15 CEEW
THE COUNCIL

नवीन एवं
नवीकरणीय ऊर्जा मंत्रालय
MINISTRY OF
NEW AND
RENEWABLE ENERGY

सत्यमेव जयते

Green Hydrogen Testing Infrastructure and Facilities in India

Developing the Ecosystem for Accelerated Implementation of the National Green Hydrogen Mission

Aditya Khator, Karthik Shetty, Rishabh Patidar, and Deepak Yadav

Report | September 2024

Suggested citation: Khator Aditya, Karthik Shetty, Rishabh Patidar, Deepak Yadav. 2024. *Green Hydrogen Testing Infrastructure and Facilities in India: Developing the Ecosystem for Accelerated Implementation of the National Green Hydrogen Mission.* New Delhi: Council of Energy, Environment and Water (CEEW)

Cover Image: Alamy

Peer reviewers: Mrs Anuja Anand, Director, National Accreditation Board for Testing and Calibration Laboratories, Gurugram; Dr Mahesh Kumar, Senior Principal Scientist, Council of Scientific and Industrial Research (CSIR), New Delhi; Mr Nitan Garg, Joint Director, National Accreditation Board for Testing and Calibration Laboratories, Gurugram; Prof. Rahul Nabar, Adjunct Associate Professor, Indian Institute of Technology Bombay; Ankur Rawal, Programme Lead, CEEW.

Publication team: Kartikeya Jain (CEEW); Alina Sen (CEEW); The Clean Copy; Madre Designs and Friends Digital Colour Solutions

Acknowledgment: The Council on Energy, Environment and Water (CEEW) is privileged to be associated with the Ministry of New and Renewable Energy (MNRE), Government of India, as Knowledge Partner on this report.

We are grateful to Shri Ajay Yadav, Ex-Joint Secretary, MNRE; Shri Abhay Bakre, Mission Director, National Green Hydrogen Mission, MNRE; Shri Sujit Pillai, Scientist F, MNRE; Dr Prasad Chaphekar, Deputy Secretary, MNRE and Shri Deepak Rai; Programme Director (Policy), National Green Hydrogen Mission Secretariat, MNRE for entrusting CEEW with this study.

The authors of the report would like to express their appreciation to Shri Deepak Agarwal, Scientist F, Bureau of Indian Standards (BIS); Shri Gaurav Jayaswal, Deputy Director, Bureau of Indian Standards (BIS); Shri Srinivasa Rao Keta, Controller of Explosives, Petroleum & Explosives Safety Organization (PESO).

Organisation: The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW has a footprint in over 20 Indian states and has repeatedly featured among the world's best managed and independent think tanks. Follow us on X (formerly Twitter) @CEEWIndia for the latest updates.

COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)
ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi – 110070, India
+91 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewindia

Green Hydrogen Testing Infrastructure and Facilities in India

Developing the Ecosystem for Accelerated Implementation of the National Green Hydrogen Mission

Aditya Khator, Karthik Shetty, Rishabh Patidar and Deepak Yadav

Report
September 2024
ceew.in

About CEEW

The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses **data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources**. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW is a strategic/ knowledge partner to 11 ministries for India's G20 presidency.

The Council's illustrious Board comprises Mr Jamshyd Godrej (Chairperson), Mr S. Ramadorai, Mr Montek Singh Ahluwalia, Dr Naushad Forbes, Dr Janmejaya Sinha, Dr Suresh Prabhu, and Ms Vinita Bali. The 330+-strong executive team is led by Dr Arunabha Ghosh. CEEW has repeatedly featured among the world's best managed and independent think tanks.

In over 14 years of operations, The Council has engaged in 500+ research projects, published 460+ peer-reviewed books, policy reports and papers, created 220+ databases or improved access to data, advised governments around the world 1400+ times, promoted bilateral and multilateral initiatives on 160+ occasions, and organised 610+ seminars and conferences. In July 2019, Minister Dharmendra Pradhan and Dr Fatih Birol (IEA) launched the CEEW Centre for Energy Finance, which is now known as CEEW Green Finance Centre (CEEW-GFC). In August 2020, Powering Livelihoods — a CEEW and Villgro initiative for rural start-ups — was launched by Minister Piyush Goyal, Dr Rajiv Kumar (then NITI Aayog), and H.E. Ms Damilola Ogunbiyi (SEforAll).

The Council's major contributions include: Informing India's net-zero goals; work for the PMO on accelerated targets for renewables, power sector reforms, environmental clearances, *Swachh Bharat*; pathbreaking work for India's G20 presidency, the Paris Agreement, the HFC deal, the aviation emissions agreement, and international climate technology cooperation; the first independent evaluation of the *National Solar Mission*; India's first report on global governance, submitted to the National Security Advisor; support to the National Green Hydrogen and Green Steel Missions; the 584-page *National Water Resources Framework Study* for India's 12th Five Year Plan; irrigation reform for Bihar; the birth of the Clean Energy Access Network; the concept and strategy for the International Solar Alliance (ISA); the Common Risk Mitigation Mechanism (CRMM); India's largest multidimensional energy access survey (ACCESS); critical minerals for *Make in India*; India's climate geoengineering governance; analysing energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka, and Viet Nam. CEEW published *Jobs, Growth and Sustainability: A New Social Contract for India's Recovery*, the first economic recovery report by a think tank during the COVID-19 pandemic.

The Council's current initiatives include: State-level modelling for energy and climate policies; consumer-centric smart metering transition and wholesale power market reforms; modelling carbon markets; piloting business models for solar rooftop adoption; fleet electrification and developing low-emission zones across cities; assessing green jobs potential at the state-level, circular economy of solar supply chains and wastewater; assessing carbon pricing mechanisms and India's carbon capture, usage and storage (CCUS) potential; developing a first-of-its-kind Climate Risk Atlas for India; sustainable cooling solutions; developing state-specific dairy sector roadmaps; supporting India's electric vehicle and battery ambitions; and enhancing global action for clean air via a global commission 'Our Common Air'.

The Council has a footprint in over 20 Indian states, working extensively with 15 state governments and grassroots NGOs. Some of these engagements include supporting power sector reforms in Uttar Pradesh, Rajasthan, and Haryana; energy policy in Rajasthan, Jharkhand, and Uttarakhand; driving low-carbon transitions in Bihar, Maharashtra, and Tamil Nadu; promoting sustainable livelihoods in Odisha, Bihar, and Uttar Pradesh; advancing industrial sustainability in Tamil Nadu, Uttar Pradesh, and Gujarat; evaluating community-based natural farming in Andhra Pradesh; and supporting groundwater management, e-auto adoption and examining crop residue burning in Punjab.

Content

Scaling testing infrastructure as the green hydrogen value chain grows is necessary to keep the industry streamlined in terms of quality, safety and reliability in performance.

image: iStock

Executive summary

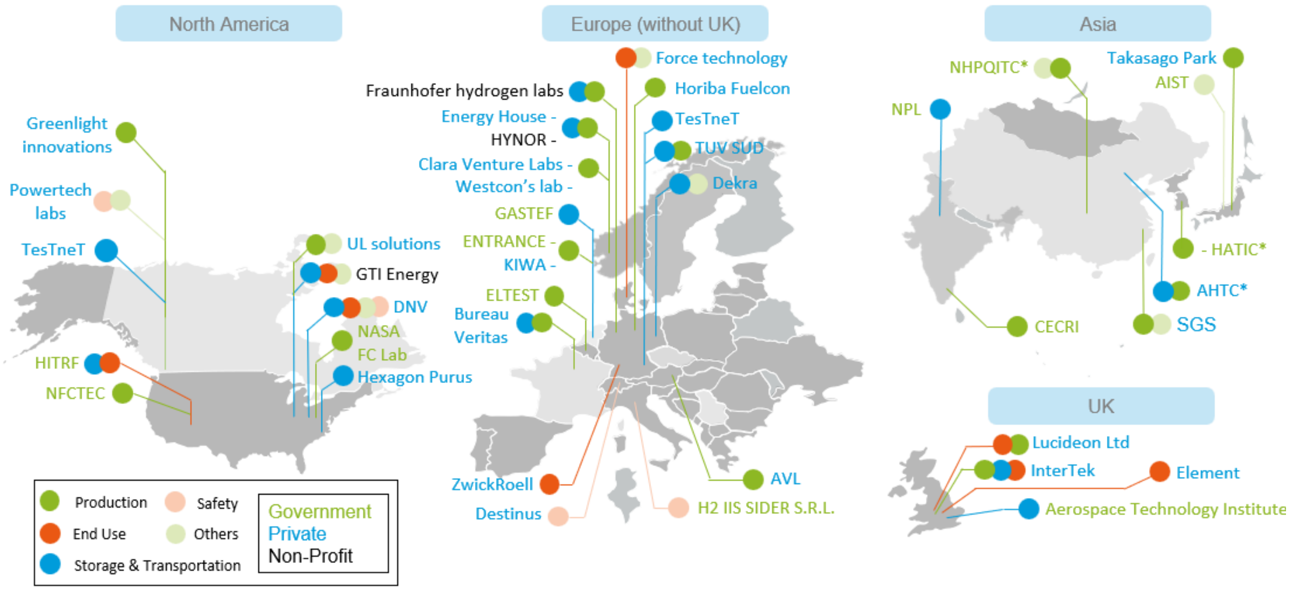
The Government of India, through its *National Green Hydrogen Mission* (NGHM), aims to position India as a global hub for the production, consumption, and export of green hydrogen and derivatives. Consequently, safety standards and testing infrastructure are fundamental for creating an ecosystem for scaling up the green hydrogen economy in India. The country needs to establish a strong network of testing infrastructure for achieving the targets set under NGHM. This will ensure quality, efficiency and safety across the green hydrogen value chain.

This report describes the status of testing infrastructure in major economies that plan to establish significant hydrogen production and outlines the current landscape of testing requirements in India. Besides, it lists labs that can perform various tests across the hydrogen value chain, such as production, storage and transportation, end-use, and general safety. This report also highlights the role of the government and private sector in scaling India's testing infrastructure. Furthermore, it recommends policy actions required to address gaps and enhance India's testing capabilities to align with its hydrogen goals.

A. Overview of global hydrogen testing infrastructure

Figure ES1 shows the major hydrogen testing laboratories in the world. The testing infrastructure is indicated across multiple layers – continent, research laboratories, and the components for which testing facilities are available. Our research shows Europe leads with 19 testing laboratories, followed by North America with nine laboratories. These laboratories can test almost all components across the hydrogen value chain. There is limited testing infrastructure in Asia, with most of it primarily located in China, India, Japan, and South Korea. The European Union (EU) has a significant diversity in testing infrastructure due to the presence of private laboratories and test setups. Electrolyser and fuel cell testing have the highest number of facilities across all the continents.

Figure ES1 Europe and North America are home to the majority of the hydrogen testing infrastructure



Source: Authors' analysis

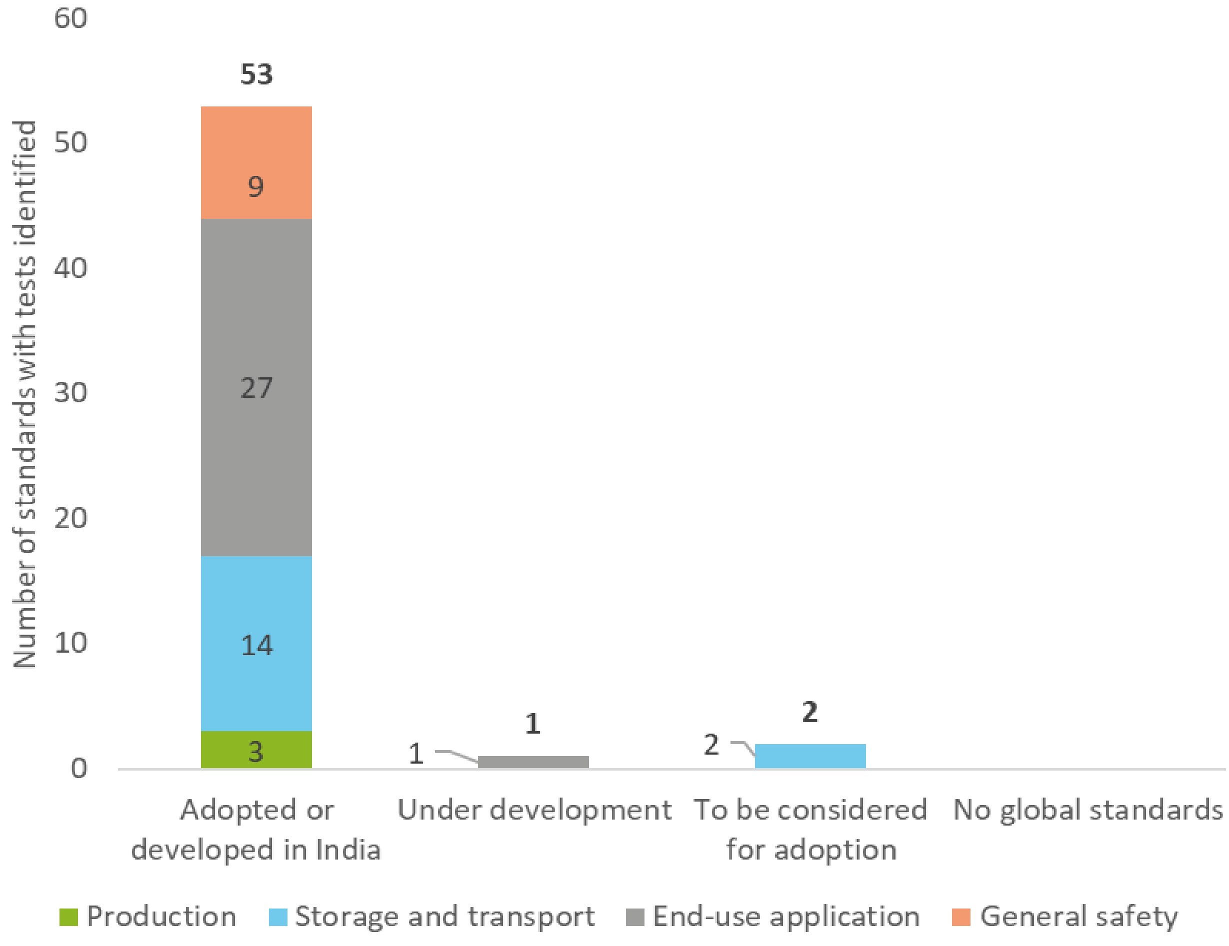
*Note:
NHPQITC: National Hydrogen Power Quality Inspection and Testing Centre; *HATIC:* Hydrogen Appliance Test & Inspection Center; *AHTC*: Advanced Hydrogen Technology Center

Indian hydrogen standards are at various stages of deployment; our previous publication provides a comprehensive listing of these standards (MNRE and CEEW 2024). In this report, we have included the new safety standards that were introduced by the Bureau of Indian Standards (BIS) after the publication of our previous report.

