw materials and components would share supply chains with existing commodities and technologies, there will be a definite need to scale current supply chains as well as establish new manufacturing capacities to produce the components and products required across the hydrogen value chain.

Specifically, electrolyzers and fuel cells, which are critical components of the hydrogen value chain, are nascent industries with limited manufacturing capacities and insufficient understanding of requirements, risks, and vulnerabilities of supply chains (DOE 2022). The technology and component requirements for which supply chains would have to be scaled or established are highlighted in Table 1.

Depending on the priorities for sectoral decarbonization and availability of resources including economical and natural (such as mineral ores, renewable energy potential, water, etc.), G20 nations will have to assess their capabilities to develop segments of the supply chain. Developing global and accessible supply chains for green hydrogen is essential to enable accelerated decarbonization of hard to abate sectors, while optimizing costs and ensuring access to green hydrogen technologies for all nations.

Table 1 | **TECHNOLOGY AND COMPONENT SUPPLY CHAIN REQUIREMENTS**

VALUE CHAIN COMPONENTS	TECHNOLOGY AND RESOURCE SUPPLY CHAIN REQUIREMENTS
GREEN HYDROGEN PRODUCTION	▪ Equipment and technology for green hydrogen production ▪ Electrolyzers ▪ Balance of Plant (water de-ionizing unit, air separators, compressors, transformers/rectifiers, heat exchangers, cooling units, etc.) ▪ Renewable electricity production ▪ Electricity transmission networks
HYDROGEN TRANSPORTATION AND STORAGE	▪ Hydrogen pipelines ▪ Trailer truck/train transportation ▪ Storage (storage bunkers, tanks, cylinders, salt caverns etc) ▪ Re-fuelling stations ▪ Maritime vessels (ammonia, methanol, LOHC carriers) ▪ Port & rail infrastructure
END-USE APPLICATIONS	▪ Fuel Cells for power/transport applications ▪ Hydrogen derivatives production (ammonia, methanol, synthetic hydrocarbon fuels) ▪ Industries (chemicals, refining, steel etc.) ▪ Export infrastructure (ports & pipelines) ▪ High temperature industrial heating

Sources: BEIS 2022a; WRI analysis.

3.1 GREEN HYDROGEN SUPPLY CHAIN

Supply chains required for a green hydrogen transition are currently at a nascent stage due to the limited capacity and scale of the green hydrogen industry. To understand how the green hydrogen supply chain will evolve, it is necessary that countries assess their supply chain requirements under different scenarios for deployment of a hydrogen economy. Many countries are looking toward green hydrogen as a key enabler for their decarbonization goals; therefore, it is important that current supply chains are well understood and development priorities identified to ease challenges with supply chain bottle necks (Figure 3).

The supply chain to support the green hydrogen economy is complex and wide ranging. It can be classified into the following subsegments:

3.1.1 RAW MINERALS & ORES

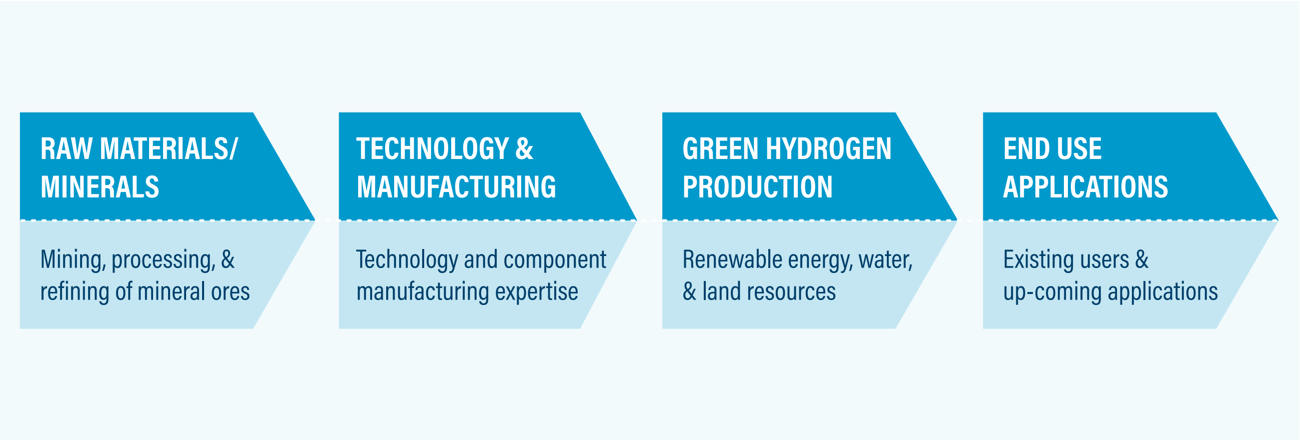
This segment of the supply chain includes the mining, processing, and refining of the raw minerals and compounds used for manufacturing of hydrogen, production technologies (electrolyzers), transportation and storage technologies (pipelines, storage cylinders, and bunkering technologies), and end-use applications (fuel cells and their components). This section of the report will focus on the critical raw minerals that are essential for the manufacturing of electrolyzers and fuel cells, which are fundamental components of the green hydrogen ecosystem.

3.1.1.1 ELECTROLYZERS

The process of electrolysis used for green hydrogen production fundamentally remains the same for all technology variations of an electrolyzer, however, the reactions at the anode and cathode differ depending on the choice of electrolyzer. To support future projected demand for green hydrogen production, four types of electrolyzers are being considered as potential technologies: alkaline (Alk), anion exchange membrane (AEM), proton exchange membrane (PEM), and solid oxide electrolyzer cell (SOEC).

Increasing patents across hydrogen production technologies have specifically been driven by innovation in electrolyzers. Electrolysis technologies are currently the most promising method for producing hydrogen from water. There are four families of electrolyzers of varying technological maturity levels that are currently available on the market (IRENA 2020):

Figure 3 | SEGMENTS OF A GREEN HYDROGEN SUPPLY CHAIN



Source: WRI analysis.

i. **Alk Electrolyzers:** They are the oldest of electrolysis technologies and are currently the most deployed globally with a steady flow of improvements and inventions over the recent years.

ii. **PEM Electrolyzers:** They are the second most preferred technology globally due to their durable lifetime and better efficiency than Alk electrolyzers. Their International Patent Families (IPFs) have been consistently higher than that of alkaline electrolyzers with an average compound growth rate of 12.5 percent in technological innovation (IEA 2022).

iii. **SOEC electrolyzers:** They are currently at a precommercial demonstration phase and are one of the most promising electrolysis technologies with even higher efficiencies. Their IPFs have been growing consistently over the 2011–2020 period with an average compound growth rate of 13.5 percent (IEA 2022).

iv. **AEM Electrolyzers:** Currently less mature compared to other electrolysis technologies, AEM technologies are at still at prototyping stages for large-scale deployment. Although the IPFs remain small as compared to other electrolysis technologies, they are growing rapidly at an average compound growth rate of 11.3 percent during 2011–2020 (IEA 2022).

Each of these technologies require raw minerals, such as platinum, palladium, iridium, nickel, zirconium, lanthanum, and yttrium, as an input for manufacturing. Based on the electrolyzer technology, the raw mineral requirement16 for manufacturing varies as shown in Table 2 below. PEM technology requires critical minerals like platinum, whereas SOEC are more dependent on rare earth minerals, and the alkaline technology is relatively less dependent on rare earth minerals compared to the latter.

According to the International Energy Agency (IEA), it is projected that the global electrolyzer capacity could reach 134-240 GW by 2030, considering projects in their nascent stages reach completion (IEA 2022b). To effectively meet this projected demand for electrolysis-based hydrogen, it is imperative to establish an adequate global manufacturing capacity for electrolyzers, necessitating the need for a comprehensive assessment and optimization of supply chains. However, based on statements from various companies, it is estimated that global manufacturing capacities could reach 65 GW and potentially exceed 105 GW annually by 2030 when factoring in projects without specified commissioning years (IEA 2022).

3.1.1.2 FUEL CELLS

Fuel cells are electrochemical cells that produce electricity through the reduction-oxidation of a fuel (in this case hydrogen). Although they are similar to electrolyzers and the fundamentals of a hydrogen fuel cell remain the same, the variation in composition of electrodes and operational characteristics of the fuel cell depend on the technology type. Common technology options for hydrogen fuel cells include PEM, Alk, phosphoric acid, solid oxide, and molten carbonate fuel cells. Fuel cell applications are primarily for converting hydrogen to electrical power and can be used in stationary as well as transportation applications.

Raw materials needed for the manufacture of electrolyzers and fuel cells first requires deposits of the natural mineral ores and then capabilities particularly focusing on mining and materials processing. Developing such material processing capabilities requires specialist engineering companies, including metals coating and semiconductor manufacturing.

Table 2 | **CRITICAL AND RARE EARTH MINERALS REQUIRED TO MANUFACTURE 1 MW OF ELECTROLYZER BY TECHNOLOGY TYPE**

CRITICAL MINERALS AND RARE EARTHS REQUIRED	MINERALS REQUIREMENTS			FOR TARGET OF 240 GW BY 2030		
	PEM	ALK	SOEC	PEM	ALK	SOEC
	kg per MW			tonnes		
Platinum	0.3			17		
Palladium	0.05			3		
Iridium	0.7			40		
Nickel		800	175		1,34,400	2520
Zirconium		~100	40		16,800	576
Lanthanum			20			288
Yttrium			5			72

Source: Author compilation based on IEA (2022c) and CEEW (2023).

The requirement of critical raw minerals and rare earth metals as inputs for manufacturing leads to a greater reliance on transportation and trade of these raw materials, resulting in complex and vulnerable supply chains due to concentrated and limited availability as well as high environmental impact during extraction and refining (CEEW-IEA-UC Davis-WRI 2023). These critical raw materials differ for each component across technologies and include nickel, platinum group metals (PGM) such as palladium, iridium, and platinum, along with other rare earth minerals such as zirconium, lanthanum, yttrium, which are the most vulnerable in the raw minerals supply chain. The critical elements required for the manufacturing of electrolyzers, and fuel cells are listed in Table 3.

3.1.2 TECHNOLOGY & MANUFACTURING

In addition to access to the raw minerals used for manufacturing, it is also essential to have technology and manufacturing capabilities as well as technical expertise to develop and manufacture various niche components across the hydrogen value chain.

Countries with advanced technological and processing capabilities would be best suited for manufacturing of technically complex components like electrolyzers and fuel cells. Several components that are nonspecific to hydrogen, such as heat exchangers, pumps, compressors, feed tanks, rectifiers, and transformers, could be manufactured relatively easily in comparison to core stack components, such as electrodes assemblies, electrolytes, and separators.

Based on the technology manufacturing requirements and complexity of the subcomponents for a fuel cell and electrolyzer, a unique combination of manufacturing expertise, subcomponents, and critical mineral processing capabilities may be required. Specialty chemicals required in the manufacturing process are also proprietary or patented by a few companies globally.

Along with manufacturing capabilities, it is also essential to develop process and assembly capabilities and access to a skilled workforce and companies with technology expertise and the

Table 3 | **COMPONENT AND MATERIAL LEVEL REQUIREMENT FOR ELECTROLYZERS AND FUEL CELLS**

	MAIN COMPONENT	SUB-COMPONENT	ALKALINE	PEM	SOE
ELECTROLYZER & FUEL CELL	**Stack**	**Electrode/Catalyst**	Ni coated perforated stainless steel	Platinum nanoparticles on carbon black/ Iridium oxide $Ir0_2$	Perovskite-type (e.g. YSZ*, LSCF, LSM
		Electrolyte	Alkaline solution (KOH)	Solid Polymer Membrane (PFSA)	$Zr0_2$ ceramic doped with Y_20_3
		Bipolar Plate	Nickel-coated stainless steel	Platinum/Gold-coated titanium	Cobalt-coated stainless steel
ELECTROLYZER (BOP)	**De-oxo dryer unit**	**De-oxidiser**	Carbon steel		
		Dryer	Carbon steel		
		Heat Exchanger	Stainless Steel 316/ titanium	Stainless Steel 316	N/A
	De-ionised water unit	**Ion polishers**	Composite Polyethylene		
		Buffer tank	Polypropylene		
		Cardon dioxide scrubber	Composite PE		
		Filters	PP & PVC-C		
	Piping	-	PE100/Stainless or carbon steel		

Sources: Author compilation based on Scottish Government (2022); IRENA (2020).

*Note: * YSZ: yttrium-stabilized-zirconia; LSCF: lanthanum strontium cobalt ferrite; LSM: lanthanum strontium manganite: $Zr0_2$: zirconium dioxide; Y_20_3: yttrium oxide.*

knowhow to manufacture the final products. Furthermore, proficiency in process, precision, machine, and electrical engineering paired with electrolyzer or fuel cell testing facilities is essential for enabling the development of the green hydrogen ecosystem. By customizing processes and technologies for high-volume manufacturing, economies of scale could be achieved for production. These initiatives can also drive further advancements in technology and system integration, resulting in significant cost reductions. Key areas of focus (DOE 2020b) include the development of

- High-speed manufacturing techniques (forming, stamping, molding, sealing, joining, coating, roll-to-roll processing)
- Optimal material and component handling practices
- Additive and automated manufacturing or assembly processes
- In-line diagnostics and quality control or assurance technologies
- Defect reduction through sensors and other high-throughput production technologies
- Efficient recycling/upcycling methods, particularly for critical materials (DOE 2020).