The hydrogen safety standards are classified under four categories: those adopted or developed in India, those under development, those considered for adoption, and those with no global standards. India has already adopted or developed 86 standards, focusing significantly on storage and transport (36 standards) and end-use application (33 standards). Additionally, 60 standards are currently under development, while 58 are being evaluated for potential adoption.

India has identified testing infrastructure requirements only for 53 out of the 86 standards developed or adopted in the country. Among these, there is a significant focus on end-use application (28 standards) and storage and transport (14 standards). Recognised labs are available for testing only six standards, four of which are partially covered, and testing infrastructure is under development for merely 15 more standards. Testing infrastructure has only been identified for those standards still being developed or under consideration for adoption (see Figure ES2). Based on the research findings it is evident that either there are no or limited testing laboratories for components across the green hydrogen value chain. This reveals a significant gap in testing infrastructure of the green hydrogen value chain in India.

Figure ES2 Out of 207 standards, testing infrastructure requirements have been identified only for 56 standards



Source: Karan Kothadiya/ MNRE-CEEW

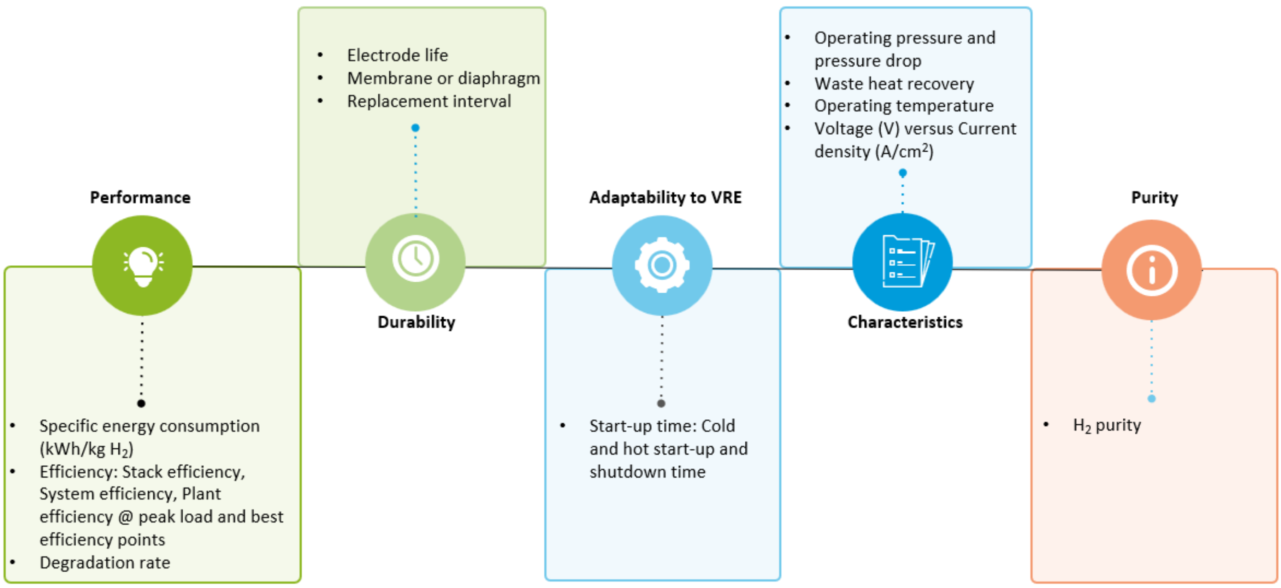
B. Testing infrastructure for performance evaluation

Performance testing of electrolysers and fuel cells is critical for ensuring the efficiency, durability, adaptability, and safety of hydrogen production systems and can be broadly classified into seven parameters. Figure ES3 lists the factors to be considered for the performance testing of electrolysers. Performance parameters include specific energy consumption (kWh/kg H_2), stack efficiency, system efficiency, plant efficiency at peak load, optimal operating points, and degradation rate.

Durability testing involves testing the lifespan of an electrolyser and its components, such as electrodes and membranes. Adaptability to variable renewable energy (VRE) is measured in terms of cold start-up time, hot start-up time, and shutdown time.

The operating characteristics of the electrolysers and fuel cells that require testing include pressure, temperature, the relationship between voltage (V) and current density (A/cm²), operation pressure and the pressure drop, and the waste heat generated due to the operation of the electrolyser over the thermo-neutral voltage. Material testing involves testing the characteristics of pipelines, tanks, and vessels, including material composition, material fatigue, and stress testing of materials that handle hydrogen. Gas quality testing for fuel cell applications requires H_2 purity of 99.99 per cent. Contaminants include O_2, CO, and N_2, which must be monitored and controlled within the limits. The hydrogen purity test involves gas chromatography, which evaluates whether the hydrogen produced meets the required purity standards (>99.99 per cent for fuel cells).

Figure ES3 Factors to be considered for performance testing of electrolysers



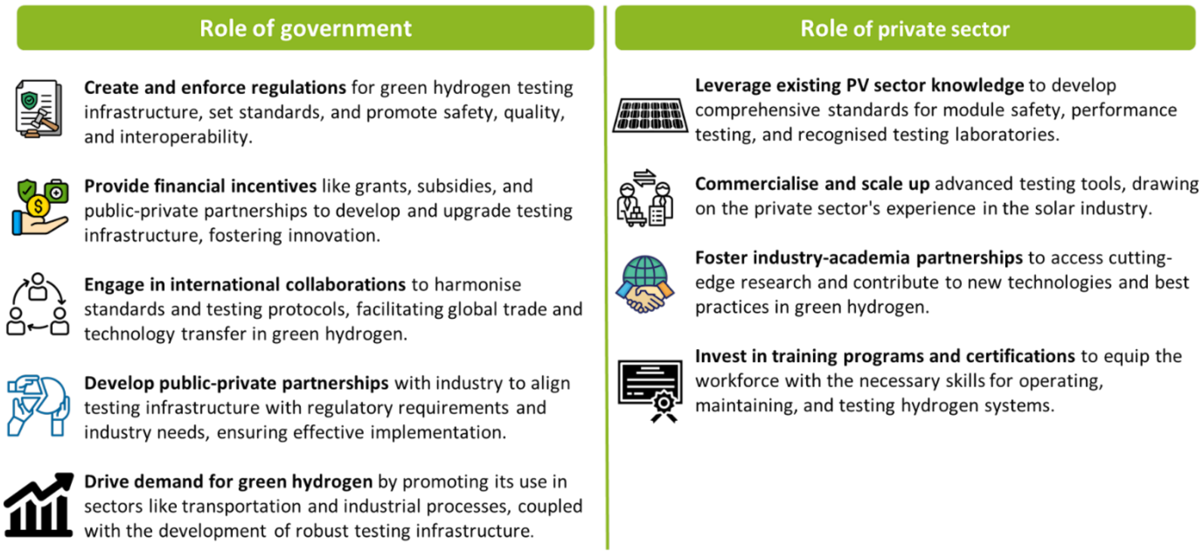
Source: Authors' analysis

Note: *VRE*-Variable Renewable Energy

C. Role of the government and private sector in developing hydrogen testing infrastructure

The government and private sector have a pivotal role to play in developing and scaling up the testing infrastructure for the green hydrogen value chain. Additionally, Mutual Recognition Arrangements (MRA) like NABL (signatory to International Laboratory Accreditation Cooperation (ILAC) as well as APAC) will also play a critical role in the accreditation process of these laboratories. Figure ES4 identifies the role of the government and private sector in accelerating the deployment of hydrogen testing facilities in India.

Figure ES4 Government and private sectors have an instrumental role in scaling up testing infrastructure deployment in India



D. Action plan on green hydrogen testing infrastructure

Establishing safety standards and testing infrastructure will play a key role in accelerating the green hydrogen economy in India. The following actions are required to strengthen testing infrastructure in India:

- Expedite standards development and identification of testing requirements by collaborating with standard-setting bodies to fast-track the adoption of standards under development. Additionally, identify necessary testing requirements and accredit relevant laboratories by NABL.

- Develop a priority list of testing infrastructure requirements and estimate the budgetary requirements by collaborating with industry stakeholders to prioritise and develop testing infrastructure for critical standards.

- Identify and develop performance testing infrastructure for critical components by focusing on the infrastructure needed for performance testing of key components such as electrolysers and fuel cells.

- Pursue international collaboration to leverage expertise from developed countries in North America and the EU and ensure interoperability in testing procedures.

- Incentivise private sector participation by encouraging investment in green hydrogen testing infrastructure, following the successful approach used in the solar sector.

Exponential growth in green hydrogen will require India to set up multiple testing setups and streamline the accreditation process to ensure a smooth transition

image: iStock

1. Introduction

Green hydrogen has emerged as one of the plausible alternatives to fossil fuels in the global transition towards a decarbonised economy. Several major economies have announced ambitious hydrogen strategies as part of their overall climate and clean energy–related efforts. The primary objectives of these strategies are to address the common challenges of maximising the production of green hydrogen, improving the usage of hydrogen in hard-to-abate sectors of the economy, advancing new technologies, and establishing supportive laws and regulations. The governmental financing and support of research and development (R&D) initiatives to generate demand and financial assistance for infrastructure development and manufacturing are critical in promoting green hydrogen as an energy carrier.

Green hydrogen is produced by the electrolysis process, which uses electricity from renewable energy sources such as solar, wind, or hydropower to split water into hydrogen and oxygen. Green hydrogen, thus produced, can help decarbonise several industrial and mobility sectors, including steel, shipping, and transportation. The demand for green hydrogen is likely to rise sharply with a decrease in the cost of production as it has the potential to unlock opportunities in the hard-to-abate sectors of the economy (Deloitte 2023). Its potential as an energy carrier depends on advancements in hydrogen production, storage, and utilisation technologies. As an import-dependent country, India must introduce initiatives to develop emerging technologies that can help improve the country's energy security. Advancements in these areas require consistent performance of all the equipment in the value chain while meeting stringent safety requirements. Therefore, establishing a robust testing infrastructure is vital to ensure the safety, reliability, and efficiency of these technologies.

At present, green hydrogen and its derivatives are yet to replace fossil fuels or fossil fuel–based feedstock due to higher costs, a lack of unified standards and regulations, supply issues, and the expensive infrastructure required to facilitate the transition. Consequently, this report aims to examine the existing state of green hydrogen testing infrastructure in India and identify gaps that must be addressed to accelerate the growth of the hydrogen economy in the country.

1.1. Green hydrogen growth trajectory in India

India aims to achieve energy independence by 2047 (PIB 2021) and net-zero emissions by 2070 (PIB 2021). Green hydrogen is anticipated to contribute significantly to reaching these objectives. India announced the launch of the *National Green Hydrogen Mission* (NGHM) in January 2023 (Ministry of New and Renewable Energy 2023). As part of the mission, India aims to develop its capacity to produce at least 5 million tonnes of green hydrogen per annum by 2030. The mission aims to substitute fossil fuels and feedstock with renewable fuels based on green hydrogen. This entails using green hydrogen instead of hydrogen derived from fossil fuels to produce ammonia and refine petroleum. Green hydrogen can also be blended in city gas distribution systems and used for producing steel and synthetic fuels (such as green methanol, green ammonia, etc.). Synthetic fuels can replace fossil fuels in mobility applications such as buses, trucks, aviation, and shipping. A key objective of the mission is to make India a leader in developing and producing electrolysers and other technologies that enable the production of green hydrogen.