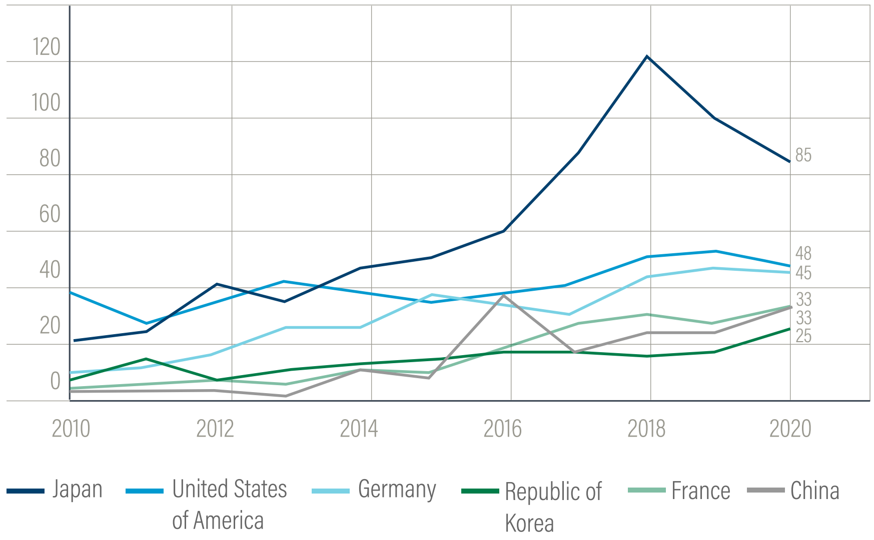
Table 4 | **COMPLEXITY OF COMPONENT MANUFACTURING FOR ELECTROLYZERS AND FUEL CELLS**

	COMPLEX COMPONENTS (PATENT CONTROLLED OR PROPRIETARY)	GENERIC COMPONENTS (EASY TO SCALE MANUFACTURING)
ELECTROLYZER	▪ Electrodes ▪ Electrolyte ▪ Separator ▪ Bi-polar Plates	▪ Transformers & rectifiers ▪ Water treatment plants ▪ Cooling unit ▪ Piping & cabling ▪ Control systems
FUEL CELLS	▪ Membrane electrode Assemblies ▪ Bi-polar plates ▪ Fuel cell stacks	▪ Power conditioner ▪ Air compressor ▪ Thermal management modules ▪ Control systems

Sources: Author compilation based on Volta Chem (2023); Scottish Government (2022).

Research on hydrogen production via water-based electrolysis has gained momentum due to its adaptability to different power sources. China's patent filings, primarily focused on the domestic market, have contributed significantly to this trend. However, it is important to acknowledge that different filing strategies by different stakeholders contribute to the overall statistics. To address this, the concept of International Patent Families (IPFs) has been introduced, which considers both the geographical coverage of patent families and the applicant's country. IPFs related to water electrolysis are led by Japan, the United States, and Germany, accounting for approximately 52 percent of the total IPFs from 2005 to 2020. Despite China’s primary domestic orientation, it has witnessed an increase in IPFs of about 38 percent as compared to Japan, which has experienced a decline of about 30 percent per year in recent years (IRENA 2022a). (See Figure 4.)

Figure 4 | **PATENTING TRENDS IN ELECTROLYSIS TECHNOLOGIES**



Source: IRENA (2022a).

3.1.3 GREEN HYDROGEN PRODUCTION

Green hydrogen production through electrolysis requires an electrolyzer, powered by renewable electricity, and de-ionised water as a feedstock. Based on the specific electrolyzer technology, it takes anywhere between 45 and 52 kWh of renewable electricity and 9 kgs of de-ionised water to produce 1 kg of green hydrogen (IRENA 2022b). Hydrogen transportation, distribution, and storage, including pipeline and vessel or vehicle transportation, underground caverns, above-ground (tank) storage, and refueling stations, are also needed to transport and supply the green hydrogen to final end-use applications.

Several countries have already set targets for green hydrogen production through their national hydrogen strategies or hydrogen road maps. With the exception of Mexico, Brazil, and Turkey, all other G20 countries have either a 2030 or 2050 target for green hydrogen.

3.1.3.1 ELECTROLYZERS

Scenario studies predict that by 2050, around 85 percent of the world's hydrogen supply will come from low-carbon pathways, with electrolysis alone accounting for approximately 60 percent (DNV 2022). It is estimated that by 2030, nearly one-third of the global hydrogen supply will be obtained from low-carbon sources.

Based on these scenarios, electrolysis could dominate future global green hydrogen production. Installed electrolyzer capacity is expected to reach 5.5 GW by the end of 2023, provided that the announced projects are completed on schedule (IEA 2022b). It is anticipated that by 2030, the world's electrolyzer capacity could reach 134–240 GW if projects in their early stages of development are considered. This could grow dramatically to over 3,000–5,000 GW by 2050, with electrolyzers contributing around two-thirds of total green hydrogen production (IRENA 2023a).

3.1.3.2 RENEWABLE ELECTRICITY

Renewable electricity utilization for hydrogen production is anticipated to be crucial in achieving long-term decarbonization objectives and enhancing energy security. Presently, renewable energy sources contribute less than 1 percent to global hydrogen production (IEA 2022a), but there is growing policy focus on hydrogen. Projections for 2022–27 indicate that approximately 50 GW of renewable capacity will be allocated for hydrogen production, constituting around 2 percent of the total growth in renewable capacity (IEA 2023b). The addition of new capacity around the world is equally divided between solar and onshore wind installations. However, the distribution of regional shares varies, depending on the availability of resources.

Although not all scenarios provide insights on the power source for electrolyzers, it is estimated that by 2050, at least 90 percent of electricity used will be low carbon. Under the projected average hydrogen demand scenario, 6,244 TWh of electricity would be required by 2030 (JRC 2022). Meeting the electricity demand for green hydrogen production via electrolysis would require dedicated solar and/or wind installations to scale up 170 percent from the global installed capacity of about 1,952 GW in 2022 (IRENA 2023b). For context, this installed capacity of wind and solar would have generated about 3,770 TWh of renewable power primarily for the electricity sector, and not specifically allocated for hydrogen production. [This number is based on the installed capacity and global average capacity utilization factor (CUF) of solar—17 percent—and wind—28 percent (JRC 2022)].

Furthermore, the electricity demand for hydrogen production between 2030 and 2050 is expected to increase to 21,000 TWh under the same projected average scenario (JRC 2022). The demand for renewable electricity for green hydrogen production highlights the need for additional renewable energy capacity installations to meet the combined generation needs of the electricity sector and green hydrogen (IEA 2022c).

3.1.4 STORAGE, TRANSPORTATION, AND DISTRIBUTION

While different storage options are available, further research is required to better estimate the requirements for safety, viability, and economics of hydrogen transportation. Critical raw materials needed for manufacturing of hydrogen storage and transportation technologies (Table 5) can be sourced relatively easier than the rare earth and platinum group metals needed for electrolyzers but are still expensive due to high input costs and complex manufacturing processes.

Essential capabilities for manufacturing hydrogen storage and transportation technologies entails proficiency in alloying and mining of metals at large scale. These raw minerals primarily include aluminium, manganese, steel, iron, and bronze, which can be sourced easily in the global market and are less vulnerable to supply chain disruptions. The technological expertise and manufacturing capabilities are the most critical aspect in the supply chain of storage and transportation for hydrogen. The cost of hydrogen transportation overseas or internal distribution is a critical driver for green hydrogen's economic feasibility.

The pace of innovation across hydrogen's storage, transportation, and distribution can be gauged based on the patents filed for various technologies. In the period 2011–2020, top industries across the chemical, automotive, and equipment manufacturing sectors led the innovation in technologies accounting for 43 percent of IPFs related to gaseous storage, 31percent for liquid storage, 46 percent for refueling, and 21 percent for networks and equipment. Patent filing led largely by

Table 5 | **HYDROGEN STORAGE AND TRANSPORTATION TECHNOLOGIES**

	MAIN COMPONENT	SUB-COMPONENT	MATERIALS
STORAGE TANKS	Type-I Cylinder	All metal	Steel/aluminium
	Type-II Cylinder	Metal liner	Aluminium
		Hoop wrapping	Carbon fiber
	Type-III Cylinder	Metal liner	Aluminium
		Composite wrapping	CFRP
	Type-IV Cylinder	Plastic liner	Polymer liner
		Composite wrapping	CFRP
GEOLOGICAL STORAGE	Salt cavern	Transmission pipeline	Carbon steel, internal coating
	Depleted gas fields		
PIPELINE	Transmission pipeline	-	Carbon steel/low alloy steel
	Gaskets	-	PTFE/PFA/FRP
	Valve	-	Cast iron/bronze
	Internal coating	-	Epoxy-based flow coat materials
SHIPPING (AMMONIA)	Storage vessels	Inner tank	Carbon-manganese steel
		Outer tank	Carbon-manganese steel
		Insulation	Flat aluminium barrier
		Support/load bearing rings	Lignostone wood

Source: BEIS (2022b).

Note: CFRP: Carbon fiber-reinforced plastic; PTFE: polytetrafluoroethylene; PFA: perfluoroalkoxy alkane; FRP: fiber reinforced polymers.

industries rather than academia suggest that these technologies are close to attaining a high level of maturity and are focused on incremental innovation and cost reduction to meet increasing demand across the hydrogen value chain (IEA 2023c).

The EU emerges as a frontrunner in well-established technologies that support the storage and transportation of hydrogen. Half of the published IPFs pertain to liquid storage, while 38 percent focus on gaseous storage. Additionally, 39 percent of IPFs are related to refueling, and 32 percent are associated with networks and relevant equipment. The United States has notably contributed to patenting activities in networks and equipment (26 percent), but its IPF shares in other established hydrogen storage technologies remain relatively low. In comparison, Japan has displayed greater involvement accounting for 28 percent of IPFs in gaseous storage, 19 percent in liquid storage, 18 percent in networks and equipment, and 32 percent in refueling (IEA 2023c). (See Figure 5.)

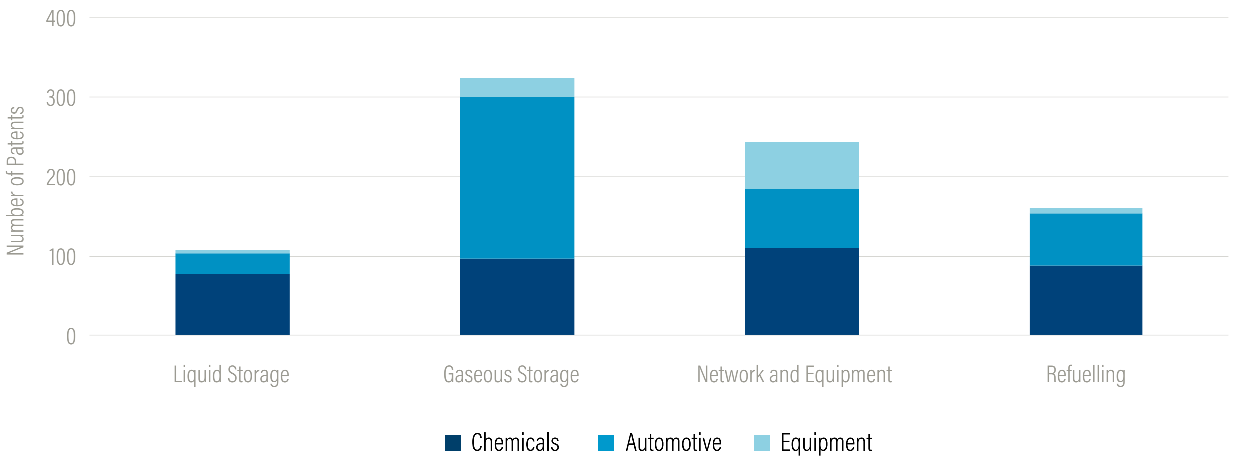
3.1.5 END-USE APPLICATIONS FOR GREEN HYDROGEN

Green hydrogen has applications as both an input chemical feedstock (manufacture of ammonia, methanol, refining, steel) as well as an energy carrier (in fuel cells, energy storage, transportation fuel, and process heating). Current applications of hydrogen are dominated by fertilizer production and petroleum refining, along with other sectors, such as methanol and steel. However, green hydrogen holds the potential to reduce carbon emissions in hard-to-abate sectors such as iron and steel refining, transportation fuel (heavy-duty vehicles, shipping, rail, and aviation), high-temperature industry process heating, and power generation (FCHEA 2023).

The rate of transition to a green hydrogen-based economy will be determined by two key parameters: ease of adoption and cost of adoption. Based on these two parameters, the order for green hydrogen adoption that is most likely to fructify, as illustrated in Table 6.

The initial adoption stage of green hydrogen is predicted to be in existing hydrogen applications with green hydrogen driving the majority of incremental hydrogen capacity expansion over the next decade. In upcoming or new use cases or applications, green hydrogen adoption is likely to be comparatively slower.

Figure 5 | **PATENTS ACROSS HYDROGEN STORAGE AND DISTRIBUTION TECHNOLOGIES AND RELATED EQUIPMENT**



Source: IEA 2023c.

Table 6 | **EASE AND COST OF ADOPTION FOR GREEN HYDROGEN**

	HIGH EASE OF ADOPTION	LOW EASE OF ADOPTION
LOW COST OF ADOPTION	**Early adoption with immediate term policy push and limited fiscal support** ▪ Refineries ▪ Fertiliser plants ▪ Chemical manufacturing	**Medium term adoption with policy push** ▪ Blending with Natural Gas ▪ Synthetic Fuels ▪ Power Generation
HIGH COST OF ADOPTION	**Medium term adoption with large fiscal support** ▪ Long-distance road ▪ Shipping and Maritime ▪ Steel production	**Policy focus dependent on technology breakthroughs and large-scale fiscal support** ▪ Energy Storage ▪ High-heat industrial processes

Source: Author compilation based on IRENA (2022b).

Global targets for green hydrogen project development reveal that the speed of adoption in the future years will vary greatly among industries. Shipping, iron and steel, and chemicals all have significant potential future need for hydrogen and hydrogen-based fuels but need advancement of technology and modifications in process engineering for hydrogen adoption (IEA 2023c).