India's green hydrogen market is already set for exponential growth, with its share of hydrogen demand projected to rise from 16 per cent in 2030 to nearly 94 per cent by 2050. This translates to a demand for 20 GW of electrolyser capacity by 2030 and 226 GW by 2050, opening up significant opportunities for indigenous manufacturing. The market value of green hydrogen in India could reach USD 8 billion by 2030 and soar to USD 340 billion by 2050, with the electrolyser market alone growing to USD 5 billion and USD 31 billion, respectively. Green hydrogen adoption is also expected to reduce CO_2 emissions by 3.6 gigatons and save between USD 246 billion and USD 358 billion in energy imports by 2050, enhancing energy security and stabilising industry costs (NITI Aayog, RMI 2022).

1.2. Need for robust testing infrastructure in India

The robust quality infrastructure is the backbone of a country's economic growth. The development of a quality infrastructure is the basis for any technology to foster and develop confidence. Advancing the development of green hydrogen will require India to focus on ensuring the safety and reliability of the technologies used across the value chain. India also needs to develop its capability to evaluate the performance of key components such as electrolysers and fuel cells while ensuring the quality of hydrogen production. Therefore, standards creation and a robust testing infrastructure need to be in place to guarantee safe hydrogen handling, quality control, and adherence to regulatory compliance.

Consumer and investor confidence can be enhanced by assuring them of the quality and safety of green hydrogen and the associated technologies through testing and certification frameworks. For example, developing a test procedure for electrolysers and creating the necessary ecosystem in India will significantly improve the project developers' and consumers' confidence regarding the performance and durability of electrolysers. This will further boost investors' confidence in the viability of the project and accelerate the adoption of green hydrogen.

Testing and certification can accrue various economic benefits, making hydrogen more competitive than traditional energy sources. Establishing testing infrastructure can drive innovation in these technologies and even reduce costs. For example, establishing electrolyser testing infrastructure will encourage R&D laboratories and academic institutions to evaluate the performance of newer electrolyser types being developed and compare them against commercially available technologies.

Therefore, developing a testing and certification framework for promoting green hydrogen in India is essential. By ensuring high standards of quality, safety, and regulatory compliance, India can build market trust to develop a green hydrogen ecosystem in India. This can also unlock economic incentives to transition to a sustainable energy future, positioning India as a leader in the global green hydrogen economy. Prioritising testing and certification support the safe and reliable integration of green hydrogen, contributing to a cleaner, more sustainable world.

1.3. Relevant agencies and organisations for identifying testing requirements

In India, the creation of standards and certification for green hydrogen and related technologies is the responsibility of various important organisations. Table 1 lists some prominent agencies that may contribute to creating standards and guidelines for testing infrastructure on green hydrogen in India.

Table 1 Organisations involved in the accreditation, certification and standardisation of hydrogen and related technologies in India

Sr. No.	Organisation	Description
1	National Accreditation Board for Testing and Calibration Laboratories (NABL)	NABL accredits labs in accordance with ISO/IEC 17025:2017 that perform tests on hydrogen purity, safety, and performance as credibility of green hydrogen technologies can be enhanced across a range of applications with testing from laboratories accredited by NABL. A NABL accreditation is a seal of approval that indicates labs follow stringent national and international standards for testing components and products across the hydrogen value chain (NABL n.d.).

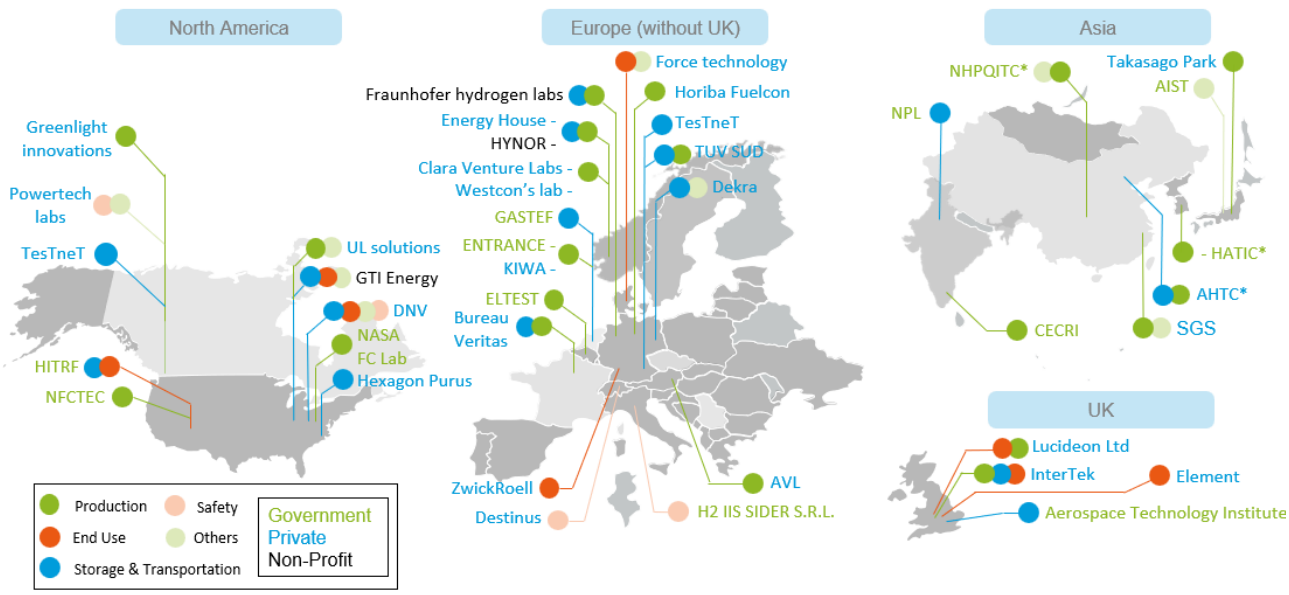
2	Ministry of Road Transport and Highways (MoRTH)	MoRTH formulates and administers policies for road transport, national highways, and transport research to increase the mobility and efficiency of the country's road transport system. MoRTH will enable the adoption of green hydrogen in the transport sector through regulations, standards, and codes, primarily for heavy commercial vehicles and long-haul operations. MoRTH will also facilitate technology development for the adoption of green hydrogen in the transport sector through testing facilities and pilot projects and provide support for infrastructure development (MoRTH n.d.).
3	Bureau of Indian Standards (BIS)	BIS is India's national standard body responsible for standardisation, marking, and quality certification of goods. BIS provides traceability and tangibility benefits to the national economy by providing safe, reliable, quality goods; minimising health hazards to consumers; promoting export and import substitution; and controlling the proliferation of varieties, etc., through standardisation, certification, and testing. BIS aims to make the handling of hydrogen safer, more reliable, and more efficient. It is working on several standards at different stages of implementation (BIS n.d.).
4	Oil Industry Safety Directorate (OISD)	OISD develops and standardises the oil and gas industry's protocols and guidelines relating to design, operation, and maintenance. It conducts audits to ensure compliance, keeps track of audit action items, investigates incidents to determine their causes, and develops action plans for the oil and gas industry, including hydrogen gas (OISD n.d.).
5	Council of Scientific and Industrial Research (CSIR)	CSIR is a national organisation for research and development. It researches numerous fields, including materials science, energy, biotechnology, chemistry, aerospace, and environmental science. In the hydrogen value chain, CSIR labs primarily focus on developing proton exchange membrane (PEM)-based fuel cells, Type III/Type IV compressed hydrogen tanks, and home modular electrolysers. CSIR has many labs in its network, some of which also deal with hydrogen testing (CSIR n.d.).
6	National Chemical Laboratory (NCL)	The NCL is a premier lab by CSIR. It conducts research in areas such as process development and materials chemistry, emphasising chemical sciences and engineering. CSIR-NCL is the nodal laboratory for the CSIR's hydrogen mission, working collaboratively to develop transformational technologies for reducing the cost of hydrogen production and its distribution, storage, and utilisation (NCL n.d.).
7	Petroleum and Explosives Safety Organization (PESO)	PESO monitors safety in the manufacturing/refining, storage, transportation, handling, and use of hazardous substances. It oversees the examination and disposal of explosives and improvised explosive devices. PESO is also responsible for safely handling and transporting green hydrogen and other related hazardous items (PESO n.d.).

1.4. Global status of testing infrastructure

The critical need for robust green hydrogen testing infrastructure has become increasingly evident as nations worldwide accelerate their transition to cleaner energy sources. As early adopters of innovative technologies, many countries are strategically positioning themselves to play pivotal roles in the global green hydrogen supply chain. The widespread adoption of green hydrogen has the potential to reshape energy trade dynamics, reduce a nation's reliance on fossil fuels, and provide energy independence for those with limited fossil fuel resources. This presents a unique opportunity for countries, even without abundant fossil fuel reserves, to diversify their energy portfolio by producing green hydrogen domestically and exploring export opportunities.

Consequently, many countries are trying to gain an edge in hydrogen deployment through various policies and incentives. Towards this end, countries are at varying stages of establishing comprehensive testing and certification frameworks for the entire hydrogen value chain, encompassing production, storage, distribution, and end-use applications. Figure 1 shows various government and private sector testing infrastructures located globally, along with the facilities available at these centres. Leading economies, such as the EU, China, Japan, and the United States (US), are making significant strides, investing heavily in developing standardised testing protocols and certification processes to ensure the safety, efficiency, and reliability of green hydrogen. These countries have specialised laboratories that primarily cater to one component of the value chain. A few laboratories have the ability to cater to multiple components. These laboratories are either government-owned or private laboratories. A few not-for-profit laboratories are also present globally. On the other hand, many developing countries are still in the nascent stages of building their testing capabilities, highlighting the need for international collaboration and support to create a cohesive global framework for green hydrogen standardisation.

Figure 1 Europe and North America are home to the majority of the hydrogen testing infrastructure

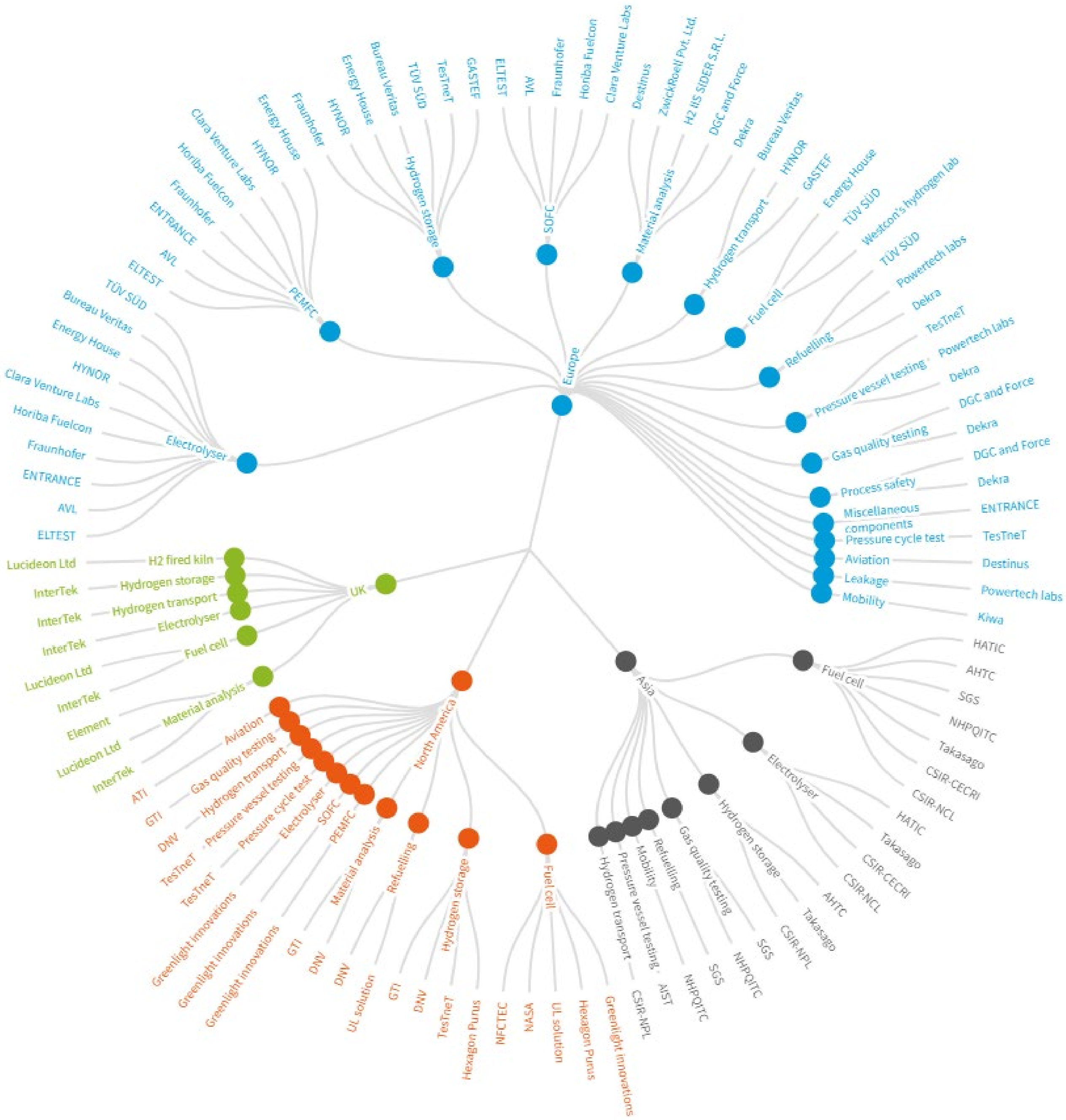


Source: Authors' analysis

*Note:
NHPQITC: National Hydrogen Power Quality Inspection and Testing Centre
HATIC: Hydrogen Appliance Test & Inspection Center
AHTC: Advanced Hydrogen Technology Center

Figure 2 illustrates the testing infrastructure of the hydrogen value chain across select geographies indicated in Figure 1. It presents the testing infrastructure under multiple categories – continent, research laboratories, and the components for which testing facilities are available. Our research shows that Europe has 19 testing laboratories, followed by North America, having nine laboratories that can test almost all components across the hydrogen value chain. There is limited testing infrastructure in Asia, located primarily in China, Japan, and South Korea. Hydrogen production, including electrolyser testing, is the most popular testing infrastructure across all continents.

Figure 2 **Multiple labs exist globally for testing of standards across the green hydrogen value chain**



Source: Authors' analysis

Table 2 provides a detailed overview of the testing facilities dedicated to hydrogen across the US and Canada. Through its *Hydrogen Shot* initiative (Office of Energy Efficiency and Renewable Energy n.d.), the US is heavily investing in reducing green hydrogen costs and driving significant advancements in hydrogen testing and certification. The US has a significant edge in terms of R&D support and finances available for its energy security. Canada has an extensive network of hydrogen testing facilities, particularly in fuel cell technology.

Table 2 Testing facilities related to hydrogen across the United States of America and Canada

Sr. no.	Testing facility; year established; and type	Description	Value chain	Specifications
A	United States of America			
1	National Fuel Cell Technology Evaluation Center (NFCTEC), Colorado; 2013; Government.	The NFCTEC manages, stores, and processes data related to fuel cell technology. It handles proprietary industry data and allows for the analysis of information on fuel cell status, development, and technical issues (NREL n.d.).	Fuel cell.	The NREL Fleet Analysis Toolkit (NRELFAT) has processing and analysis capabilities for various applications such as fuel cell vehicles, material handling equipment (forklifts), backup power, laboratory data, etc.
2	National Aeronautics and Space Administration (NASA) - Fuel Cell Testing Laboratory, Ohio; 2011; Government.	The Fuel Cell Testing Laboratory at NASA Glenn Research Center tests hydrogen fuel cells. The facility has multiple test stations and can handle nitrogen, oxygen, and hydrogen gases. This setup enables testing and analysing various fuel cell technologies (NASA n.d.).	Hydrogen/air and hydrogen/oxygen fuel cells.	Gas supply system Test cell supplied with hydrogen, oxygen, and nitrogen gases from 2,400 psig tube trailers and 12 Pack K-Bottle Station. Pump 10 GPM at 60 psi. Fuel cell capacity 1 to 125 kW.
3	Hydrogen Technology Center of Gas Technology Institute (GTI) Energy, Des Plaines, Illinois; 2020; Non-profit.	Hydrogen Technology Center by GTI is an integrated testing and demonstration facility. It has R&D capacity across the entire hydrogen value chain (production, storage, delivery, and use). GTI Energy operates over a dozen separate labs and facilities for testing, modelling, and designing hydrogen technology (GTI Energy n.d.).	High-pressure hydrogen storage, gas quality testing, materials analysis, hydrogen production, hydrogen compression, and evaluation of hydrogen compatibility with end-use equipment.	---
4	Hexagon Purus, Maryland; 2020; Private	Hexagon Purus is a major provider of hydrogen Type 4 high-pressure cylinders and systems, battery systems, and vehicle integration solutions	Storage and distribution systems. (They have in-house test capabilities for hydraulic, leak, burst testing, bonfire, penetration, and	Cylinder Available in the pressure levels 250, 300, 500, 700, and 950 bar. Distribution system

		including testing for fuel cell electric and battery electric vehicles (Hexagon Purus n.d.).	permeation to ensure safety and quality standards.)	Flexible sizes ranging from 10 ft to 45 ft are available as standard modules.
5	Det Norske Veritas (DNV), Columbus, Ohio; 2021; Private.	DNV sets and checks requirements for safe and reliable design, construction, and use of hydrogen. It publishes risk studies and develops and supports regulatory documentation. It also has a dedicated lab for quantifying material performance for hydrogen transportation and storage applications and offers services in general material compatibility, fracture, and fatigue performance evaluation (DNV n.d.).	Materials testing, transportation and storage assets, hydrogen systems and components on board maritime vessels, hydrogen refuelling stations, developing guidelines and standards for hydrogen safety and quality, identifying safe limits for hydrogen in natural gas appliances, and reviewing concept designs of hydrogen carriers.	25 dedicated hydrogen test frames running fracture toughness, fatigue crack growth, and constant load tests in hydrogen environments. 5 to 15 kip: all equipped with high-precision potential drop system for crack growth measurement. Autoclaves capable of H_2 pressure up to 300 bar.
6	UL Solutions, Illinois; Private.	It provides testing and certification services to gauge the safety, reliability, and performance of fuel cells and products powered by alternative fuels such as hydrogen (UL Solutions n.d.).	Hydrogen dispensing systems, fuel cell testing, and certification.	The lab has the capability to test fuel cells as per the following standards: UL 2267 UL 2262A UL 2265A UL 2265C, ANSI CSA FC1 ANSI CSA FC3 IEC 62282-2 IEC 62282-3-100.
B	Canada			
7	TesTneT (by UL Solutions), Vancouver; 2020; Private.	TesTneT provides testing services to the alternative fuels industry, including high-pressure hydrogen fuel systems (TesTneT n.d.).	Storage, hydrogen gas cycle testing, component pressure testing.	It performs material tests according to the following standards: ANSI/CSA HPRD 1 ANSI/CSA HGV 3.1 ANSI/CSA HGV 4.1 to 4.7 EU 406-2010 / EC 79-2009 ISO 19880-3: 2018 ISO 19880-5: 2018 ISO 17268: 2019 ISO 17628 SAE J2600 ISO 15500: 2015 ISO 12619: 2014

				UNECE R134 / UN GTR 13.
8	Powertech Labs, Vancouver; Private.	The Fuel Systems Testing Lab of the Powertech Labs performs various tests and develops custom test apparatuses to meet vehicle OEM internal performance or durability test procedures on high-pressure vehicle fuel systems (Powertech labs n.d.).	Hydrogen fuelling tests, hydrogen gas pressure-cycling, static and dynamic hydrogen leakage testing, and drive cycle simulation.	Fuel cell temperature -40°C to +50°C. Hydrogen storage 87.5 MPa and 95 MPa.
9	Greenlight Innovations, Burnaby; 1992; Private.	Greenlight Innovation manufactures testing and assembly equipment for hydrogen fuel cells and electrolysers (Greenlight Innovation n.d.).	Electrolysers and fuel cell	Fuel cell: 100W-300kW. Electrolyser: up to 4 MW.

Table 3 presents an in-depth overview of the testing facilities focused on hydrogen technologies throughout Europe, excluding the United Kingdom (UK). It encompasses various institutions, laboratories, and research centres that advance hydrogen technology and safety. These facilities help develop and certify hydrogen technologies, reflecting Europe's commitment to advancing sustainable energy solutions. European nations have led decarbonisation efforts with early net-zero targets compared to other countries. Hence, they have paved the way for the widespread adoption of hydrogen-related testing infrastructure, mirroring the region's early adoption of solar technologies.

Table 3 Testing facilities related to hydrogen in Europe (excluding the UK)

Sr. No.	Testing facility; year established; and type	Description	Value chain	Specifications
A	European Union (EU)			
10	ELTEST, Belgium; 2022; Government	This electrolyser testing facility tests electrolysers, fuel cells, and stacks for performance and durability assessment, as well as the harmonisation and standardisation of test methods and protocols (EU Science Hub n.d.).	Electrolysers and fuel cells.	---

11	High Pressure Gas Testing Facility (GASTEF), Petten; Government.	The GASTEF facility is designed to test high-pressure tanks for hydrogen storage according to the procedures prescribed by current type approval regulations (GASTEF n.d.).	Storage and transportation.	Tests according to the European Regulation EU 406/2010 on type-approval of hydrogen vehicles and by other international regulations and standards such as UN Regulation No. 134 or ISO and SAE standards.
B	**Germany**			
12	HORIBA Fuelcon, Barleben; Private.	HORIBA Fuelcon has facilities to test electrolyser manufacturing plants. Their goal is to create solutions that bundle together all competencies in the field of electrolysis and hydrogen tests (Horiba Fuelcon n.d.).	Electrolysers and fuel cells.	Pressure management Up to 100 bar. Power requirements 10 W to 5 MW. Current requirements Up to 16,000 A. Voltage requirements Up to 1,200 V.
13	TesTneT (by UL Solutions), Munich; 2015; Private	TesTneT is dedicated to providing testing services to the alternative fuels industry, specialising in high-pressure hydrogen fuel (TesTneT n.d.).	Storage, hydrogen gas cycle testing, component pressure testing.	They perform various material tests according to the following standards: ANSI/CSA HPRD 1 ANSI/CSA HGV 3.1 ANSI/CSA HGV 4.1 to 4.7 EU 406-2010 / EC 79-2009 ISO 19880-3: 2018 ISO 19880-5: 2018 ISO 17268: 2019 ISO 17628 SAE J2600 ISO 15500: 2015 ISO 12619: 2014 UNECE R134 / UN GTR 13.
14	Technischer Überwachungsverein (TÜV SÜD), Garching; 2022; Private.	TÜV SÜD operates a laboratory that conducts tests on hydrogen components, fuel cells, and storage systems. Their testing services cover products for industrial, energy, and vehicle component manufacturers. The laboratory performs component and material testing related to hydrogen, assessing product safety and component performance over time (TUV SUD n.d.).	Fuel cells, hydrogen fuel stations, fuel cell modules, electrolysers, and hydrogen storage systems.	Pressure cycle, leakage, and tightness tests; overpressure, burst and flow tests; hydrogen permeation and compatibility testing; hydraulic tests; environmental simulation tests; electromagnetic compatibility tests; and vibration tests.

15	Dekra, Klettwitz; 2019; Private.	DEKRA is authorised by the Clean Energy Partnership to independently test and certify hydrogen refuelling stations (Dekra 2023).	Inspection of pressure equipment and certification, non-destructive testing (NDT) of material, process safety, hydrogen quality testing, and hydrogen refuelling stations.	They test refuelling stations for compatibility with ISO 19880-1c.
16	Fraunhofer Hydrogen Labs, Bremerhaven; 2022; Non-profit.	The Fraunhofer Hydrogen Labs are engaged in multiple stages of hydrogen production and use process. Their facilities include electrolysis optimisation, electrolyser manufacturing, and green hydrogen storage and transport systems. The labs contain pilot plants engaged in various stages of hydrogen production and distribution process (Fraunhofer hydrogen labs n.d.).	Electrolysers, fuel cells, and storage units.	Electrolysis stack test benches up to 2 MW. Fuel cells with a total capacity of 12.3 MW
17	ZwickRoell Pvt. Ltd., Ulm; Private.	They offer testing of mechanical materials in the hydrogen industry pertaining to the entire value chain (ZwickRoell n.d.).	Fuel cells and material testing.	Autoclave testing in a compressed hydrogen environment up to 400 bar; special versions up to 1,000 bar. Hollow specimen testing under compressed hydrogen environment up to 200 bar.
C	Norway			
18	Energy House (The Switch), west coast of Norway; 2021; Private.	The test centre has the potential to test energy generators for future energy sources, such as ammonia, hydrogen, liquefied natural gas, biogas, and synthetic fuels. Companies can rent space and equipment to test individual components as well as complete systems (Energy House n.d.).	Electrolysers, fuel cells, and storage tanks.	Electrolyser Distribution capacity: 18 kg/h. Outlet pressure: 35 bar. Storage tank Storage capacity: 271 kg /20 ft container. Distribution capacity: 18 kg/h. Outlet pressure: < 6 bar(g). Fuel cell Electric power: 185 kW.