Recent technological developments in end-use applications of hydrogen have been primarily driven by established applications of hydrogen to produce methanol and ammonia. This is because ammonia and methanol for fuel applications offer competitive advantages over pure hydrogen owing to extensive existing infrastructure and trade of ammonia as a commodity. Electrically heated reactors for ammonia synthesis, for example, have the potential to remove the need for fossil fuels if hydrogen is obtained by water electrolysis.

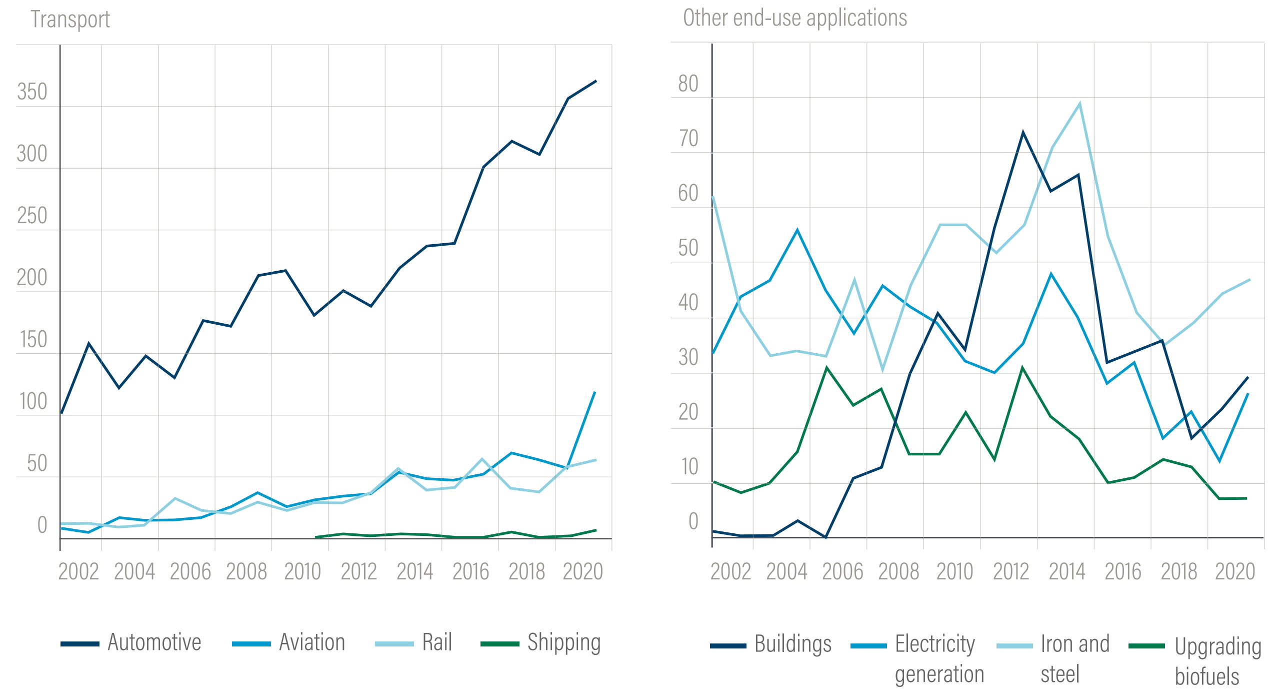
From 2002 to 2020, the number of patent applications related to hydrogen's applications across various sectors has also grown steadily. The transportation sector has been particularly active in filing patents for hydrogen applications, with the automotive industry being a major contributor (DOE 2020). In recent years, many automakers have been investing in the development of hydrogen fuel cell vehicles, which has led to a surge in patent filings related to fuel cell technology as seen in Figure 6.

3.2 FACTORS FOR ESTABLISHING A GREEN HYDROGEN SUPPLY CHAIN

Based on the hydrogen strategies and road maps of individual nations, the priorities of these nations to develop supply chains for hydrogen will depend on factors such as their economic readiness, existing industrial setup for production and manufacturing, and availability of resources including renewable energy and raw minerals (Riera and Lima 2023).

As of 2022, there is limited deployment of green hydrogen production facilities as well as transportation or distribution infrastructure for hydrogen across the globe. Therefore, G20 nations must plan to develop existing and new infrastructure for harnessing their renewable energy resources, scale

Figure 6 | **PATENTING TRENDS FOR END-USE APPLICATIONS OF HYDROGEN**



Source: IEA 2023c.

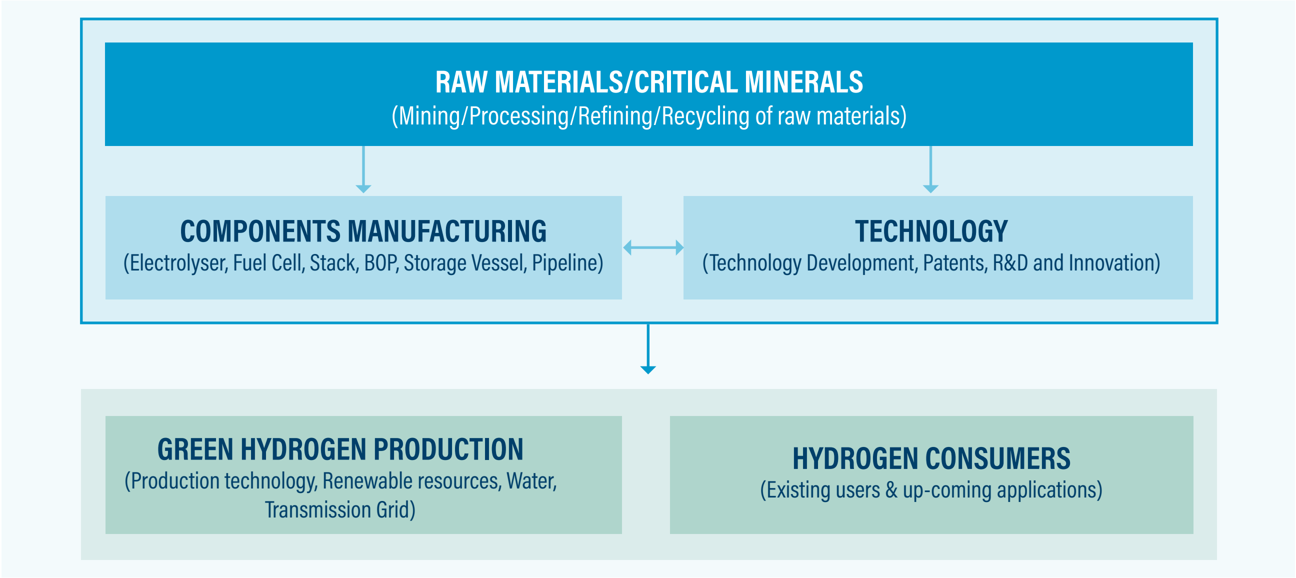
manufacturing, and domestic and international demand (for export focused nations) to capture segments of the green hydrogen supply chain.

Based on the availability of natural resources, manufacturing proficiency, and economic capabilities, countries can have none, one, or two or, in rare cases, all five parameters listed in Figure 7—i.e., raw materials and critical minerals, technology development and research for niche green hydrogen technologies, expertise and capacity for equipment and component manufacturing, and resources for green hydrogen production and green hydrogen consumers for end-use application.

Abundant availability of rare earth and critical minerals would ideally position a country as a partner to nations that have the technology expertise and manufacturing capabilities for equipment like electrolyzers, and fuel cells. Similarly, nations with plentiful renewable energy resources would be ideal producer nations for green hydrogen, and countries with a strong industrial base and inability to produce their own green hydrogen would become potential consumers of green hydrogen.

Although it is unlikely that a single country would have access to all five parameters required for a fully integrated green hydrogen supply chain, there might be a few countries that check the boxes for more than one parameter. Therefore, it is essential that the G20 nations work together to develop diversified supply chains and leverage each other's strengths to accelerate the development of a supply chain and meet global targets for green hydrogen production. The road toward a global green hydrogen ecosystem is not just a function of technical and economic factors. The emergence of a green hydrogen economy will need to be shaped through bilateral and multilateral relationships that are vital to creating resilient and robust supply chains. (See Figure 8.)

Figure 7 | **FOCUS OF COUNTRIES FOR DEVELOPING A GREEN HYDROGEN SUPPLY CHAIN**



Source: WRI India

Figure 8 | **G20 COUNTRIES HYDROGEN ECOSYSTEM ANALYSIS**

Sources: Author compilation based on USGS (2023), CEEW (2023), CEEW-IEA-UC Davis-WRI (2023).

3.3 KEY RECOMMENDATIONS FOR G20 TO DEVELOP SUPPLY CHAINS FOR GREEN HYDROGEN

CHANNELIZE INVESTMENTS AND DEVELOP INFRASTRUCTURE FOR TRADE AND MOVEMENT OF GOODS

A significant amount of investment is expected across the board (mining to commissioning) to accelerate the development of a green hydrogen supply chain. The green hydrogen value chain is expected to create opportunities for many nations from movement of the raw minerals to the flow of green hydrogen derivatives like green ammonia or methanol. It is critical for countries to conduct an assessment to understand the need for investment and development of infrastructure to support the green hydrogen value chain.

These investments could be toward development of ports, pipelines, hydrogen hubs, or storage bunkers. As demand for green hydrogen and its derivatives (ammonia, methanol, green steel, and so on) increase, there will be a need to create import and export capabilities to meet their demand.

PROMOTE RESEARCH, INNOVATION AND COLLABORATION TO REDUCE DEPENDENCE ON CRITICAL MINERALS

Developing technologies such as fuel cells and electrolyzers with reduced dependence on critical minerals or alternative materials that are abundantly available can reduce mineral intensity for rare earth and critical minerals. Promoting collaborative innovation through joint calls for research and providing fiscal and monetary incentives for focused research outputs to be shared globally can reduce dependence on critical minerals and make supply chains more resilient and robust.

TRACKING GLOBAL MANUFACTURING AND TRADE DATA ACROSS THE SUPPLY CHAIN

With countries scaling their targets for green hydrogen production and electrolyzer manufacturing capacities, it is essential to understand the flow (quantum of materials) of these critical and rare earth minerals that go into the manufacturing of these products. Sharing manufacturing and trade data, along with ensuring accountability, can improve the efficiencies and support end-of-life recycling of these systems as a majority of the critical minerals can be recycled back into manufacturing, reducing the environmental burden of mining and extraction.

ACCESS TO ELECTRICITY FROM RENEWABLE SOURCES

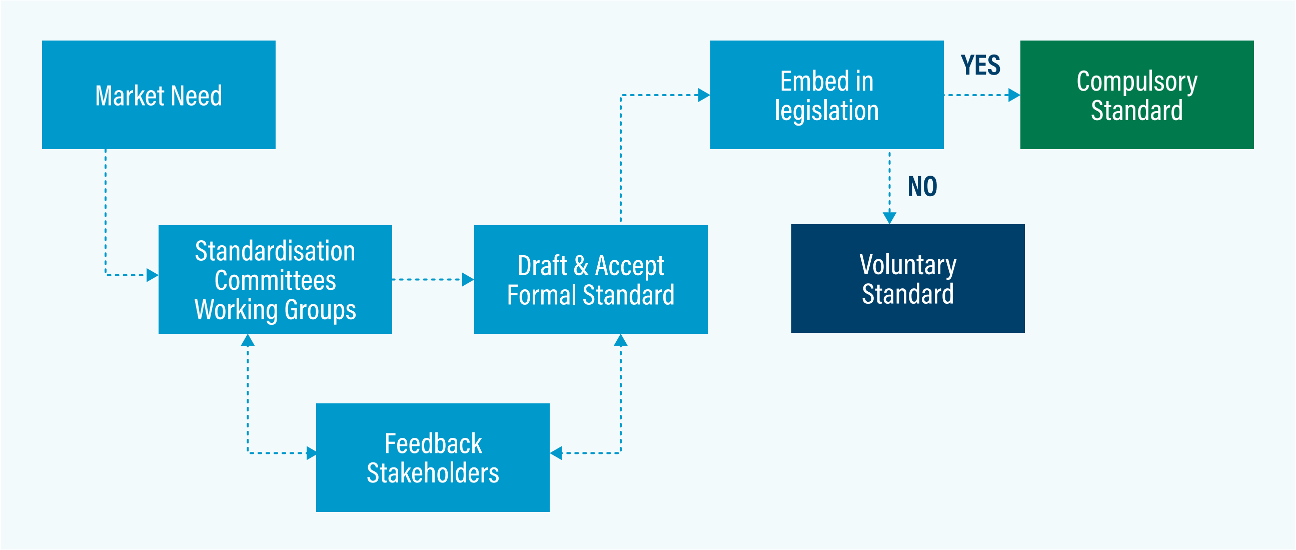
Production of hydrogen from electrolyzers at scale, would require large quantities of renewable energy generation. Failure to generate and supply electricity from renewable sources can compromise the sustainability of green hydrogen production. Therefore, it is also essential to ensure that supply chains and manufacturing capacities for renewable energy installations are also developed in parallel.

4. FRAMEWORK FOR GREEN HYDROGEN STANDARD AND CERTIFICATION

Harmonization of technical and regulatory standards across the hydrogen value chain is crucial to proving the sustainability and low-carbon nature of hydrogen production. Although there are many independent green hydrogen certification and standards, there is no globally accepted standard. Multiple standards and regulations among countries might impede ecosystem growth since producers, exporters, and importers may need to build capacity to adhere to various standards and norms for the same product across geographies. It is vital that globally acceptable green hydrogen standard and certification mechanisms are developed to enable accelerated adoption and reduce barriers for trade of green hydrogen. The process for developing a standard is illustrated in Figure 9.