19	Clara Venture Labs, Bergen; Private.	Clara Venture Labs has test facilities for various small-scale gas solutions, including hydrogen. It has an energy lab for fuel cell testing and other tests (Clara Venture Labs n.d.).	Electrolyser and fuel cells.	Research on fuel cells for space technologies.
20	HYNOR, Kjeller; 2003; Non-profit	HYNOR is IFE's (Institute for Energy) test centre for hydrogen. It tests new core technologies for hydrogen, such as water electrolysis or fuel cells. HYNOR has laboratories for blue and green hydrogen production, liquid hydrogen storage, and test facilities for PEM fuel cells (HYNOR n.d.).	Electrolyser, fuel cells, storage, and transportation.	Electrolyser capacity 33 kW. Fuel cell capacity 20 kW. Sorption-enhanced reformer (SER) plant capacity 20 kg H_2 /day.
21	Westcon's Battery and Hydrogen Lab, Stord; 2020; Private.	This lab provides a testing facility for the next generation of hydrogen and hybrid systems for future marine and mobility projects. It has a fully integrated test bed for energy systems, including fuel cells (Westcon's battery and hydrogen lab n.d.).	Fuel cells.	---
D	Rest of Europe			
22	Anstalt für Verbrennungskraftmaschinen List (AVL), Austria; 2022; Private.	AVL is involved in fuel cell development and testing. The company provides testbed systems, measurement devices, and tools for the hydrogen fuel cell industry, including applications in the automotive and aviation sectors. It supports the development and testing of fuel cells for both stationary and mobile uses (AVL n.d.).	Electrolyser and fuel cells.	Pressure variants LP / HP / HP+ 25 bar / 70 bar / 400 bar. Ambient conditions Main Module: 5–50 °C. UUT Module: - 40–85 °C. Fuel cell capacity 5 kW to 400 kW.
23	Destinus, Switzerland; 2024; Private.	The facility is designed to test high-performance propulsion systems, turbomachinery, and cryogenic equipment using gaseous hydrogen and oxygen, liquid hydrogen and nitrogen, and conventional kerosene (Destinus n.d.).	Material testing and applications of liquid and gaseous hydrogen in the aviation industry.	The test site will be capable of testing 50 kN motors at a flow rate of 0.5 kg/s of liquid hydrogen and nitrogen in a controlled environment.
24	Bureau Veritas, France; Private.	Bureau Veritas offers hydrogen risk assessment and safety-related services, hydrogen supply chain quality assurance, technical advisory, owner's engineering, and independent quality testing (Bureau Veritas n.d.).	Electrolyser, fuel cells, storage, and transportation.	European market according to Directive 79/2009 (Dir. 79/2009). American market according to HGV 3.1.

25	Danish Gas Technology Center (DGC) and FORCE technology, Denmark; 2021; Private.	The hydrogen technology testing centre of DGC, in partnership with FORCE technology, offers testing and analysis to all green transformation actors involved in the production, transportation, and use of hydrogen for all hydrogen technologies. The testing centre assists with everything from boilers to fuel cells (Force Tehnology n.d.).	Testing materials and components, hydrogen quality testing, energy system efficiency and safety, on-site inspections (land and offshore), and modelling and calculation.	Fuel cell capacity kW to GW scale.
26	H2 IIS SIDER S.R.L., Italy; 2022; Government	The Italian Institute of Welding (IIS) and SIDER TEST have tests for materials in a hydrogen environment under pressure (H2 IIS SIDER n.d.).	Material testing (Static, long term and cyclic tests).	Pressure Up to 1500 Bar.
27	ENTRANCE centre of expertise energy, Netherlands; 2023; Government	Facilities are available to test new equipment, electrolyser stacks, components, and materials in the Hydrohub MegaWatt Test Center (ENTRANCE energy n.d.).	Electrolyser and fuel cell components.	Two different electrolysis installations of 250 kilowatts each: a PEM electrolyser and an alkaline electrolyser (AE).
28	Kiwa, Netherlands; Private.	Kiwa offers testing and certification services for automotive components in the hydrogen sector. Kiwa is authorised to issue the E4 certification by the Dutch Vehicle Authority (RDW) (Kiwa n.d.).	Test centre for automotive vehicles using hydrogen.	Pressure up to 1.100 bar Fuel cell Temperature -50 and 120 ^oC

Table 4 offers a detailed overview of the testing facilities dedicated to hydrogen technologies within the UK. The UK government has taken a colour-agnostic stance on hydrogen, suggesting the UK supports all forms of low-carbon hydrogen (UK Government 2021). This aligns with the UK's broader strategy of establishing itself as a leader in hydrogen technology and a first mover in hydrogen supply chains. As a result, it has developed and incentivised key policy measures to establish robust testing infrastructure.

Table 4 Testing facilities related to hydrogen in the United Kingdom

Sr. No.	Testing facility; year established; and type	Description	Value chain	Specifications
A	United Kingdom			
29	Aerospace Technology Institute, Bedford; 2023; Government.	The institute is establishing medium-scale hydrogen test hubs in the UK to provide the required testing infrastructure, LH_2 supply and expertise to satisfy UK aerospace priority test needs (Aerospace Technology Institute 2024).	Hydrogen supply and storage handling for aviation fuel.	---

30	Lucideon Ltd, Staffordshire, 2022; Private.	The company has an R&D facility for intermittent/batch ceramic kilns using hydrogen fuel. They also perform R&D for materials used in the fuel cells and provide evaluation services. Additionally, they are actively engaged in conducting material testing for various components of the hydrogen value chain (Lucideon n.d.).	Hydrogen-fired kilns, fuel cells, and material testing.	Kiln Temperature Up to 1650°C (in oxidising and reducing atmospheres).
31	Element, London; 2023; Private.	Element has extensive technical expertise in testing materials, coating, and electrochemistry in environmental conditions (Element n.d.).	Material testing.	Cryogenic testing for mechanical and fracture mechanics in cryogenic environments as low as -268°C.
32	Intertek, Surrey; 2022; Private.	InterTek delivers comprehensive quality, safety, and sustainability assurance across the hydrogen value chain. From initial project feasibility and product design to hydrogen production, delivery, and storage, and end-use product compliance and certification (InterTek n.d.).	Material testing, electrolyser, fuel cell, storage, and transportation.	---

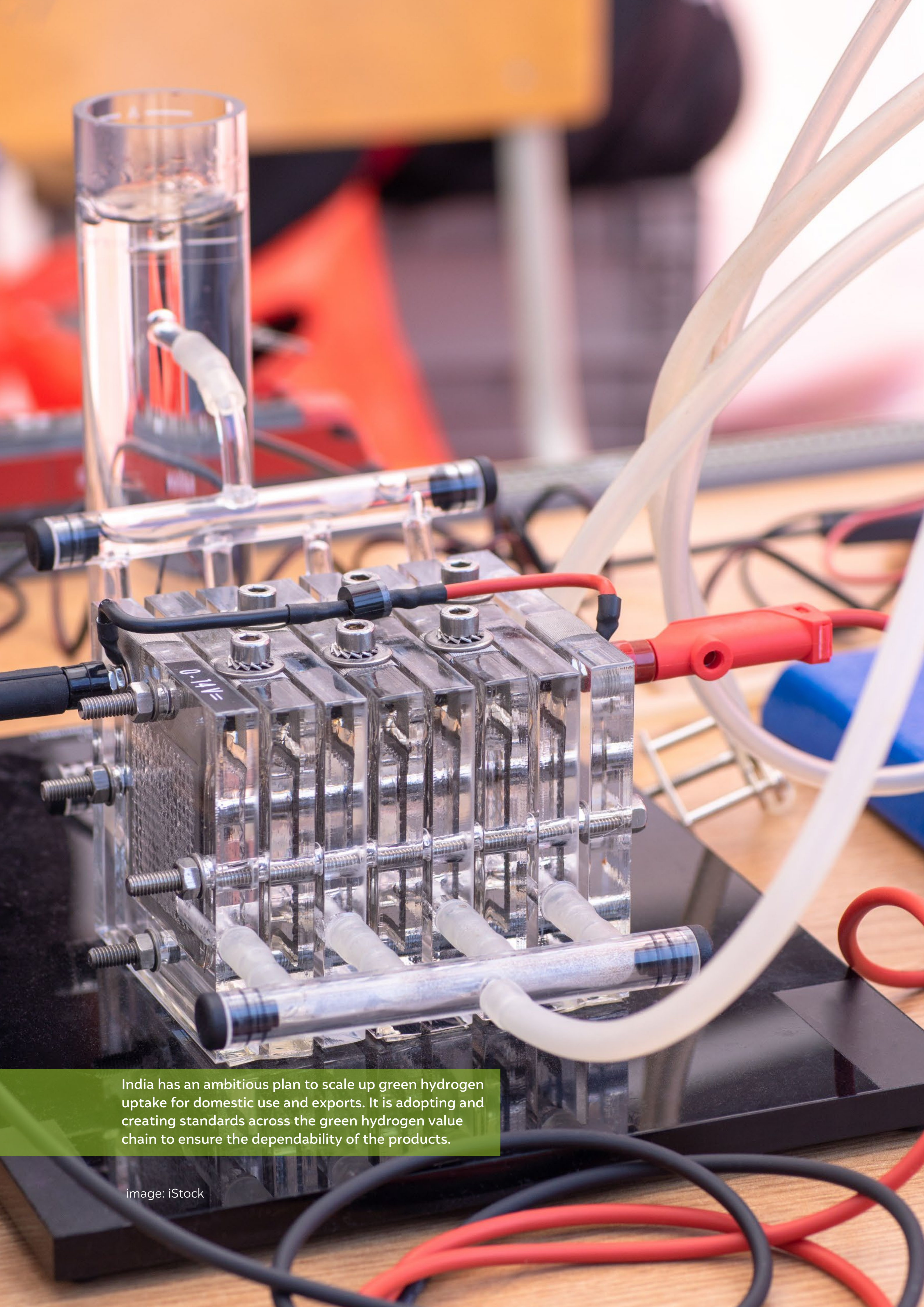
Table 5 provides a comprehensive summary of testing facilities dedicated to hydrogen technologies in Asia. China, Japan, and South Korea have been at the forefront of developing extensive testing infrastructure to meet their respective green hydrogen targets. India is also expanding its testing facilities with the help of various public and private initiatives. China aims to dominate green hydrogen production and supply chain, which it has already achieved in combination with other renewable energy technologies such as solar, wind, and batteries. Unfortunately, little information is available on testing infrastructure plans in Asia compared to North America and Europe. Table 5 lists the limited information available from China, India, Japan, and South Korea regarding testing the infrastructure for green hydrogen.

Table 5 Testing facilities related to hydrogen across Asia

Sr. No.	Testing facility; year established; and type	Description	Value chain	Specifications
A	China			
33	National Hydrogen Power Quality Inspection and Testing Centre (NHPQITC), Chongqing; 2023; Government.	The centre conducts tests for fuel cell vehicles, hydrogen quality, and motor batteries, encompassing the whole industrial chain of hydrogen energy. Additionally, a big data platform for hydrogen energy production, storage, transportation, processing, and vehicle scheduling has been developed (Leigh 2023).	Hydrogen quality, fuel cells, and vehicles and their parts.	Fuel cell temperature -40°C to +80°C

34	Advanced Hydrogen Technology Center (AHTC), Baoding; 2019; Private.	The Hynergy team has contributed to the planning, implementing, and commissioning of China's most Advanced Hydrogen Technology Center in Baoding, northwest China. The centre undertakes prototyping and testing facilities for almost all the value chains of fuel cell electric vehicles (FCEV) (Hynergy n.d.).	Fuel cells and storage.	---
35	SGS, Shanghai; 2022; Private.	SGS has an ISO/IEC 17025 accredited laboratory and is one of the first independent laboratories to analyse hydrogen to full specification against various standards listed in the specification column (SGS 2022).	Fuel cells, hydrogen quality testing, and fuelling stations.	ISO 21087:2019 (which covers gas analysis – PEM fuel cell applications for road vehicles) ISO 14687:2019 (which covers hydrogen fuel quality and product specification) GB/T 37244-2018 (which covers PEM fuel cells for automotive use)
B	India			
36	CSIR-CECRI and CSIR-NCL	The fuel cells and electrolyser testation facilities at CSIR are Indigenously developed and assembled (CSIR - CECRI n.d.).	Fuel Cells and electrolysers	Upto 30 kW Fuel Cells at CSIR CECRI AEM electrolyser testation up to 12 kW at CSIR-NCL
37	CSIR-NPL	Developing the capability of various teste as per IS /ISO for Hydrostatic Test, Pneumatic Leakage Test etc (CSIR-NPL n.d.)	---	---
C	Japan			
38	Takasago Hydrogen Park- Mitsubishi, Hyogo Prefecture; 2023; Private.	Takasago Hydrogen Park is an integrated validation facility for technologies ranging from hydrogen production to power generation. It has three divisions based on hydrogen-related functions: production, storage, and utilization (Mitsubishi Heavy Industries Group n.d.).	Fuel cells, electrolysers, storage, and utilisation.	Electrolyser capacity: 1,100Nm3/h Storage capacity: 39,000 Nm3

39	National Institute of Advanced Industrial Science and Technology (AIST), Tokyo; 2022; Government.	AIST is developing a set of hydrogen technologies using electric power generated by fluctuating renewable energy: hydrogen production by water electrolysis, chemical conversion to a hydrogen energy carrier, and utilisation of hydrogen. Basic technologies such as producing hydrogen energy carriers, catalysts and hydrogen engines are applied to large-scale demonstration equipment (AIST n.d.).	Direct coupled photovoltaic-electrolyser system, various analysers, and high-pressure hydrogen facility.	Hydrogen generation capability by alkaline water electrolysis: 34 Nm3/h Hydrogenation to toluene: 70 L/h (Methyl cyclohexane production capacity). Methyl cyclohexane storage capacity: 20 kL (conversion to power generation: about 10 MWh). Cogeneration output (electric power and heat): power 60 kW and heat 35 kW
C	**South Korea**			
40	Hydrogen Appliance Test and Inspection Center; 2024; Government	KGS is one of the important Korean hydrogen certifications. It mainly concerns fuel cells (fixed and portable) and electrolysers (including PEM and AEM hydrogen generators). In applications using liquified hydrogen, additional safety requirements and permits are needed to obtain approval for components such as pressure vessels or entire facilities. In the hydrogen transportation sector, safety valves and pressure vessels on trailers or ammonia-cracking plants are also relevant for KGS approvals (Busch 2024).	Electrolysers, fuel cells, hydrogen refuelling, and pressure vessels.	---



India has an ambitious plan to scale up green hydrogen uptake for domestic use and exports. It is adopting and creating standards across the green hydrogen value chain to ensure the dependability of the products.

image: iStock

2. Overview of Indian testing infrastructure

Testing infrastructure for green hydrogen is crucial for India's progress towards its climate and strategic goals. India, therefore, needs to establish comprehensive testing facilities that address every facet of the hydrogen value chain, including production, storage, transportation, end-use, and safety. Collaboration between government and private entities will be essential to develop these infrastructures.

India's testing infrastructure for green hydrogen is currently in its early stages. However, it is poised to develop rapidly to support the growing demand for hydrogen technologies. NABL accredited labs will be sensitised to scale up and come forward to develop infrastructure for testing as per recently developed standards and support the Green Hydrogen Mission.

The country has a limited number of specialised laboratories, the Central Institute of Petrochemicals Engineering and Technology (CIPET), or BIS specialised labs capable of testing mainly the storage part in the value chain of green hydrogen. These include cylinder and leak testing, primarily housed within government research institutions and a few industrial R&D centres. The Indian Institute of Petroleum, CSIR labs, and select Indian Institutes of Technology, among others, can support India's testing infrastructure as they already have R&D centres for green hydrogen technologies.

CSIR NCL has developed an indigenous multi station testing facility to test AEM stacks with various capacities using local resources. This single facility is capable of parallelly testing AEM stacks of a few 100 W to few kW capacity under four well-integrated inbuilt test benches. It is automated to operate stacks for long durations with safety systems for gas mixing hazards, safety alarms, emergency stops, nitrogen dilution, safety shutdown etc. Apart from routine electrochemical data collection, it is also capable of real-time monitoring of downstream gas production rates, hydrogen purity, individual cell voltage data, temperature and pressure data that are crucial for technology development.

Fuel cell testing, particularly for automotive applications, is also in progress, with centres such as the Automotive Research Association of India (ARAI) planning to develop a dedicated testing facility (ARAI 2023). Additionally there are a few private labs as well which perform testing and are listed in the table 6-10 below. Despite these capacities, India faces several challenges in developing green hydrogen testing infrastructure. The current setup is insufficient to meet the projected demand across the value chain, and there is a need to establish an extensive network of facilities that can match international testing standards. Moreover, the lack of standardised testing protocols for green hydrogen poses a significant challenge. Addressing these gaps requires substantial investments to upgrade existing facilities and establish new ones.

India plans to expand its testing infrastructure through various government initiatives and by promoting private sector investments. The plans include developing new testing facilities to validate and certify these elements, ensuring their safety and efficiency. Upgrading existing facilities with cutting-edge capabilities is equally essential to maintain high standards in testing. The Government actively supports these efforts through its *National Green Hydrogen Mission* (NGHM) (Ministry of New and Renewable Energy 2024). The proposed new testing facilities aim to accelerate and expand India's current capability, ensuring the necessary infrastructure is in place to support large-scale hydrogen deployment. International collaboration will also play a pivotal role in this growth, ensuring that Indian facilities meet global standards and contribute to the international hydrogen market. By investing in infrastructure, developing standards, and through strategic global partnerships, India aims to build a robust testing ecosystem to support its ambitious green hydrogen goals.

2.1. Methodology for the compilation of testing procedures across the green hydrogen value chain in India

Our findings of the hydrogen testing infrastructure and procedure in India are based on engagement with key regulatory and research bodies, including the BIS, PESO, MoRTH, OISD, CSIR and NCL and accreditation bodies like NABL. The objective was to gather information on the current status of tests and standards related to green hydrogen, identify ongoing efforts, and recognise gaps that need to be addressed. We contacted these key regulatory and research bodies and requested detailed information using a standardised template. The template was designed to categorise the data into three areas:

1. Pre-existing standards: Safety standards in place before the launch of NGHM (4th January, 2023) and those launched after NGHM were listed under this category.
2. Standards under development: Standards being developed at the national level by the respective regulatory bodies were listed in this category.
3. Standards to be developed: Areas requiring new standards to ensure the safe, efficient, and sustainable use of green hydrogen were listed under the category.

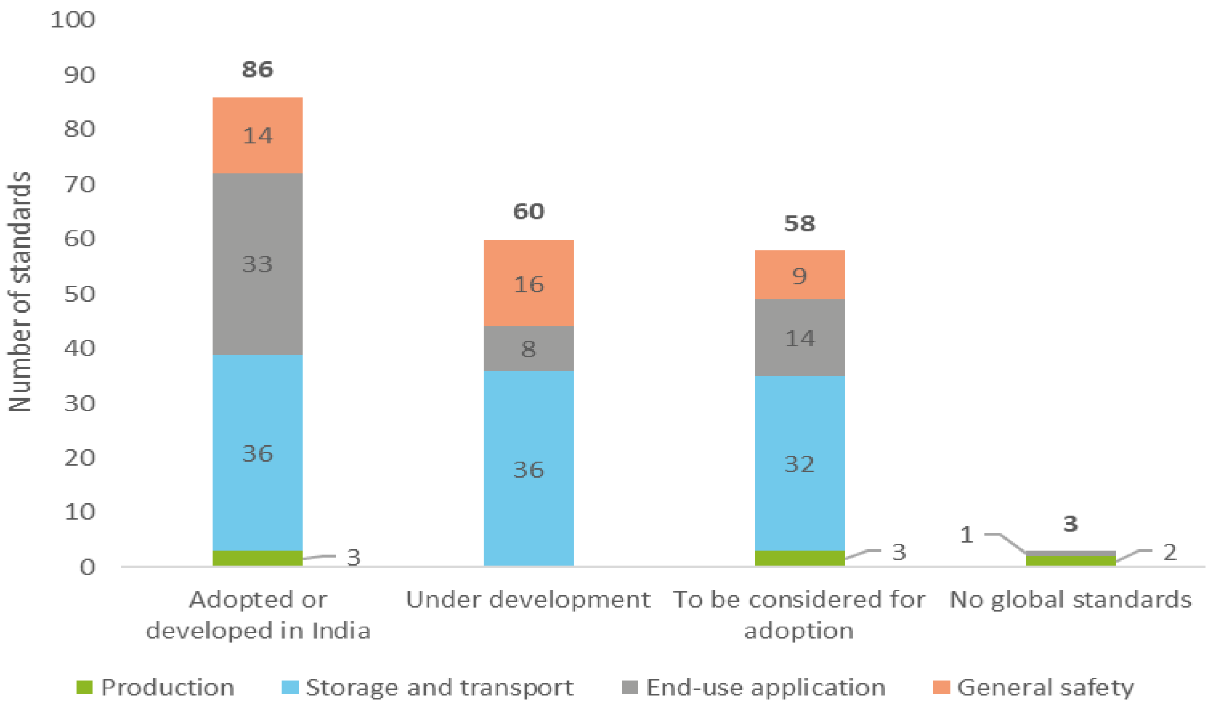
A detailed description of standards under each category can be found in our previous publication (MNRE and CEEW 2024). In addition to safety standards, we reviewed the literature on performance testing, especially for critical components such as electrolysers and identified key parameters to be measured in the testing infrastructure.

2.2. Testing infrastructure for safety standards in India

Establishing standards in hydrogen testing infrastructure indicates a country's active approach to building a comprehensive regulatory framework for hydrogen technologies. A comprehensive listing of all standards can be found in our previous publication (MNRE and CEEW 2024). Figure 3 presents the current state of hydrogen standards in India; it includes a few new standards that BIS included after the publication of our previous report. The safety standards are distributed across four categories: those adopted or developed in India, those under development, those being considered for adoption, and those with no global standards.

India has already adopted or developed 86 standards, focusing significantly on storage and transport (36 standards) and end-use application (33 standards). Additionally, 60 standards are currently under development, while 58 are being evaluated for potential adoption. However, out of the 86 existing standards in India, recognised labs for testing are available for only six standards, four of which are covered partially. Moreover, testing infrastructure is under development for 15 additional standards. This highlights a significant deficiency in testing infrastructure across India's green hydrogen value chain in India (MNRE and CEEW 2024).

Figure 3 India can develop and adopt about 207 standards across the green hydrogen value chain

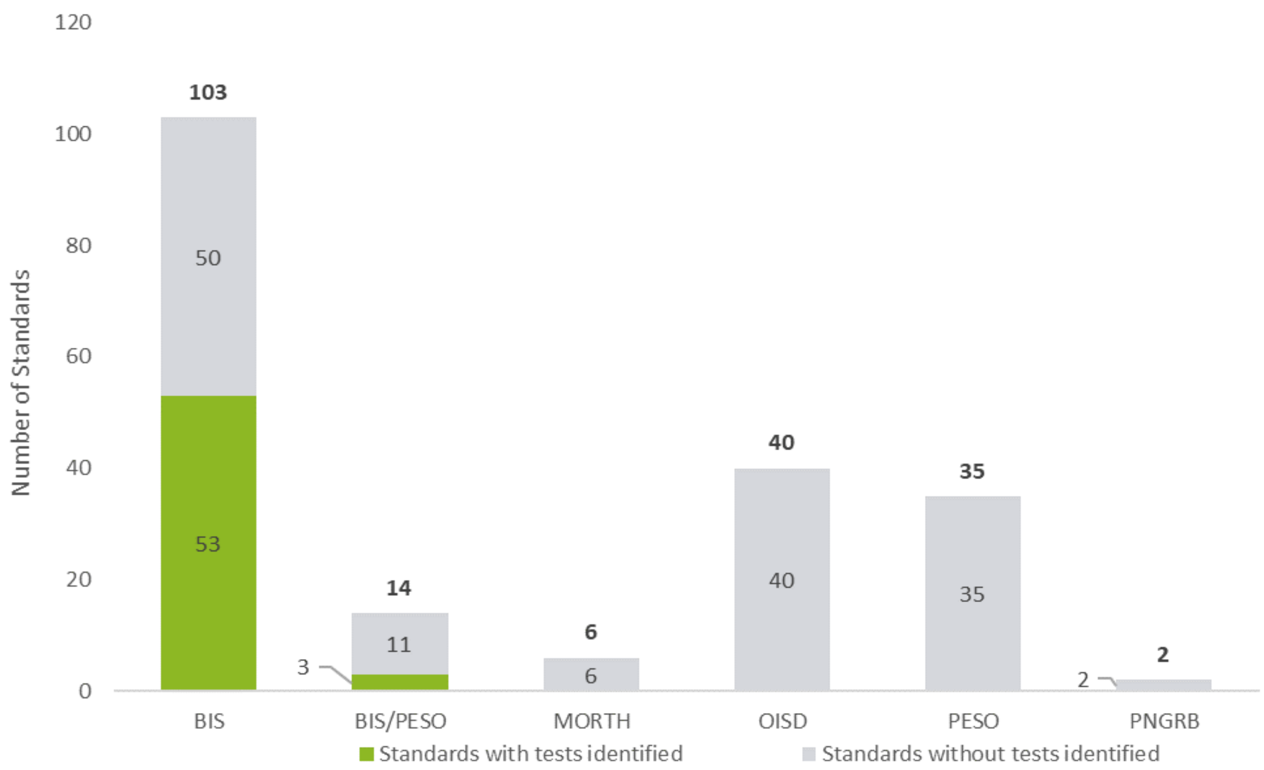


Source: Karana Kothadiya/ MNRE-CEEW

2.3. Mapping of testing infrastructure requirements

The Government of India is prioritising the development of testing infrastructure in the country. As a first step, the regulatory bodies in India are working towards identifying the testing requirements under specific safety standards and labs that can conduct these tests. Figure 4 lists the total number of standards within the purview of various regulatory bodies in India. The standards for which testing infrastructure has been identified are indicated in green in the figure. In contrast, those for which the testing requirements are yet to be identified are indicated in grey. Out of 103 standards under its purview, BIS has identified testing requirements for 53 standards. Further, BIS and PESO together have identified testing requirements for 3 out of 14 standards. However, the testing infrastructure requirements for other standards are yet to be identified by the relevant agencies in India. This shows that the development of testing infrastructure is at a very nascent stage in India.