While countries pursue low-carbon hydrogen options, the development of a metholdology for a low-carbon hydrogen standard including green hydrogen is expected to be an integral part of decarbonization strategies of many G20 nations. Organizations such as the International Partnership for Hydrogen and Fuel cells (IPHE), CertifyHy, TUV SUD, and the Green Hydrogen Organization, are developing these methodologies for classification of low-carbon hydrogen, including green. Some of these organizations are also providing certification mechanisms for the classification of low-carbon and green hydrogen. Organizations such as IPHE, based on international governmental partnership consisting of 21 member countries and the European commission, have

Figure 9 | **PROCESS FLOW FOR THE IMPLEMENTATION OF A FORMAL STANDARD**



Source: Abad and Dodds (2020).

established a working group specifically focussed on regulations, codes, standards, and safety, along with task forces for hydrogen production and trade. (See Table 15.)

CertifyHy (CertifyHy 2023), a consortium of public and private agencies that includes producers, consumers of hydrogen, and regulators, has developed hydrogen certification mechanisms catering to various compliance norms, including RED II (IEA, 2022b). Similarly, organizations such as ISCC, which is an established global voluntary scheme recognized by the EC, has aimed to expand its portfolio toward classifying green hydrogen (EC 2023). TÜV SÜD, a technical testing, inspection, and certification agency, has also published a voluntary hydrogen standard in place for the transportation sector and a CMS 70 standard for the industry (TÜV SÜD 2021).

Despite the presence of multiple such standards and certification mechanisms, given the nascency of the green hydrogen ecosystem, there is yet to be an internationally recognized standard or certification mechanism that is interoperable across multiple geographies. This chapter highlights the opportunity for the G20 nations to work toward recognizing a framework or methodology for classification and certification of green hydrogen to accelerate its adoption.

4.1 GREEN HYDROGEN CERTIFICATION

A green hydrogen standard would essentially prescribe the scope of emissions (direct and indirect) and eligibility criteria for various production pathways, along with the boundary conditions for estimating emissions and the threshold on GHG emissions. The certification mechanism will validate that the hydrogen produced is compliant with the sustainability criteria set by the green hydrogen standard. Agreement among the G20 nations on the methodology for such a standard would be a crucial step toward defining green hydrogen based on a quantitative assessment of GHG emissions. This standard can then be adopted by various certification bodies to issue proof of the low-carbon nature of hydrogen, ensure compliance through audits and testing, and enable the issuance of green hydrogen certificates.

To quantify the low-carbon nature of the hydrogen or the derivatives it produces, it is essential that the certification process consider the entire value chain of hydrogen production and supply as shown in Figure 2. The certification process based on the hydrogen standard must consider the sustainability dimensions across various segments of the hydrogen value chain, described as follows (IEA 2023a; Sino-German Energy Partnership 2023):

1. Technology and Production Pathway
This includes renewable energy projects, electrolysis technologies, sea water desalination plants, and production technologies for hydrogen and its derivatives.

2. System Boundary
The certification process can cover various segments of the hydrogen value chain, such as a well-to-gate system boundary, which encompasses a supply of fuel used in the hydrogen production process. Alternativerly, a well to point of delivery or well to gate system boundary would include the transportation of hydrogen up to the point of consumption.

3. Scope
Consideration of scope 1 (direct) and scope 2 (indirect) emissions must be defined within the certification mechanism. Most existing and proposed certification schemes currently cover both direct and indirect emissions associated with electricity generation, including upstream and midstream emissions.

4. Emission Intensity

The certification mechanism must establish that the GHG emissions per unit of hydrogen produced must be within the threshold emissions limit as determined by the hydrogen standard.

5. Treatment of Derivatives

While current certification schemes only consider the production of hydrogen, the scheme must also be capable of certifying the sustainable nature of derivatives produced from green hydrogen, such as ammonia, methanol, and steel.

Along with the value chain considerations, the certification process must also ensure that the resources consumed to produce hydrogen meet the requirements as per the hydrogen standard. Thus, a life-cycle analysis (LCA) of the hydrogen production pathway is necessary for all forms of hydrogen since it would define the criteria and requirements that encompass all segments of the hydrogen production process, including mining for raw materials, manufacturing of components (including electrolyzers and renewable energy), transportation and distribution, water consumption, and social economic aspects. The LCA must take into consideration the sustainability criteria of various segments of the hydrogen production value chain mentioned earlier to enable a holistic assessment of the environmental and social impact.

The certification should also consider sustainability of immediate GHG emissions related to establishment of infrastructure; supply and usage of currently available technologies; raw materials for manufacturing; electricity, water, and other input materials for producing hydrogen; land use; and constraints that would occur in the transitional period during project development.

It must be noted that aiming to cover all sustainability criteria immediately may prove to be a huge burden for project developers. A modular approach must be employed by regulators and certification agencies, starting from the emissions intensity of production and then moving on to encompassing other criteria. A comprehensive list of sustainability criteria that a green hydrogen certification would have to ultimately address is highlighted in Figure 10.

4.1.1 KEY STAKEHOLDERS FOR GREEN HYDROGEN STANDARD & CERTIFICATION

There are several key stakeholders that would have to work collaboratively to classify and certify the low-carbon nature of green hydrogen. The process of certifying green hydrogen by a certification body must meet the evaluation criteria set by the organization that develops the green hydrogen standard. Several existing and proposed certification mechanisms and standards for green hydrogen have already been developed by public-private consortia and certification agencies.

An accreditation body is responsible for overseeing and regulating activities of a certification body, given the international presence of accreditation bodies for various certification activities, no new accreditation bodies are expected to emerge specifically for hydrogen (BEIS 2022).

The stakeholders are mentioned in Table 8, along with public and private market participants, would be responsible for implementing and adhering to the proposed certification scheme. Compliance and acceptance of these standards, however, is limited to geographies where these standards were originally developed; and most of them are yet to gain international acceptance across borders.

Figure 10 | SUSTAINABILITY CRITERIA IN HYDROGEN PRODUCTION AND SUPPLY TO BE CONSIDERED BY A CERTIFICATION SCHEME

ELECTRICTY SUPPLY

- Classification of renewable electricity based on various technologies
- Emissions from electricity generation, including electricity used for desalination, conversion of hydrogen into derivatives
- Impact on electricity grid due to large-scale demand from hydrogen production
- Socioeconomic and ecological impacts due to additional renewable electricity demand

WATER SUPPLY

- Availability of fresh water and diversion from exisiting applications
- Sea water desalination and brine disposal with low ecological impact

TRANSPORT OF HYDROGEN

- Energy consumption for transportation (including compression, liquefication, & conversion)
- Losses during transportation (boil-off for liquefied transportation)

LAND USE AND BIO-DIVERSITY

- Competing and alternative land use
- Ecology and biodiversity impact of land conversion
- Socio-cultural significance of land

SOCIO-ECONOMIC IMPACTS, HUMAN RIGHTS & SAFETY

- Human rights for the workforce across the value chain
- Potential of value addition through exports of hydrogen and derivaties
- Safety issues, handling of hazardous goods, health of workers and local population

RAW MATERIALS

- Raw material mining for electrolyzers, fuel cells, renewable energy plants including rare earth elements
- Ecological impact on environment of extraction, refining, transportation, and recycling

Source: Oeko-Institute (2021).

Table 7 | KEY ACTORS AND THEIR FUNCTIONS

KEY ACTOR	FUNCTIONS
STANDARD DEVELOPMENT ORGANIZATION	Defines a set of rules and procedures that outline the product, process, or service to be certified; establishes the stated standards that must be satisfied; and offers the methodology for evaluation.
CERTIFICATION BODY	Assesses a product, method, or service to ensure that the standards stipulated in the certification system have been met.
ACCREDITATION BODY	Checks that the certification body is independent and unbiased and that it can provide the expertise and personnel required for certification.

Source: Australian National University (2020).

4.2 CURRENT GREEN HYDROGEN STANDARDS & CERTIFICATIONS

Hydrogen that meets certain sustainability criteria has been termed as green hydrogen. Although there are already multiple standards across various regions for classification of green hydrogen, there is variance in how sustainability of green hydrogen is defined and where boundary conditions for emissions are drawn along the supply chain.

Although both public and commercial institutions are spending significant resources for the development of green hydrogen and derivative certification schemes, their scope and methodologies differ across regions, thus creating barriers for project developers and investors. A group of nations such as the G20 agreeing upon a common methodology for a hydrogen standard, if ratified through legislation, can benefit a large share of the potential global hydrogen market (IEA 2023a).

There are a growing number of terminologies and frameworks for assuring the low-carbon nature of hydrogen production, including certification schemes, guarantees of origin, standards, regulations, rules, codes, classifications, taxonomies, branding, and labeling. While they have some similarities, they also have divergent characteristics. Instead of derivatives like ammonia, most regulations focus on production of hydrogen and emissions within a well-to-gate boundary condition.

Most standards and certifications also include the direct and indirect emissions related to electricity and heat generation, while indirect emissions associated with manufacturing of technologies and aggregation of the required raw materials are typically excluded.

This section aims to highlight existing green hydrogen standards and certification schemes that the G20 can consider for creating a harmonized methodology for classification of green hydrogen as shown in Table 8.

Table 8 | **KEY FEATURES OF CURRENT HYDROGEN CERTIFICATION MECHANISMS**

	CERTIFHY	AUSTRALIAN GO	AEA	SMART ENERGY COUNCIL	GH2	TÜV SÜD
SCHEME TYPE	Certification of low-emissions hydrogen	Certification of quality of information about hydrogen emissions and production	Certification of quality of information about ammonia emissions and production	Certification of renewable hydrogen	Certification of green hydrogen	Certification of Carbon-Neutral Hydrogen
SCHEME OWNER TYPE	Public-private partnership	Public	To be decided	Private	Private	Private
CERTIFICATION TYPE	Third-party conformity assessment	-	-	Third-party conformity assessment	Third-party conformity assessment	Third-party conformity assessment
INTENDED SCHEME GEOGRAPHIC COVERAGE	EU focused at present but expanding	Initially Australian, intended to be international	Internationally	Internationally	Internationally	EU focused
OWNS A MARK OF CONFORMITY	Yes	No	No	Yes	No	Yes

Source: The Australian National University (2020); IEA (2023a).

Based on the priorities and use cases of these various certification mechanisms, the boundary conditions for the certification process, treatment of derivatives or co-products and scope of emissions differ for each mechanism.

The highlights of these individual methodologies used for defining a green hydrogen standard along with the status are given in Table 9:

Table 9 | **ASSESSMENT OF METHODOLOGIES FOR CLASSIFICATION OF HYDROGEN**

AGENCY	STATUS	SCHEME BOUNDARIES	EMISSIONS SCOPE	TREATMENT OF DERIVATIVES	PRODUCTION PATHWAYS	EMISSIONS INTENSITY THRESHOLD (KG CO_2EQ/ KG H_2)
CERTIFHY	Completed pilot program	Well-to-gate (factory)	Scope 1, 2, upstream 3 (feedstock)	not mentioned;	Renewable Electricity	Green Hydrogen: 4.4
					Nuclear Electricity, fossil fuel with CCUS	Low-carbon hydrogen: 4.4
AUSTRALIAN GOVERNMENT GOO	Trials proceeding	Initially, Well-togate (factory) with the intention to extend to cover conversion, storage, and transport	Scope 1, 2, upstream 3 (feedstock)	Discussed in detail;	Renewable Electricity	-
AEA	Discussion paper	Well-to-gate (factory)	Scope 1, 2, upstream 3 (feedstock)	Mentioned as a reporting metric	All	-
Smart Energy Council	The first pilot facility has been certified	Well-to-gate (factory)	Scope 1, 2, upstream 3 (feedstock), a planned expansion for downstream	Details to be published in an audit report	Renewable Electricity	-
GH2 STANDARD	Standard draft (March 2022)	As per IPHE although proposed extensions to storage, transport, and use	As per IPHE with some modification	Developing standards for derivatives	Renewable Electricity	1
TÜV SÜD	Operational	Well-to-gate (factory) with an intention to cover conversion, storage, and transport	Scope 1, 2, upstream 3	not mentioned	Renewable Electricity	1.1
					Biomethane, glycerine	2.3-3.4

Source: Australian National University (2020), IEA (2023a).

4.3 KEY RECOMMENDATIONS FOR HARMONIZATION OF A GLOBAL GREEN HYDROGEN STANDARD AND CERTIFICATION

Although nations are at liberty to adopt a green hydrogen standard and certification mechanism based on their economic, social, and political priorities, the G20 nations can initiate consensus on a standard for enabling a green hydrogen ecosystem. Development of a global hydrogen market would involve nations beyond the G20 members, who could also benefit from the creation of a global market for hydrogen and its derivatives.

Thus, multilateral cooperation efforts need to be accelerated through existing or new hydrogen platforms that are pursuing green hydrogen to explore the possibilities of collaboratively developing a standard definition and certification mechanism for green hydrogen. The authors offer the following key recommendations for the development of a global green hydrogen standard:

ESTABLISH CONSENSUS ON A METHODOLOGY FOR DEVELOPING A GREEN HYDROGEN STANDARD

Through the methodology, various production pathways used to produce hydrogen can be classified, based on the technology pathways and emissions intensity. The methodology must include defining system boundary conditions for calculating the GHG emissions from various hydrogen production pathways and set an indicative emissions benchmark for low-carbon and green hydrogen.

At minimum, the methodology must target the direct emissions from hydrogen production and indirect emissions associated with supply input resources (e.g., renewable energy, water, heat). The methodology for developing a standard must also provide a clear definition of the emissions threshold for green hydrogen production while also retaining the flexibility to accommodate emissions related to transportation to facilitate trade as well as production of green hydrogen derivatives like ammonia and methanol.

ENABLE A GLOBAL CERTIFICATION MECHANISM FOR GREEN HYDROGEN AND DERIVATIVES

Based on the low-carbon hydrogen standard, a global certification mechanism must be developed through international consensus among stakeholders across industry and governments. The green hydrogen certification mechanism must leverage mutual recognition agreements and harmonized standards to facilitate a global acceptance and transferability of the certificates across the G20 nations. Collaboration among the G20 nations through ongoing sustainability initiatives and certification programs to share best practices and ensure compatibility with broader sustainability frameworks can further support the development of a global certification mechanism.