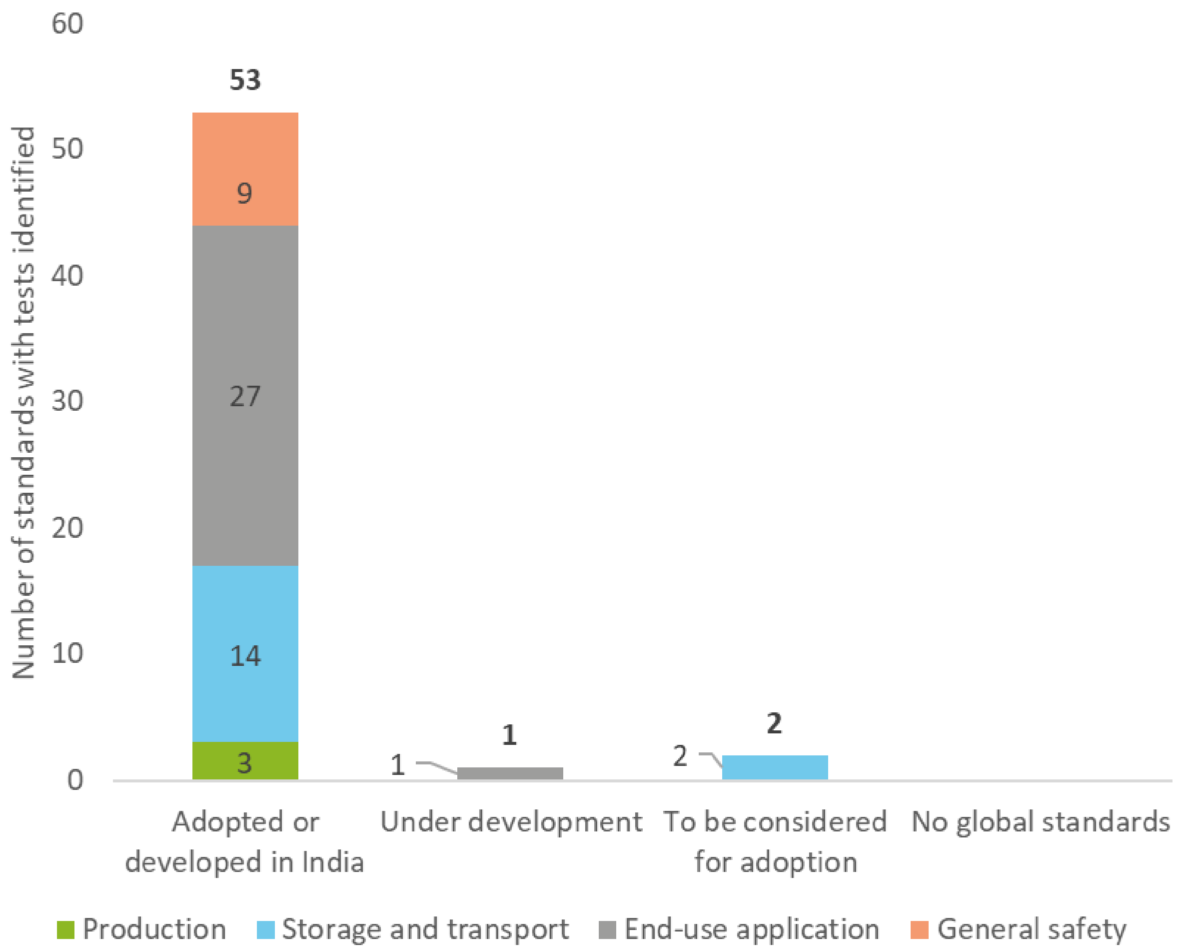
Figure 4 Testing requirements related to green hydrogen are yet to be fully identified in India



Source: Authors' analysis

Figure 5 presents the current state of hydrogen standards (whose tests have already been identified) being developed in India. These standards are distributed under four categories: those adopted or developed in India, those under development, those being considered for adoption, and those with no global standards. India has already identified testing infrastructure requirements for 53 standards developed or adopted in the country. The identification of the testing infrastructure requirement is low for standards under development or standards that must be considered for adoption. Overall, there is a significant focus on end-use applications (28 standards) and storage and transport (14 standards).

Figure 5 Out of 207 standards for Hydrogen, testing requirements have been identified only for 56 standards

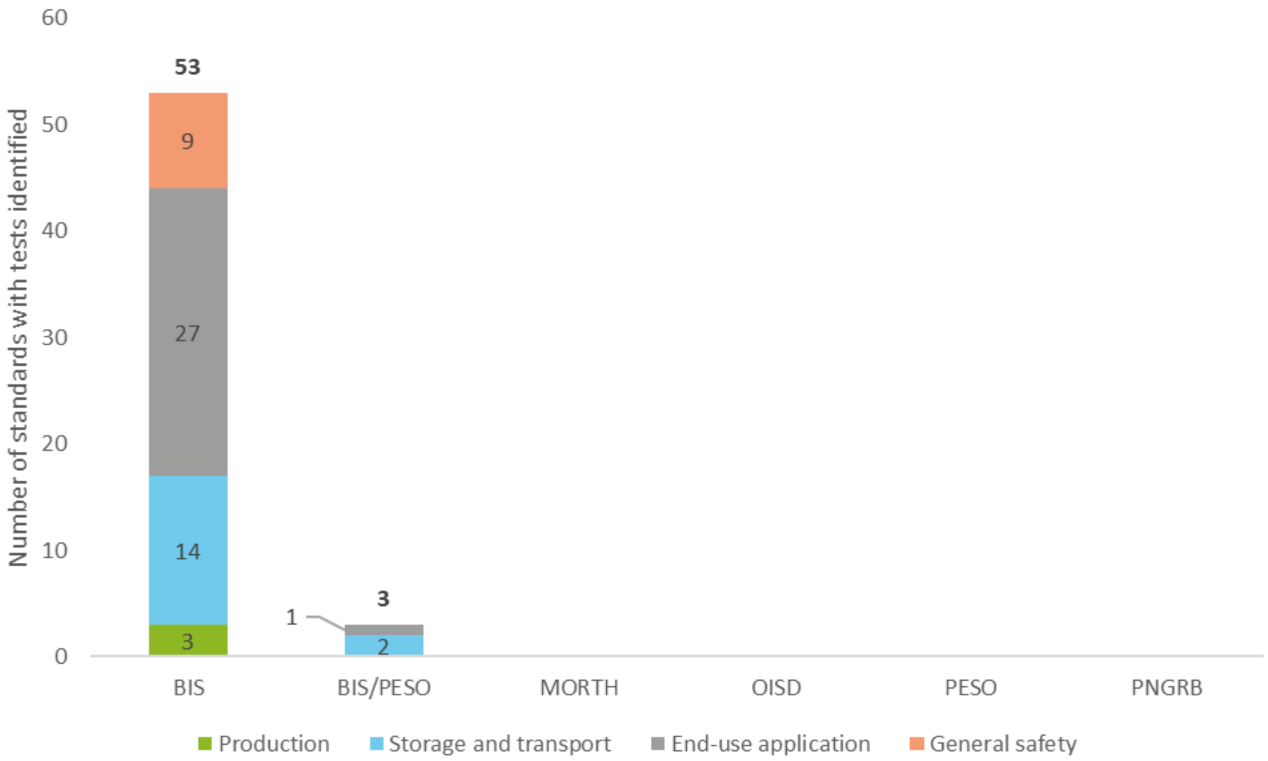


Source: Authors' analysis

Figure 6 represents the standards (with tests identified) across different regulatory bodies responsible for developing them in India. As seen in Figures 4 and 5, BIS has identified testing requirements for 53 standards, of which 27 are for end-use applications, and 14 correspond to storage and transportation-related aspects. The remaining standards are for hydrogen production and general safety.

End-use applications like automotive has the maximum number of tests identified

Figure 6 Standards (with test identified) for green hydrogen value chain



Source: Authors' analysis

2.4. Detailed listing of testing infrastructure requirements

Tables 6 to 9 outline the testing standards developed by BIS across different hydrogen value chain stages, including production, storage, end-use, and general safety. Table 10 outlines the testing procedure for standards developed by PESO for the hydrogen storage facilities. These tables provide a detailed account of the various testing procedures that ensure the quality, safety, and efficiency of hydrogen production processes.

BIS has identified the testing requirement for a total of 54 standards, of which 53 have already been published; one standard is under development. In Tables 6–10, some standards are combined or merged under one row. For example, IS 18538 (Gaseous hydrogen fuelling stations) has four parts but has been shown in one row as they have common testing requirements. Similarly, PESO has identified the testing requirements for two standards– ISO 11623 and ISO 19078 – both of which pertain to gas cylinder safety inspection regulations and are categorised as 'to be considered for development'.

Table 6 provides a list of standards for hydrogen production. It can be seen that all standards related to hydrogen production are pre-existing standards. Most standards across green hydrogen value chain have been notified recently. It is expected that the number of laboratories will increase in the future as the green hydrogen economy scales up. NABL accredited labs will be sensitised to scale up and come forward to develop infrastructure for testing as per recently developed standards and support the National Green Hydrogen Mission.

Table 6 Testing standards developed by BIS for hydrogen production

Sr. no.	Code	Standard title	Tests to be conducted	Labs accredited for the standard
			Pre-existing	
1	IS 16509	Hydrogen generators using water electrolysis: Industrial, commercial, and residential applications	1. Electrical tests 2. Pressure test 3. Leakage test 4. Dilution tests 5. Protection against the spread of fire tests 6. Temperature tests 7. Environmental test 8. Hydrogen and oxygen production rate test 9. Hydrogen and oxygen quality test 10. Spillage, overflow, and drain test 11. Mechanical strength 12. Stability test 13. Vent tests 14. Sound level test	---
2	IS 1070: 1992	Reagent-grade water specification	1. Specific conductivity µmhos/cm at 25°C 2. pH 3. Total solids or non-volatile residue at 105°C 4. Silica (as SiO_2) 5. Colour retention of $KMnO_4$ 6. Organics, total organic carbon (TOC) 7. Bacteria	Envirocare Labs
3	IS 5639: 1970	Pumps handling chemicals and corrosive liquids: Technical requirement for rotodynamic pumps for handling corrosive liquids.	1. Pump tests 2. Determination of pump performance.	---

Testing standards have been categorised into pre-existing, developed after the NGHM, currently under development, and those to be considered for development

Table 7 provides a list of testing standards for hydrogen storage and transportation. There are a total of 16 standards for which testing requirements have been identified. Out of these, Indian laboratories have the capability to test five standards that were pre-existing. There is no testing infrastructure for standards released after NGHM or those under development in India.

Table 7 Testing standards developed by BIS for hydrogen storage and transportation

Sr. no.	Code	Standard title	Tests to be conducted	Labs accredited for the standard
		Pre-existing		
4	IS/ISO 13985: 2006	Liquid hydrogen: Land vehicle fuel tanks.	1. Inner tank burst pressure test 2. Thermal autonomy test 3. Maximum filling level test 4. Accessory type tests 5. Pressure test 6. Leak test 7. Verification of the dimensions 8. Destructive and non-destructive tests of welded joints 9. Visual inspection	---
5	IS 17613: 2021	Gas cylinders. Refillable welded aluminium alloy cylinders: Design and construction.	1. Tensile test on parent material 2. Tensile test in the pressure-bearing welds 3. Bend test on parent material 4. Bend test across the welds 5. Nick-break test on the pressure-bearing welds 6. Hydrostatic test 7. Pneumatic leakage test 8. Hydraulic burst test 9. Integrity impact test and drop test	---
6	IS 16507	Transportable gas cylinder cascades.	1. Periodic testing 2. Assembly leak test 3. First, fill leak test	---

7	IS 14885	Polyethylene pipes for the supply of gaseous fuels: Specifications.	A. Tests on materials: PE compound in granules form 1. Conventional density 2. Melt flow rate (MFR) 3. Thermal stability (oxidation induction time) 4. Volatile content 5. Water content 6. Pigment dispersion 7. Anti-oxidant 8. UV stabilizer B. Tests on materials: PE compound in pipe form 1. Resistance to gas condensate 2. Resistance to weathering 3. Tensile yield strength 4. Elongation 5. Resistance to slow crack growth rate 6. Effect of gas condensate on hydrostatic strength 7. Long-term hydrostatic strength test C. Tests on Pipes 1. Dimensions of pipes: outside diameter, out-of-roundness (ovality), wall thickness, length 2. Finish 3. Colour 4. Hydraulic characteristics 5. Reversion test 6. Density 7. Melt flow rate 8. Pigment dispersion 9. Thermal stability (oxidation induction time) 10. Volatile matter content 11. Tensile yield strength 12. Elongation at break 13. Resistance to weathering 14. Slow crack growth rate 15. Squeeze-off test	1. Central Institute of Petrochemicals Engineering and Technology (CIPET), Raipur 2. Atmy Analytical Labs Pvt. Ltd. 3. CIPET: Centre for Skilling and Technical Support (CSTS) - Aurangabad 4. CIPET: CSTS - Agartala Plastics Testing Laboratory 5. Pioneer Testing Laboratory Private Limited 6. CIPET, Jaipur 7. CIPET, Lucknow 8. BIS, Eastern Regional Laboratory (ERL) 9. CIPET: CSTS - Bhopal 10. CIPET, Ahmedabad 11. CIPET, Bhubaneswar 12. CIPET, Hyderabad 13. CIPET, Vijayawada