Creating a certification mechanism for green hydrogen by leveraging existing global systems within international standard agencies can simplify the process of establishing a green hydrogen certification. The mechanism must contain the scope for expansion to certify the derivatives produced from the green hydrogen (e.g., ammonia, methanol, green steel).

Leveraging existing institutional structures for standard development and certification mechanisms can provide a ready-made platform for discussions and deliberations and accelerate the process of certification.

DEFINING AND CERTIFYING RENEWABLE ENERGY CONSUMED FOR GREEN HYDROGEN PRODUCTION

Due to the intermittency of renewable energy, most green hydrogen production plants would also have to depend on energy storage and/or energy accounting mechanisms to reliably produce green hydrogen. The renewable energy used for production of green hydrogen must be defined by technology, point of production and consumption, the temporal nature of the renewable electricity, and additionality to ensure development of the renewable energy sector without affecting the transition of the electricity sector.

Many of the G20 nations have already developed certification and tracking systems for renewable electricity. Examples for tracking green electricity include guarantees of origin in Europe, renewable energy certificates (RECs) in India and North America, and international renewable energy certificates, managed by a nonprofit organization, which enable producers to register key information on the electricity produced (i.e., origin, capacity, and so on). Producers of hydrogen can utilize these certificates as proof of purchase and consumption of renewable electricity for green hydrogen production. Given the certificates' widespread adoption in electricity markets, standardizing and adopting a relevant certification mechanism can be applied to green hydrogen production as well.

TRANSPARENT AND COST-EFFECTIVE TRACKING MECHANISM FOR ENSURING COMPLIANCE

A cost-effective tracking system that is transparent in nature and accessible to relevant stakeholders across the green hydrogen ecosystem would enhance the tradeability of green hydrogen and its derivatives. Co-adoption and interaction with existing tracking mechanisms (such as renewable energy) must be carefully evaluated to ensure credibility and accuracy of the tracking system and avoid double counting and unwanted interactions with existing schemes.

Although a tracking mechanism might add to the cost of green hydrogen production, innovative approaches, such as block chain registries, could help reduce the cost of certification and tracking for green hydrogen producers and consumers. The tracking mechanism must be cost effective and transparent without increasing regulatory burdens that escalate costs or delay project development. Both renewable electricity and green hydrogen tracking mechanisms must adhere to transparency, reliability, simplicity, and flexibility and must be facilitative to ensure that green hydrogen production is affordable and reliable.

5. GLOBAL PLATFORMS FOR COLLABORATION ON GREEN HYDROGEN TECHNOLOGIES

According to IEA's Net Zero by 2050 Road Map, R&I across clean energy technologies is essential to meet global climate and energy transition goals. Most of the necessary technologies for reducing carbon emissions to combat climate change, such as green hydrogen, are yet to be fully developed for commercialized operations, especially for hard-to-abate industrial sectors (IEA 2021a).

R&I through international collaboration focused toward developing clean energy solutions is essential to overcome challenges associated with green hydrogen deployment. Directing efforts through existing multilateral forums can distribute costs and risks of innovation across multiple stakeholders, enable best practices in policy development and support development of harmonized standards and regulations.

Through focused R&I collaborations on green hydrogen, G20 nations can scale and accelerate efforts with the intent to have the best minds and infrastructure among nations dedicated to solving critical technology challenges across the hydrogen value chain. The focus will be on evolving an ecosystem that encourages technology transfers, shared innovation, and funding of projects for accelerated development of promising hydrogen technologies.

5.1 ENHANCING INTERNATIONAL COLLABORATION

International collaboration for green hydrogen technologies can be accelerated through initiatives like bilateral and multilateral calls for research, joint research and innovation projects, multilateral funding programs, and demonstration and development challenges. Such initiatives can bring numerous benefits to participating nations, such as facilitation of exchange of knowledge and best practices, accelerated development of hydrogen technologies, and reduction in costs.

Therefore, it is important for G20 nations to deepen institutional cooperation and synergize research programs through multilateral platforms (such as Mission Innovation, CEM, IEA-TCP, and so on) to promote partnerships among industry, academia, and governments and ensure that research and development activities are coordinated and the outcomes effectively distributed among stakeholders.

The Mission Innovation: Collaborative Models for International cooperation in clean energy research and innovation framework illustrates various models for transnational collaborative R&I models that include scope for both intergovernmental cooperation and collaborations through ongoing networks or initiatives by existing international organizations (Mission Innovation 2018), as shown in Table 10.

Table 10 | **COLLABORATIVE MODELS FOR TRANSNATIONAL R&I ACTIVITIES**

MODEL	MODE OF IMPLEMENTATION
Bilateral/multilateral coordinated calls	Two or more nations agree to support R&I activities on mutually beneficial themes with each nation launching separate calls, open for international collaboration. Each nation funds only domestic participants and implements the call autonomously, while projects are selected based on mutual benefits for both nations.
Bilateral/multilateral Joint calls	Two or more nations jointly float a call for proposals based on mutually beneficial themes, the proposals are jointly evaluated. Each participating nation commits a portion of the funding for supporting the selected proposals.
Open call for global participation	A nation can float a global call for proposal to which any foreign entity (including private) can apply, without any funding from the participants' home country. However, there may be limitations on how these funds can be used.
Matching or co-fund mechanism	A nation may provide financial assistance to its own research organization if the organization's proposal is selected in a call for research proposals submitted in another nation. The research organization, if selected, would receive assistance from both its home nation and the nation where the call was floated.
Mutual opening agreements	Open agreements of research programs among nations can enable participation of research teams in project calls for research in each other's nations as well as receive cross-border financial support. In this model, a nation can stipulate its own specific research programs for which participants from partner nations can receive funding.
Collaborative platforms	A collaborative platform is created or an existing platform leveraged to drive research collaborations by connecting multiple research teams and sharing research projects among participating nations. In this model, there is no common funding pool available, and nations support their own research teams.
International research and innovation program with joint funding	Multiple nations agree to establish a joint fund, which is implemented through a single entity (new or existing), e.g., an international development organization that would provide funding to institutions or research consortia.

Source: Mission Innovation (2021).

The operational models in combination with a time-bound and outcome-oriented approach for deliverables that are agreed to beforehand can enable an efficient mechanism for international collaboration. Additionally, these models can promote engagement of industry, academia, and government ecosystems through working groups and task forces. Focused engagement on specific aspects of the green hydrogen value chain can lead to international multistakeholder collaborations on green hydrogen technologies.

Through ongoing initiatives across multilateral forums mentioned in the following section, G20 nations can benefit from exchange of data, knowledge, and best practices and collaborate on joint research, development, and innovation of green hydrogen technologies.

5.1.1 CLEAN ENERGY MINISTERIAL

The Clean Energy Ministerial (CEM) is an international discussion forum tasked with advancing the adoption of renewable energy technologies through creative policies and projects (CEM 2023a). The forum aims to promote the transition to a global clean energy ecosystem while disseminating lessons acquired from global best practises.

The CEM bases its initiatives on areas of shared interest among the member governments and other forum participants. The CEM brings together a community of the biggest nations and top business and international experts under a shared goal of accelerating sustainable energy transitions (Table 11).

Eighteen G20 countries are part of the CEM as members (highlighted in green). Ninety percent of installed renewable energy capacity, 80 percent of all investments in renewable energy, and the majority of public research and development activities are represented by CEM members.

Table 11 | **LIST OF CEM MEMBER COUNTRIES**

G20 MEMBERS	CEM MEMBERS	G20 MEMBERS	CEM MEMBERS
Argentina		Japan	■
Australia	■	Republic of Korea	■
Brazil	■	Mexico	■
Canada	■	Russia	■
China	■	Saudi Arabia	■
France	■	South Africa	■
Germany	■	Turkey	
India	■	United Kingdom	■
Indonesia	■	United States	■
Italy	■	European Union	■

Source: CEM (2023a).

In addition to the 29 member countries, there are 22 participating countries in CEM, along with several leading international organizations and influential stakeholders participating as partners.

CEM's focus on hydrogen

The hydrogen initiative (CEM H2I), which was launched in May 2019, is a voluntary multigovernment initiative based on the CEM framework document. The CEM H2I aims to advance policies, programs, and projects that accelerate the commercialization and deployment of hydrogen and fuel-cell technologies across all aspects of the economy. CEM H21 is run under the auspices of CEM and involves nonbinding agreements between participating national government ministries.

The effort focuses on hydrogen's potential to decarbonize energy systems while also boosting sustainability, resilience, and energy security. The initiative has three primary emphasis areas:

1. Assistance in ensuring the successful deployment of hydrogen in present industrial applications;

2. Enabling the implementation of hydrogen technology in transportation (for example, freight, mass transit, light rail, and maritime); and

3. Investigating the function of hydrogen in satisfying community energy needs.

Five key activities take place under the purview of CEM H2I for cross-sectoral adoption of hydrogen in sectors such as transportation, industries, and heating. Coordinated by the IEA, the following five key activities are led by five co-leads and 18 participating countries:

1. Aspiration Goals
This activity seeks to keep track of all existing national goals or targets, as well as any additional techniques to help integrate hydrogen into long-term strategies (IEA and CEM 2022). The results of this analysis are designed to inform the creation of new CEM hydrogen initiative campaigns that align with government objectives and assist them in accomplishing those objectives.

2. Global Ports Hydrogen Coalition
The coalition aims to improve policy discussions and project-based collaborations in coastal industrial zones to increase the production and use of low-carbon hydrogen and hydrogen-based fuels (IEA and CEM 2021). The coalition expands on current dialogues to investigate the feasibility of incorporating hydrogen into port operations, such as those held by the International Association of Ports and Harbours, the World Ports Climate Action Program, and the Hydrogen Council.

3. Roundtable On North-West European Region
This initiative intends to create a new regional hydrogen market in North-West Europe by bringing together government leaders and major industry stakeholders to identify growth potential, overcome hurdles, and investigate policy and regulatory needs (IEA 2021b).

4. Hydrogen Trade
The goal of this working group is to create a platform to share knowledge, best practices, and experiences (CEM 2023b). The working group ultimately aims to address barriers and define a road map to facilitate the development of an international hydrogen market that can allow hydrogen trade from regions with low-cost hydrogen production potential to regions with high hydrogen demand but limited production capabilities.

5. H2 twin cities initiative
This initiative aims to increase awareness and promote best practises and information exchange on the use of hydrogen and fuel cell technologies at scale in specific areas, towns, and cities through targeted collaborations to speed hydrogen deployment and user acceptability in communities (Office of Energy Efficiency and Renewable Energy 2022).

5.1.2 MISSION INNOVATION

Mission Innovation is an international movement that aims to catalyze action and investment in research, development, and demonstration to make clean energy affordable, appealing, and accessible to all. Mission Innovation hopes to accelerate progress toward the Paris Agreement targets and establish a path to net zero emissions for its member nations. It is a worldwide project spearheaded by 22 nations and the European Commission, on behalf of the European Union. Fourteen G20 countries are part of Mission Innovation as member countries (highlighted in green). There are seven key missions under Mission Innovation, as follows:

Clean Hydrogen Mission: The mission's purpose is to boost green hydrogen's cost-competitiveness by lowering end-to-end prices to a tipping point of $2/kg by 2030 (Mission Innovation 2023). To reach this aim, the Clean Hydrogen Mission will concentrate on the following three areas:

Table 12 | **LIST OF MISSION INNOVATION MEMBER COUNTRIES**

G20 MEMBERS	MI MEMBERS	G20 MEMBERS	MI MEMBERS
Argentina		Japan	■
Australia	■	Republic of Korea	■
Brazil	■	Mexico	Observer Country
Canada	■	Russia	
China	■	Saudi Arabia	■
France	■	South Africa	
Germany	■	Turkey	
India	■	United Kingdom	■
Indonesia		United States	■
Italy	■	European Union	■

Source: Mission Innovation (2023a).

1. Stimulating Research, Development, and Innovation

Determine the top research and development goals that have the most potential to generate cost reductions in manufacturing, distribution, storage, and end-use applications, according to the following R&I priorities:

- Innovation to reduce clean hydrogen production cost, including innovation concerning electrolytic hydrogen

- Large-scale, low-cost hydrogen storage and distribution system, requiring R&I in conversion and reconversion of hydrogen, rehabilitating the existing gas network, optimizing and increasing the efficiency of hydrogen storage, and distribution infrastructure; and.

- Hard-to-decarbonize applications, including decarbonizing steel, ammonia, and cement and manufacturing heavy-duty off-road equipment, such as mining vehicles, agriculture, and construction equipment.

Seventeen countries and the European Commission, including Australia, Austria, Canada, Chile, China, France, Germany, India, Italy, Japan, Korea, Morocco, Norway, Saudi Arabia, the United Kingdom, and the United States voted on topics of interest for R&D and innovation across the hydrogen value chain (Mission Innovation 2021). Members of the working group were thereby encouraged to propose themes and ideas for new R&D projects, webinars, activities, and workshops for consideration to advance the objectives of the broader hydrogen mission.

Snapshots of the focus areas across production, distribution and storage, end-use, and demonstrations are highlighted in Figure 11:

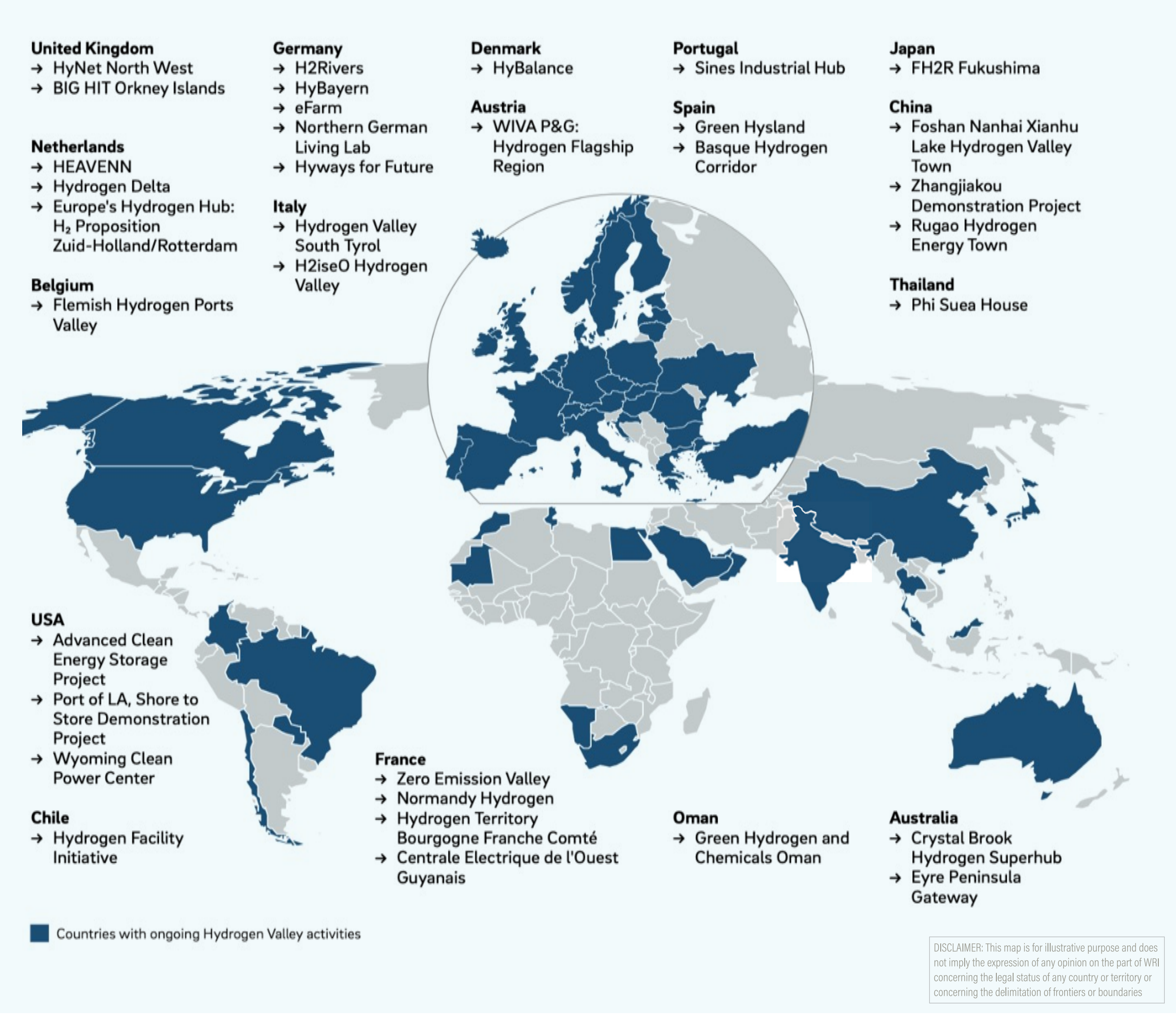
Figure 11 | **FOCUS AREA ACROSS PRODUCTION, DISTRIBUTION AND STORAGE, END-USE, AND DEMONSTRATIONS**

Source: Mission Innovation (2023a).

2. Integrating production, storage, distribution, and end-use applications in hydrogen valleys
Deliver 100 clean hydrogen valleys worldwide by 2030. Total Investment of EUR 33,495 million (Mission Innovation 2023b). Out of these, 37 hydrogen valleys across 20 countries are under development (Figure 12).

3. Preparing the ground for the scale-up of the hydrogen economy
Create a coalition of partners to establish a clear and coherent enabling environment in order to lay the groundwork for the scale-up of the hydrogen economy.

Figure 12 | GLOBAL HYDROGEN VALLEY ACTIVITIES AND EXAMPLE PROJECTS FROM MISSION INNOVATION HYDROGEN VALLEY PLATFORM



United Kingdom
- → HyNet North West
- → BIG HIT Orkney Islands

Netherlands
- → HEAVENN
- → Hydrogen Delta
- → Europe's Hydrogen Hub: H_2 Proposition Zuid-Holland/Rotterdam

Belgium
- → Flemish Hydrogen Ports Valley

Germany
- → H2Rivers
- → HyBayern
- → eFarm
- → Northern German Living Lab
- → Hyways for Future

Italy
- → Hydrogen Valley South Tyrol
- → H2iseO Hydrogen Valley

Denmark
- → HyBalance

Austria
- → WIVA P&G: Hydrogen Flagship Region

Portugal
- → Sines Industrial Hub

Spain
- → Green Hysland
- → Basque Hydrogen Corridor

Japan
- → FH2R Fukushima

China
- → Foshan Nanhai Xianhu Lake Hydrogen Valley Town
- → Zhangjiakou Demonstration Project
- → Rugao Hydrogen Energy Town

Thailand
- → Phi Suea House

USA
- → Advanced Clean Energy Storage Project
- → Port of LA, Shore to Store Demonstration Project
- → Wyoming Clean Power Center

Chile
- → Hydrogen Facility Initiative

France
- → Zero Emission Valley
- → Normandy Hydrogen
- → Hydrogen Territory Bourgogne Franche Comté
- → Centrale Electrique de l'Ouest Guyanais

Oman
- → Green Hydrogen and Chemicals Oman

Australia
- → Crystal Brook Hydrogen Superhub
- → Eyre Peninsula Gateway

■ Countries with ongoing Hydrogen Valley activities

Source: Mission Innovation (2023b).

5.1.3 INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME (IEA-TCP)

The IEA established the Hydrogen Technology Collaboration Programme (IEA-TCP) in 1977 to promote collaborative hydrogen research and information sharing among its member nations. The IEA TCP has enabled and coordinated a wide variety of hydrogen R&D and analytical operations through the establishment and execution of 40 tasks.

With more than 40 years of working history, 26 contracting parties (24 nations plus the EC and UNIDO) and 7 sponsor members, the IEA-TCP envisions a hydrogen future based on a clean, sustainable energy supply that plays a significant role in all sectors of the global economy.

Nine G20 countries are part of the IEA-TCP.

IEA-TCP priorities for R&D and innovation: The IEA-TCP aims to accelerate hydrogen implementation and widespread adoption to optimize environmental protection, improve energy security, and promote economic development internationally (IEA 2021c). The IEA-TCP aims to facilitate coordination, innovation, and R&D activities through international cooperation and information exchange. The IEA-TCP functions in five-year cycles with a strategic term plan that sets out the way forward before the start of a cycle and an end-term report at the end of the cycle.

Table 13 | **IEA-TCP CONTRACTING PARTIES**

G20 MEMBERS	IEA-TCP MEMBERS	G20 MEMBERS	IEA-TCP MEMBERS
Argentina		Japan	■
Australia	■	Republic of Korea	■
Brazil		Mexico	
Canada	■	Russia	
China	■	Saudi Arabia	
France	■	South Africa	
Germany	■	Turkey	
India		United Kingdom	■
Indonesia		United States	■
Italy	■	European Union	Sponsors

Source: IEA (2021c).

IEA-TCP's 2015–20 end-of-term report showcased the aim to champion hydrogen's transformative role as a flexible energy vector. It prioritized the development of hydrogen infrastructure, focusing on storage, safety, and cost reduction. Through productivity and progress, the IEA-TCP aimed to foster closer cooperation with other organizations and promote a broader business orientation. During this period, the IEA-TCP managed 18 tasks in various stages: 5 ongoing, 7 completed, and 6 in the initial stages. Notably, these tasks placed significant emphasis on analysis and production to achieve their objectives.

IEA-TCP's 2020–25 strategic work plan aims to leverage hydrogen's contribution to deep decarbonization and long-term energy system sustainability in various sectors. It will prioritize research and international cooperation with a focus on production, storage, infrastructure, distribution, and safety. The plan seeks to drive global demand for hydrogen and power-to-gas, particularly in high-growth economies, by developing a strong long-distance supply chain and trade. The IEA-TCP also aims to establish itself as a central hub for international collaboration on hydrogen research and development within the IEA Technology Network and the broader energy community.

The IEA-TCP's collaborative research and development focuses on end-use devices, hydrogen production, storage, and hydrogen integration in infrastructure, including hydrogen carriers. The following main tasks are under consideration for the 2020–25 strategic plan's time period (IEA 2022d):

- Task 34 - Biological production and conversion of H_2 for energy and chemicals
- Task 35 - Renewable hydrogen production
- Task 37 - Hydrogen safety
- Task 38 - Power to hydrogen; hydrogen to X
- Task 40 - Energy storage and conversion based on hydrogen

The proposed approach to IEA-TCP tasks for the next five-year term includes approving and executing successor tasks to ensure continuity and progress. This entails assessing opportunities and barriers in the development and deployment of hydrogen technologies. Furthermore, it also includes investigating the application of hydrogen and hydrogen energy carriers in industrial sectors, such as steel and chemicals. The approach lays out the groundwork to expand infrastructure efforts and collaboration with other TCPs like wind, bioenergy, International Smart Grid Action Network, and Advanced Fuel Cells.

IEA-TCP's approach aims to accelerate the adoption of hydrogen in transportation and stationary power, constructing road maps and pathways for its rapid implementation. Their approach emphasizes collaboration with other TCPs and external partners, particularly in the area of low-carbon and renewable hydrogen. This would help in formulating messages derived from R&D activities to effectively communicate insights to decision-makers within the IEA and beyond.

5.1.4 INTERNATIONAL PARTNERSHIP FOR HYDROGEN AND FUEL CELLS IN THE ECONOMY

The IPHE was instituted in 2003 to promote and accelerate the transition toward clean and efficient energy and mobility systems using fuel cell and hydrogen technologies across various applications and sectors (IPHE 2022). The partnership comprises 21 participating G20 countries:

Table 14 | **LIST OF IPHE MEMBER COUNTRIES**

G20 MEMBERS	IPHE MEMBERS	G20 MEMBERS	IPHE MEMBERS
Argentina		Japan	■
Australia	■	Republic of Korea	■
Brazil	■	Mexico	
Canada	■	Russia	
China	■	Saudi Arabia	
France	■	South Africa	
Germany	■	Turkey	
India	■	United Kingdom	■
Indonesia		United States	■
Italy	■	European Union	■

Source: IPHE (2022).

The IPHE provides a platform to exchange information about policies, technological advancements, safety measures, regulations, codes, and standards to accelerate the cost-efficient shift to hydrogen and fuel-cell technologies in the economy. In addition, the IPHE raises awareness among various stakeholders, such as policymakers and the public, about the advantages and obstacles of implementing hydrogen and fuel-cell technologies on a large scale in the economy.

The IPHE has two working groups: the Education & Outreach Working Group and the Regulations, Codes, Standards, and Safety Working Group. It also has two task forces: The Hydrogen Production Analysis Task Force and the Hydrogen Trade Rules Task Force.

5.1.5 COLLABORATION FRAMEWORK ON GREEN HYDROGEN: IRENA

IRENA's Collaboration Framework on Green Hydrogen (CFGH) functions as an efficient platform for fostering discussions, cooperation, and harmonized efforts to expedite the advancement and use of green hydrogen and its derivatives in the global shift toward renewable energy. CFGH maximizes its potential by drawing on IRENA's endeavours in green hydrogen, the extensive knowledge and expertise within IRENA's membership, and the advantageous outcomes attainable through broader international collaboration with various entities. With the exception of Brazil, all G20 countries are members

The scope of work for the CFGH is divided into nine areass:

1. A global knowledge database for green hydrogen
2. Cooperation with existing hydrogen initiatives and other relevant actors
3. Nexus between electrolysers and renewable power
4. Transportation and distribution of hydrogen
5. Standards and Regulatory frameworks
6. Financial support
7. End-use Sectors
8. Environmental, safety aspects and social acceptance of hydrogen development
9. Applicability and relevance of hydrogen in small markets (e.g. small countries)

Currently the primary focus is on evaluating the global implementation of hydrogen following years of strategizing and project declarations. The initial CFGH gathering in 2023 deliberated on the most recent advancements in hydrogen and its by-products, with a specific emphasis on the perspective of hydrogen demand. Valuable insights and experiences were exchanged through collaborations with consumers in sectors such as steel, maritime, and aviation, highlighting both the lessons learned and the factors that facilitated progress. The second assembly discussed the supply aspect, specifically addressing the advancements and challenges faced in establishing hydrogen production facilities and their derivatives. Above all, the meeting centered around the opportunities and obstacles encountered by developing nations aspiring to emerge as potential producers of hydrogen and its derivatives.

Table 15 | **LIST OF IRENA CFGH MEMBER COUNTRIES**

G20 MEMBERS	MEMBERS	G20 MEMBERS	MEMBERS
Argentina	■	Japan	■
Australia	■	Republic of Korea	■
Brazil		Mexico	■
Canada	■	Russia	■
China	■	Saudi Arabia	■
France	■	South Africa	■
Germany	■	Turkey	■
India	■	United Kingdom	■
Indonesia	■	United States	■
Italy	■	European Union	■

Source: IRENA (2023c).

5.2 OPPORTUNITIES FOR G20 TO LEAD COLLABORATIVE R&I ACROSS THE HYDROGEN VALUE CHAIN

India’s G20 presidency aims to advance the past presidency’s efforts on strategic cooperation initiatives for accelerated deployment and cost reduction in green hydrogen production, storage, delivery, and utilization. The proposed actions would build on existing or ongoing global dialogues and collaborations under the COP26 breakthrough agenda, CEM, Mission Innovation, IPHE, and the extensive analytical and advisory actions by IEA TCP.

Engaging in a collaborative manner through these forums, the G20 nations can avoid duplication of efforts, efficiently utilize resources, and ensure complementarity among R&I activities. The following section highlights specific focus areas across the hydrogen value chain that require coordinated efforts for scaling and commercializing green hydrogen globally.

5.2.1 HYDROGEN PRODUCTION

Extensive research is needed for an improved understanding of performance, cost, and durability of electrolyzer systems so that these technologies can be scaled to meet future green hydrogen demand. A major portion of the electrolyzer capital cost can be assigned to the stack that is composed of precious metals and requires highly sophisticated manufacturing processes.

Of primary concern is understanding the electrolyzer stack's energy efficiency and developing strategies to mitigate its degradation processes for increased operational lifetimes. Ongoing research efforts focus on developing electrodes that use non-noble materials, thinner organic membranes, and electrolyzer cells that operate at high pressures, as is evident from recent patent insights (IRENA 2022d).

The increasing demand for electrolyzers and renewable energy in the coming decade is expected to ramp up demand for critical minerals. Reducing dependence on these minerals can help address associated with restricted resource availability and adverse environmental consequences from mineral extraction and processing. There is a need to develop alternative electrode materials as well as explore alternative pathways for green hydrogen production. Research efforts can also be directed to upgrading the existing tracking systems and making them cost effective since a credible hydrogen tracking system requires some costs to the clients. One such focus area could be the elimination of double counting of the certificates for the same unit of green hydrogen.

5.2.2 STORAGE AND DISTRIBUTION

Hydrogen storage and transportation is another key focus area as large-scale deployment for green hydrogen is not possible in the absence of efficient and cost-effective storage and transportation technologies for hydrogen. Currently, hydrogen is stored in compressed gas tanks on industrial sites. Although relatively expensive, this method is feasible only for small-scale usage.

Table 16 | **ILLUSTRATIVE RESEARCH PROJECTS FOCUSED ON GREEN HYDROGEN PRODUCTION**

HYDROGEN PRODUCTION	
ELECTRODE MATERIALS FOR ELECTROLYZERS AND FUEL CELLS	▪ U.S. Department of Energy, Electrocatalyst Consortium (PGM-free electrolyzers and fuel cells ▪ CSIR-CMERI, 2D transition metal-layered double hydroxides
SUPPLY CHAINS	▪ Mission Innovation, Integration of solar & wind with electrolyzers ▪ World Bank, critical minerals intensity for clean energy transition ▪ FuelCellsWorks, "3+2" collaborative industrial research and development program to optimize H_2 production and integrate it into industry value chain
ALTERNATIVE PATHWAYS FOR GREEN HYDROGEN PRODUCTION	▪ U.S. Department of Energy, solar hydrogen production theory and modeling for photoelectrochemical water splitting ▪ Mission Innovation, pyrolysis for direct decomposition of methane to hydrogen, Mission Innovation

Sources: Author compilation based on DOE (2023a); CSIR-CMERI (2023); World Bank (2023); FuelCellsWorks (2023); DOE (2023b); Mission Innovation (2021).

Thus, development of efficient processes that can convert hydrogen into inexpensive chemicals like methanol and ammonia (lower complexity and safety required for storage and transportation) is warranted. This would not only reduce the cost of storage but also make it easier to use hydrogen for long-distance mobility, including aviation and maritime transportation. Ammonia is currently the most viable option for transporting hydrogen over a long distance because of its technological maturity and existing supply chains.

Although current ammonia shipments amount to approximately 20 million tonnes per year, ongoing research explores its potential as a fuel for ships. Specifically, there is interest in using separate cargo tanks to carry both LPG and ammonia simultaneously, enabling flexible adjustment to demand patterns (IEA 2022f). Furthermore, improvements in processes for repurposing existing natural gas pipeline and ships to accommodate hydrogen would also minimize cost inflation by using existing infrastructure.

5.2.3 END USE APPLICATIONS

For end-use applications of hydrogen, innovation has been largely driven by ammonia and methanol synthesis, followed by fuel-cell technologies. Research is primarily focused on improving energy efficiency by combining heating applications. In case of fuel-cell technologies, much of the research focus is on developing applications for stationary power and transportation, that is, hydrogen-powered trucks, airplanes, trains, and ships.

Polymer electrolyte membrane fuel cells (PEMFCs), often referred to as proton exchange membrane fuel cells, are currently the only low-temperature fuel cell technology with significant development support. PEMFCs could be used as both a backup power source and a dispatchable generator for the grid. They are also anticipated to be employed for applications in transportation, such as heavy-, medium-, and light-duty trucks; material handling equipment; and trains. Other research areas include usage of hydrogen as process heat in kilns, buildings, and turbines for electricity generation.

Table 17 | **ILLUSTRATIVE RESEARCH PROJECTS FOCUSED ON HYDROGEN STORAGE AND TRANSPORTATION**

HYDROGEN STORAGE AND TRANSPORTATION	
HYDROGEN STORAGE TANKS	- U.S. Department of Energy, novel materials for H_2 storage (complex hydrides and nanostructured materials) - University of Kentucky (Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks), H2@scale, USA - HyCARE project (CNRS and partners)
HYDROGEN AS DERIVATES	- Mission Innovation, sustainable production of industrial intermediates; H_2 for export - CSIRO, Australia, nitrogenase enabling solar-powered ammonia
GEOLOGICAL STORAGE OF HYDROGEN	- IEA TCP, Sun Storage & Hychico (mixed H_2 storage in gas fields) - IEA, hydrogen TCP Task 42: underground hydrogen storage - Energystock, IEA TCP, HySTOCK (salt cavern storage in the Netherlands)

Sources: Author compilation based on DOE (2023c); DOE (2020a); CSIRO (2021); IEA (2023d); RAG (2023); IEA (2023d); Energystock (2023).

Table 18 | **ILLUSTRATIVE RESEARCH PROJECTS FOR END-USE APPLICATIONS OF HYDROGEN**

HYDROGEN END-USE APPLICATIONS	
TRUCKS AND BUSES	▪ IEA-AMF, Tasks 54, 56, and 58: fuels for heavy-duty vehicles ▪ DEUTZ AG, HyCET Consortium on sustainable transportation logistics using hydrogen trucks, Germany
SHIPPING & AVIATION	▪ ZAL, Fuel Cell Lab, fuel cells for aviation ▪ Lufthansa Group, German Aerospace, Germany, liquid hydrogen for aviation ▪ Hemholtz Research Field. Helmholtz-Zentrum HEREON aviation and marine application of hydrogen
INDUSTRIAL DECARBONISATION	▪ Mission Innovation, decarbonizing transportation sector (road/rail) ▪ Mission Innovation, decarbonizing mining & other hard-to-abate industries ▪ HYSTEEL (decarbonizing steelmaking), H2@scale, USA

Sources: Author compilation based on IEA-AMF (2022); DEUTZ AG (2023); ZAL (2023); Lufthansa Group (2022); Hemholtz Research Field (2023); World Bank (2023).

5.3 KEY RECOMMENDATIONS FOR DRIVING COLLABORATIVE RESEARCH & INNOVATION

Countries, including G20 nations, are working toward scaling green hydrogen deployment to meet decarbonization targets and net-zero goals. Limited understanding around technologies for green hydrogen production, storage, transportation, and end applications necessitates focused research and innovation to develop and deploy green hydrogen technologies.

Executing research and innovation through collaborative platforms can address challenges related to the selection of research areas, structuring of a cooperative approach for achieving outcomes, and leveraging expertise and resources across geographies. The following key recommendations are made for enhancing collaborative research and innovation across G20 nationsw:

DEVELOP FLEXIBLE COLLABORATION MECHANISMS TO DRIVE RESEARCH AND INNOVATION ACTIVITIES

Enhancing R&I collaboration necessitates prioritizing the identification of collaboration areas and promoting the inclusion of a diverse range of participants. By doing so, ample opportunities for discussions arise, fostering an environment that encourages an open exchange of ideas. Moreover, multilateral initiatives commonly encounter challenges stemming from varying approaches, processes, and funding models that impede efficient collaboration. To overcome these obstacles, it is advisable to adopt flexible models that enable participants to align their approaches with those of other initiatives, thereby facilitating effective collaboration.

For the development of a flexible and efficient collaboration mechanism, the platform must consider identification of common priority areas for research among the contracting parties and create opportunities for exchange of ideas and expertise. For instance, the IEA TCP platform already has several research and innovation projects that are being carried out between more than two collaborating countries. Successful initiatives like these can be used as a model for future international collaboration platforms for driving R&I activities.

ASSESSMENT OF CRITICAL FOCUS AREAS TO OPTIMIZE OUTCOMES AND ACCELERATE GREEN HYDROGEN TECHNOLOGY DEVELOPMENT

To accelerate the adoption of hydrogen as an enabler for a green transition, collaborative research efforts should focus on key areas in each segment of the hydrogen supply chain, that is, production, storage, distribution, and utilization. Developing a shared research agenda can help coordinate focused research initiatives and leverage strengths of the G20 member nations and research organizations to promote knowledge sharing and avoid duplication of efforts. To maximize the impact of new R&D initiatives, it is crucial for individual nations to comprehensively map the existing research landscape, assess needs, and identify potential gaps.

By identifying significant gaps and barriers to the progress of green hydrogen technologies, such as electrolyzer stack performance, transportation and storage of hydrogen, and development of testing and safety protocols for commercial applications, a customized approach can be designed to tackle critical area for research through collaboration. These focus areas should also have a targeted outcome-based approach with clear timelines based on their potential for commercialization

ENABLING FUNDING TO PROMOTE RESEARCH AND INNOVATION FOR HYDROGEN TECHNOLOGIES

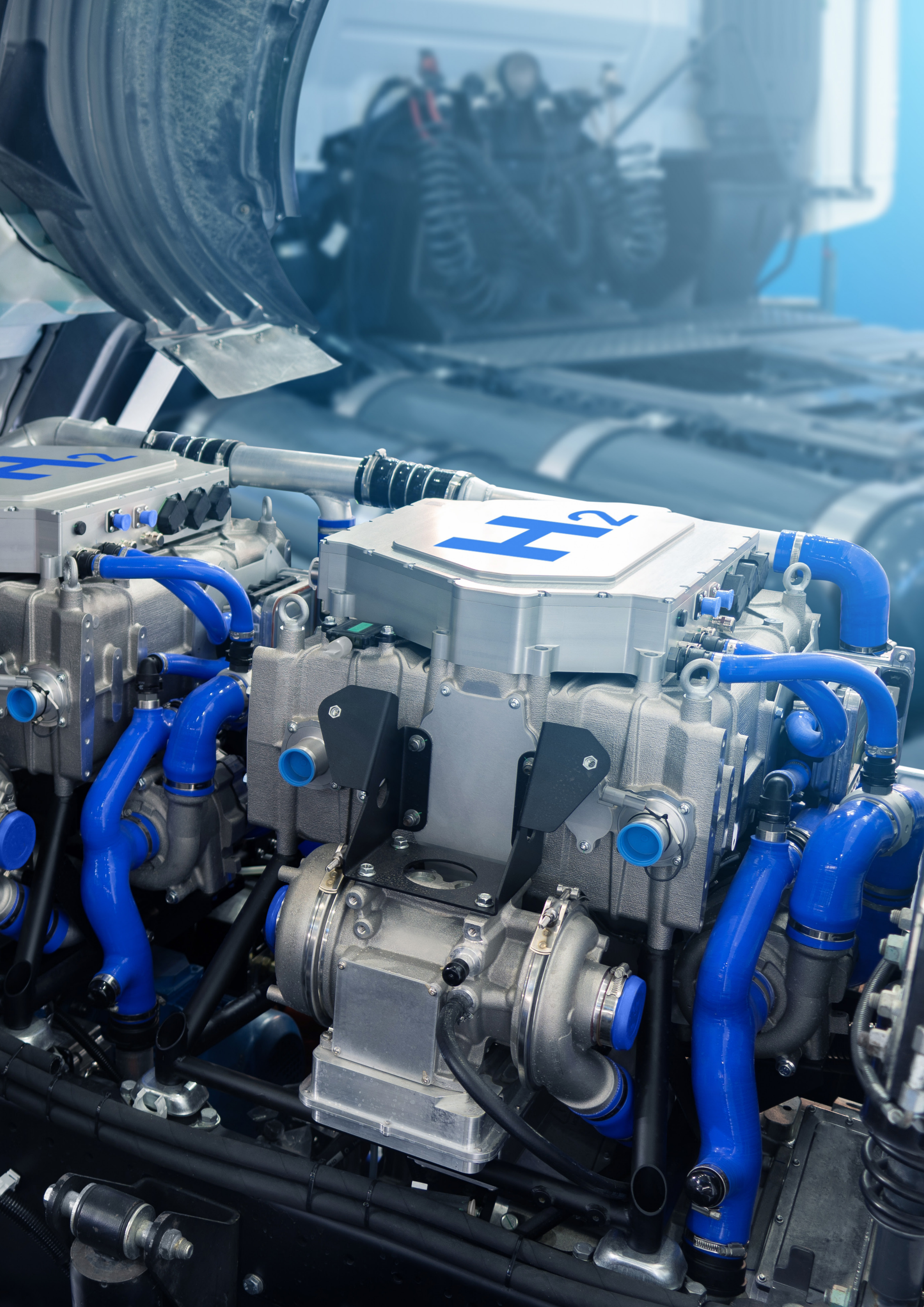
Using existing collaboration platforms, such as CEM and Mission Innovation, the G20 can establish funding programs that focus specifically on research collaboration on green hydrogen across nations. These programs can be designed to encourage joint research projects, technology sharing, and knowledge transfer. Such programs can be supported through public funding for R&D or by offering tax incentives for private-sector investments in R&D.

Industry and academia partnerships can also be promoted through such mechanisms by providing access to funding, expertise, and equipment that might not be available in individual countries. Establishing joint research centers and providing incentives for companies to work with academic researchers can also be pursued to attract further investment to this sector.

INTEGRATING AND STREAMLINING COLLABORATION INTO DECISION-MAKING PROCESSES

Integrating collaboration into mission statements and R&D road maps can enable institutional mechanisms for continued cooperation across research and innovation activities. Similarly, streamlining collaboration through standardized template documents, legal frameworks, and well-defined procedural steps can enhance opportunities for partnering nations.

These template documents can provide a valuable framework for other multilateral initiatives seeking to optimize collaboration processes. By adopting these measures, collaboration will become a standard practice that transcends individual networks and facilitates streamlined collaboration for diverse multilateral endeavors (IEA 2021a).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REFERENCES

Abad, Anthony Velazquez, and Paul E. Dodds. 2020. "Green Hydrogen Characterisation Initiatives: Definitions, Standards, Guarantees of Origin, and Challenges." Elsevier Energy Policy 138: 111300. https://www.sciencedirect.com/science/article/abs/pii/S0301421520300586.

ABB. 2020. Partnering for Our Energy Future—Strengthening the Hydrogen Value Chain. https://library.e.abb.com/public/99373e3d80cb42549767381a4e52ddcf/24809%20ABB%20Hydrogen%20Whitepaper_Ltr_20201008%20(2).pdf.

Australian National University. 2020. Approaches to certifying Australia-Germany Green Hydrogen Supply Chains. https://iceds.anu.edu.au/files/HySupply%20Certification%20Report_Final.pdf.

BEIS (Department of Business, Energy and Industrial Strategy, UK). 2022a. Supply Chains to Support a Hydrogen Economy. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1092371/supply-chains-to-support-uk-hydrogen-economy-wood-template.pdf.

BEIS. 2022b. A Consultation on Hydrogen Transport and Storage Infrastructure. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1101296/hydrogen-transportation-storage-consultation.pdf.

CEEW (Council on Energy, Environment and Water). 2023. Developing Resilient Renewable Energy Supply Chains for Global Clean Energy Transition. https://www.ceew.in/sites/default/files/developing-resilient-renewable-energy-supply-chains-for-global-clean-energy-transition.pdf.

CEEW, IEA, University of California-Davis, and World Resources Institute. 2023. Addressing Vulnerability in the Supply Chain of Critical Minerals through International Collaboration. https://www.ceew.in/sites/default/files/addressing-critical-minerals-supply-chain-vulnerabilities-india.pdf.

CEM (Clean Energy Ministerial). 2023a. Clean Energy Future. https://www.cleanenergyministerial.org/. Accessed March 1, 2023.

CEM. 2023b. Hydrogen. https://www.cleanenergyministerial.org/initiatives-campaigns/hydrogen-initiative/. Accessed March 1, 2023.

CertifHy. 2023. Hydrogen Certification Schemes. https://www.certifhy.eu/. Accessed January 12, 2023.

CSIR-CMERI (Council of Scientific & Industrial Research-Central Mechanical Engineering Research Institute). 2023. Projects. https://www.cmeri.res.in/projects/2d-transition-metal-layered-double-hydroxides-cost-effective-catalyst-hydrogen-production. Accessed March 12, 2023.

CSIRO (Council of Scientific and Industrial Research). 2021 Nitrogenase: Enabling Solar-Powered Ammonia. https://research.csiro.au/hydrogenfsp/our- research/projects/nitrogenase-enabling-solar-powered-ammonia/. Accessed March 1, 2023.

DNV (Det Norske Veritas). 2022. Hydrogen Forecast to 2050. https://www.dnv.com/focus- areas/hydrogen/forecast-to-2050.html. Accessed February 15, 2023

DOE (U.S. Department of Energy). 2020a . H2@Scale New Markets Funding Opportunity Announcement (FOA). https://www.energy.gov/sites/default/files/2020/07/f76/hfto-h2-at-scale-new-markets-foa-selections-for-release.pdf. Accessed on January 20, 2023

DOE. 2020b. Hydrogen Program Plan. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.

DOE. 2022. Achieving American Leadership in the Hydrogen Supply Chain. https://www.energy.gov/sites/default/files/2022- 02/Fuel%20Cells%20%26%20Electrolyzers%20Supply%20Chain%20Fact%20Sheet.pdf.

DOE. 2023a. Electrocatalysis Consortium. https://www.electrocat.org/about/partners/. Accessed January 31, 2023.

DOE. 2023b. DOE Technical Targets for Hydrogen Production from Photoelectrochemical Water Splitting. Office of Energy Efficiency and Renewable Energy. https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-photoelectrochemical-water-splitting. Accessed January 15, 2023

DOE. 2023c. Hydrogen Storage. https://www.hydrogen.energy.gov/storage.html. Accessed March 31, 2023.

DEUTZ AG . 2023. "HyCET Research Project." https://www.deutz.com/en/media/press-releases/hycet-research-project-consortium-promotes-sustainable-transport-logistics-using-hydrogen-trucks. Accessed January 14, 2023.

EC (European Commission). 2023. Voluntary Schemes. https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/voluntary-schemes_en. Accessed January 12, 2023.

FCHEA (Fuel Cell and Hydorgen Association). 2023. Hydrogen in Industrial Applications. https://www.fchea.org/hydrogen-in-industrial-applications. Accessed on January 20, 2023.

Energystock. 2023. Hydrogen Conversion. https://www.energystock.com/hydrogen-conversion. Accessed March 31, 2023.

FuelCellsWorks. 2023. "3+2" Collaborative Industrial Research and Development Program. https://fuelcellsworks.com/news/supporting-collaborative-research-projects-between-canada-and-germany-in-low-carbon-hydrogen-technologies/. Accessed March 27, 2023.

G20 Information Center. 2021. G20 2021 Rome Climate Change Performance. http://www.g20.utoronto.ca/analysis/211227-warren-climate-performance.html. Accessed April 24, 2023.

G20 India. 2023. About G20. https://www.g20.org/en/about-g20/#overview. Accessed January 14, 2023.
Helmholtz Research Field. 2023. https://www.hereon.de/institutes/hydrogen_technology/index.php.en. Accessed March 31, 2023.

IEA (International Energy Agency). 2021a. Enhancing Collaboration between Multilateral Initiatives. https://iea.blob.core.windows.net/assets/55bc172a-901e-4718- 8f57-8455565c9da2/Enhancingcollaborationbetweenmultilateralinitiatives.pdf. Accessed on April 20, 2023.

IEA. 2021b. Hydrogen in North-Western Europe. https://www.iea.org/reports/hydrogen-in-north-western-europe. Accessed March 1, 2023.

IEA. 2021c. Hydrogen TCP. https://www.ieahydrogen.org/vision-and-targets-2/. Accessed January 25, 2023.

IEA 2021d. Global Hydrogen Review. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

IEA. 2022a. Global Hydrogen Review. https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e-626a11c4/GlobalHydrogenReview2022.pdf.

IEA. 2022b. Electrolysers. https://www.iea.org/reports/electrolysers. Accessed February 2, 2023.

IEA 2022c. The Role of Critical Minerals in Clean Energy Transitions. https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a- 2b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf.

IEA. 2022d. Hydrogen TCP. Closed Tasks. https://www.ieahydrogen.org/tasks/closed-task/. Accessed January 25, 2023.

IEA. 2022f. ETP Clean Energy Technology Guide. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedVCStep=Transport&selectedSector=Hydrogen. Accessed June 11, 2023.

IEA and CEM. 2022. Global Hydrogen Targets. https://www.cleanenergyministerial.org/content/uploads/2022/07/aspirational-targets-briefing-150722.pdf.

IEA 2023a. G7 Hiroshima Summit. "Toward hydrogen definitions based on their emissions intensity." https://iea.blob.core.windows.net/assets/acc7a642- e42b- 4972-8893- 2f03bf0bfa03/Towardhydrogendefinitionsbasedontheiremissionsintensity.pdf.

IEA. 2023b. Renewables: Analysis and Forecast to 2027. https://iea.blob.core.windows.net/assets/ada7af90-e280-46c4-a577-df2e4fb44254/Renewables2022.pdf.

IEA. 2023c. Hydrogen Patents for a Clean Energy Future. https://iea.blob.core.windows.net/assets/1b7ab289-ecbc-4ec2-a238-f7d4f022d60f/Hydrogenpatentsforacleanenergyfuture.pdf.

IEA. 2023d. Hydrogen TCP-Task 42: Underground Hydrogen Storage. https://www.ieahydrogen.org/download/17/task-reports/7067/task42_uhs_technologymonitoringreport.pdf.

IEA-AMF (Advanced Motor Fuels). 2022. Technology Collaboration Programme on Advanced Motor Fuels. https://www.iea-amf.org/. Accessed February 3, 2023.

IEA and CEM (Clean Energy Ministerial). 2021. CEM Global Ports Hydrogen Coalition. https://iea.blob.core.windows.net/assets/fb84e952- e15d- 444b- a59e- 72609ea0759d/CEMGlobalPortsHydrogenCoalition-draftprogramme1st-meeting.pdf.

IPHE (International Partnership for Hydrogen Fuel Cells in the Economy). 2022. https://www.iphe.net/. Accessed March 2, 2023.

IRENA (International Renewal Energy Agency). 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf.

IRENA. 2022a. Innovation Trends in Electrolysers for Hydrogen Production. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_EPO_Electrolysers_H2_production_2022.pdf.

IRENA. 2022b. Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Part III–Green Hydrogen Cost and Potential. https://www.irena.org/publications/2022/May/Global-hydrogen-trade-Cost. Accessed June 9, 2023.

IRENA. 2023a. World Energy Transitions Outlook 2023. https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Mar/IRENA_WETO_Preview_2023.pdf?rev=c4c2398e169a4243ad37cf67dc441fa8.

IRENA. 2023b. Renewable Capacity Statistics. https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Mar/IRENA_RE_Capacity_Statistics_2023.pdf?rev=d2949151ee6a4625b65c82881403c2a7. Accessed June 11, 2023.

IRENA. 2023c. Collaborative Framework on Green Hydrogen. https://www.irena.org/Events/2023/Apr/Collaborative-Framework-on-Green-Hydrogen-CFGH. Accessed April 26, 2023.

JRC (Joint Research Centre). 2022. The Role of Hydrogen in Decarbonisation Scenarios. Technical Report. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC131299/JRC131299_01.pdf.

Lufthansa Group. 2022. Collaborating in Making German Aviation Fit for Hydrogen. Cleantech Hub. https://cleantechhub.lufthansagroup.com/en/focus-areas/between-and-beyond/hydrogen-aviation-lab-hamburg.html. Accessed May 12, 2023

Mission Innovation. 2018. Collaborative Models for International Co-Operation in Clean Energy Research and Innovation. http://mission- innovation.net/wp- content/uploads/2019/09/AJR-Paper-on-Multilateral-Collaboration-models_FINAL.pdf.

Mission Innovation. 2021. Determination and Prioritisation of Clean Hydrogen Mission Activities. http://mission-innovation.net/wp-content/uploads/2021/11/Clean-Hydrogen-Mission-Discussion-Paper-APPENDIX-1.pdf.

Mission Innovation. 2023a. Clean Hydrogen. https://explore.mission-innovation.net/mission/clean-hydrogen/. Accessed February 10, 2023.

Mission Innovation. 2023b. Hydrogen Valley Platform. https://h2v.eu/. Accessed February, 10, 2023.

Oeko-Institute. 2021. "Sustainability Dimensions of Imported Hydrogen." Working Paper. https://www.oeko.de/fileadmin/oekodoc/WP-imported-hydrogen.pdf.

Office of Energy Efficiency and Renewable Energy. 2022. H2 Twin Cities. https://www.energy.gov/eere/h2twincities/h2-twin-cities. Accessed February 13, 2023.

Overland, I., J. Juraev, and R. Vakulchuk. 2022. "Are Renewable Energy Sources More Evenly Distributed Than Fossil Fuels?" Renewable Energy 200: 379–386. https://doi.org/10.1016/j.renene.2022.09.046.

RAG Austria AG. 2023. Underground Sun Conversion. https://www.rag- austria.at/fileadmin/bilder/0_NEU_RAG_Austria_AG/Unternehmen/sunconversion_broschuere_engl_180907_fin.pdf. Accessed March, 24, 2023

Riera, Jefferson, A., and Ricardo M. Lima. 2023. "A Review of Hydrogen Production and Supply Chain Modeling and Optimization." Science Direct. https://www.sciencedirect.com/science/article/pii/S0360319922060505. Accessed March 19, 2023.

Scottish Government. 2022. Assessment of Electrolysers. https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2022/10/assessment-electrolysers-report/documents/assessment-electrolysers-final-report/assessment-electrolysers-final-report/govscot%3Adocument/assessment-electrolysers-final-report.pdf.

Sino-German Energy Partnership, German Federal Ministry for Economic Affairs and Climate Action. 2023. "Certification of Green Hydrogen: Recent Efforts and Developments in the European Union." https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/2022/Certification_of_green_hydrogen_EN.pdf.

TÜV SÜD (Technischer Überwachungsverein). 2021. Standard CMS 70: Production of Green Hydrogen. https://www.tuvsud.com/en/-/media/global/pdf-files/brochures-and-infosheets/tuvsud-cms70-standard-green-hydrogen-certification.pdf.

TÜV SÜD. 2023. Explore the Hydrogen Value Chain. https://www.tuvsud.com/en- in/themes/hydrogen/explore-the-hydrogen-value-chain. Accessed January 19, 2023.

USGS (U.S. Geological Survey). 2023. Mineral Commodity Summary https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf.

Volta Chem. 2023. Electrolysers: Opportunities for the High-Tech Manufacturing Industry. https://www.voltachem.com/images/uploads/Electrolysers_opportunities_for_the_high-tech_manufacturing_industry_20230331.pdf.

World Bank. 2023. Climate-Smart Mining: Minerals for Climate Action. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf Accessed May 12, 2023.

ZAL (Zentrum für Angewandte Luftfahrtforschung) . 2023. Fuel Cell Characteristics. https://fuelcell.zal.aero/. Accessed February 13, 2023.

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