8	IS 3224:2021	Valve fittings for compressed gas cylinders, excluding LPG cylinders.	1. Hydraulic burst pressure test 2. Resistance to mechanical impact (valve impact test) 3. Valving torque test 4. Excessive torque test 5. Internal leak tightness test 6. External leak tightness test 7. Visual examinations 8. Flame impingement test 9. Condensate corrosion resistance test 10. Vibration test 11. Leakage test at low and high temperatures 12. Activation test 13. Tensile strength and elongation test 14. Izod impact test 15. Internal and external tightness test	Partial test facilities are available at: 1. BIS, Eastern Regional Laboratory (ERL) 2. BIS, Western Regional Laboratory (WRL) 3. BIS, Central Laboratory (CL)
9	IS/ISO 15761:2020	Steel gate globe and check valves for sizes DN 100 and smaller for petroleum and natural gas industries.	1. Shell test 2. Closure leakage test 3. Optional closure leakage test for gate valves 4. Backseat leakage test 5. Fugitive emission testing	Partial test facilities are available at: 1. BIS, Eastern Regional Laboratory (ERL)
10	IS/ISO 11114 Part 4	Transportable gas cylinders: Compatibility of cylinder and valve materials with gas contents (Part 4: test methods for selecting steels resistant to hydrogen embrittlement. Product standards).	1. Disc test (Method A) 2. Fracture mechanics test (Method B) 3. Specimen measurement 4. Fracture specimens 5. Tensile specimens 6. Fatigue precracking 7. Tensile tests	---
11	IS 15660	Gas cylinders: Refillable seamless aluminium alloy gas cylinders. Design, construction, and testing.	1. Pressure cycling test 2. Test requirements for high-strength and/or low-elongation gas cylinder designs 3. Tensile test 4. Bend test 5. Flattening test 6. Hydraulic bursting test 7. Interpretation of test 8. Hydraulic test (volumetric expansion test) 9. Hardness test 10. Leakage testing 11. Examination for neck folds	Partial test facilities are available at: 1. BIS, Central Laboratory (CL)

12	IS 7285: Part 1	Refillable seamless steel gas cylinders: Specification. Part 1: Normalised steel cylinders (fourth revision).	1. Prototype tests 2. Hydraulic bursting test 3. Test installation 4. Pressure cycling test 5. Tensile test 6. Impact test 7. Bend test and flattening test 8. Hydrostatic stretch test 9. Hardness test 10. Leakage test	Partial test facilities are available at: 1. BIS, Eastern Regional Laboratory (ERL) 2. BIS, Western Regional Laboratory (WRL) 3. BIS, Central Laboratory (CL)
13	IS 19035	Gas cylinders: Flexible hose assemblies. Specification and testing.	1. Production pressure tests 1.1. Strength test 1.2. Leak test 2. Type tests 2.1. General 2.2. Burst pressure test (3 samples /type) 2.3. Pressure cycle test (3 samples /type) 2.4. Oxygen compatibility test (3 samples/type) 2.5. Acetylene compatibility test (3 samples) 2.6. Gas material compatibility 2.7. Test of the safety cable (2 samples) 3. Additional tests 3.1. Kink test (1 sample) 3.2. Side impact test (1 sample) 3.3. Tensile pull test (1 sample) 3.4. Fatigue cycling test under pressure (cyclic bending test) 3.5. Torsion test 3.6. Permeability test	---
14	IS 7285 Part 2	Quenched and tempered steel cylinders with a tensile strength of less than 1100 Mpa.	1. Pressure cycling test 2. Base check 3. Sulphide stress cracking resistance test 4. Sulphide stress cracking test for steel 5. Tensile test 6. Impact test 7. Bend test 8. Hydraulic bursting test 9. Hardness test 10. Leakage test (pneumatic) 11. Hydrostatic stretch test	---

After NGHM				
15	IS 19037/ISO 16111	Transportable gas storage devices: Hydrogen absorbed in reversible metal hydride.	1. Type/qualification tests 1.1. General 1.2. Fire test 1.3. Initial burst tests for MH assemblies with an internal volume of 120 ml or less 1.4. Drop or impact test 1.5. Leak test 1.6. Hydrogen cycling and strain measurement test 1.7. Shut-off valve impact test 1.8. Thermal cycling test 1.9. Type test reports 2. Batch tests 2.1. General requirements 2.2. Burst test for shell-batch 2.3. MDP test for hydride-batch 3. Routine tests and inspections 3.1. Routine tests 3.2. Certificates of manufacture	---
16	IS/ISO 9809-2	Design, construction and testing of refillable seamless steel gas cylinders and tubes. Part 2: Quenched and tempered steel cylinders and tubes with tensile strength greater than or equal to 1100 MPa.	1. Pressure cycling test 2. Flawed cylinder burst test 3. Bend test and flattening test 4. Ring flattening test 5. Tensile test 6. Impact test 7. Hydraulic bursting test 8. Proof pressure test 9. Volumetric expansion test 10. Hardness test 11. Leak test	---
Under Development				
17	ISO 20421-1: 2019	Cryogenic vessels or large transportable vacuum-insulated vessels. Part 1: Design fabrication inspection and testing.	1. Hydraulic strength test for complete valve 2. Excessive torque for complete valve 3. Internal/external leak tightness 4. Flame impingement 5. Flow capacity of the Pressure Relief Device (PRD): Thermal type 6. Flow capacity of the PRD: Bursting disc type 7. Valving torque test for complete valve	---
18	IS 16735: 2018 (being revised)	Cylinders for on-board storage of compressed gaseous hydrogen and hydrogen blends as a fuel for automotive vehicle specification (first revision of IS 16735).	Measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals.	---

19	New standard under development	Compressed gaseous hydrogen CGH_2 and hydrogen-natural gas blends valve integrated with solenoid operation remotely controlled for automotive use specification.	Residual embrittlement in both metallic-coated and uncoated externally threaded articles and rods.	---

Table 8 lists the testing infrastructure required for standards already developed or those BIS aims to develop. While the testing requirements have been identified for nine standards, there is no testing infrastructure within India for any of these standards. This emphasises the importance of prioritising the development of laboratories with testing infrastructure for hydrogen safety.

Table 8 Testing standards developed by BIS for general safety related to hydrogen

Sr. no.	Code	Standard title	Tests to be conducted	Labs accredited for the standard
			Pre-existing	
20	IS 16253	Hydrogen detection apparatus: Stationary applications.	1. Standard response test 2. Measuring range and calibration 3. Stability 4. Alarm set point(s) 5. Temperature 6. Pressure 7. Humidity 8. Vibration 9. Orientation 10. Flow rate for aspirated apparatus 11. Air velocity 12. Time of response and time of recovery 13. Selectivity 14. Poisoning 15. Operation above the measuring range 16. Power supply variations 17. Power supply interruptions, voltage transients, and step changes of voltage 18. Warm-up time after restart 19. Electromagnetic immunity 20. Field calibration	---
21	IS 16017	Transportable gas cylinders: Periodic inspection and testing of seamless aluminium alloy gas cylinders.	1. Proof pressure test 2. Volumetric expansion test 3. Ultrasonic test	---

22	IS 15319: 2020	Natural gas: Organic components used as odorants. Requirements and test methods.	1. Composition 2. Cloud point of the undried odorant 3. The boiling point of the components of the odorants and diluent 4. The vapour pressure curve of the odorant and diluent 5. Mass fraction of the evaporation residue 6. Insoluble matter 7. Solubility in water	---
After NGHM				
23	IS 18463	Metallic and other inorganic coatings: Pre-treatment of iron or steel to reduce the risk of hydrogen embrittlement.	1. Tensile strength 2. Temperature 3. Time 4. Hardness testing	---
24	IS 18436	Metallic and other inorganic coatings post-coating treatments of iron or steel to reduce the risk of hydrogen embrittlement.	1. Tensile strength 2. Temperature 3. Time 4. Hardness testing	---
25	IS 18435-11	Corrosion of metals and alloys: Stress corrosion testing. Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking.	1. Measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique 2. Stress corrosion testing.	---
To be considered for Development				
26	ISO 17081: 2014	Method of measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique.	Measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals.	---
27	ISO 10587: 2000	Metallic and other inorganic coatings: Test for residual embrittlement in both metallic-coated and uncoated, externally threaded articles and rods. Inclined wedge method.	Residual embrittlement in both metallic-coated and uncoated externally threaded articles and rods.	---
28	ISO 2626:1973	Copper: hydrogen embrittlement test.	Hydrogen embrittlement test	---

Table 9 lists the testing infrastructure required for 27 standards related to the end-use applications identified by BIS. A few standards have been merged in the table for ease of readability as they have common testing infrastructure requirements. For example, IS/ISO 12619 (Parts 1–16) has 16 separate standards, as shown in Figure 5. However, in Table 9, they have been merged into one common standard for brevity. The standards and testing requirements indicated in Table 9 primarily correspond to fuel cells, hydrogen mobility, hydrogen-enriched compressed natural gas (H-CNG), etc. Tests regarding hydrogen quality are also included. NABL accredited labs will be sensitize to scale up and come forward to develop infrastructure for testing as per recently developed standards and support the Green Hydrogen Mission.

Table 9 Testing standards developed by BIS for end use related to hydrogen

Sr. no.	Code	Standard title	Tests to be conducted	Labs accredited for the standard
		Pre-existing		
29	IS/ISO 17268: 2020	Fuel cell for road vehicles: Energy consumption measurement; Vehicles fuelled with compressed hydrogen.	1. Nozzle tests 2. Receptacle tests 3. User-machine interface 4. Dropping 5. Leakage at room temperature 6. Valve operating handle 7. Receptacle vibration resistance 8. Abnormal loads 9. Low and high temperatures 10. Durability and maintainability 11. Sealing material ageing test 12. Non-metallic material hydrogen resistance test 13. Electrical resistance 14. Hydrostatic strength 15. Corrosion resistance 16. Deformation 17. Contamination test 18. Thermal cycle test 19. Pre-cooled hydrogen exposure test 20. Misconnected nozzle test 21. Upward/downward nozzle compatibility test 22. Washout test 23. User abuse test 24. Freezing test 25. Rocking test 26. Communication test	---
30	IS 16061	Hydrogen fuel quality product specification.	1. Hydrogen fuel index (minimum mole fraction) 2. Total non-hydrogen gases 3. Maximum water content 4. Maximum total hydrocarbons except for methane 5. Maximum methane 6. Oxygen 7. Helium 8. Nitrogen 9. Argon 10. Carbon dioxide 11. Carbon monoxide 12. Total sulphur compounds 13. Formaldehyde 14. Formic acid 15. Ammonia 16. Halogenated compounds content 17. Maximum particulate concentration 18. Maximum particle diameter 19. Para-hydrogen (minimum mole fraction, %)	---

			20. Maximum mercury content 21. Density	
31	IS 1090:2002	Sampling and testing for compressed hydrogen.	1. Oxygen 2. Nitrogen 3. Water 4. Carbon dioxide 5. Carbon monoxide 6. Mercury 7. Hydrocarbons 8. Hydrogen 9. Nitrogen 10. Water vapour 11. Hydrocarbons 12. Sulphur compounds 13. Argon	---
32	IS/ISO 12619 (Parts 1–16)	Road vehicles: Compressed gaseous hydrogen (CGH_2) and hydrogen/natural gas blends fuel system components. General requirements and definitions. Performance and general test methods, pressure regulator, check valve, manual cylinder valve, automatic valve, gas injector, pressure indicator, Pressure relief valve, pressure relief device, excess flow valve, gas-tight housing and ventilation hoses, rigid fuel line in stainless steel, flexible fuel line, filter, and fittings.	Test methods mentioned in IS/ISO 12619 – 2: 2014: 1. Hydrostatic strength test 2. Leakage test 3. Excess torque resistance test 4. Bending moment test 5. Continued operation test 6. Corrosion resistance test 7. Oxygen ageing test 8. Ozone ageing test 9. Electrical over-voltages test 10. Non-metallic immersion test 11. Vibration resistance test 12. Brass material compatibility test 13. Non-metallic material compatibility to hydrogen test 14. Metallic material compatibility to hydrogen test 15. Pre-cooled hydrogen exposure test 16. Insulation resistance test 17. Ultraviolet resistance of external surfaces test 18. Automotive fluid exposure test Note: Other parts refer to test methods outlined in Part 2 of IS/ISO 12619.	---
33	IS/ISO 23828: 2013	Fuel cell road vehicles: Energy consumption measurement. Vehicles fuelled with compressed hydrogen.	1. Fuel consumption tests 2. Measurement and calculation over applicable driving test (ADT) 3. Correction of the test results for FCHEV.	---
34	IS 17314: 2019	Hydrogen enriched compressed natural gas (HCNG) for automotive purposes: Specifications.	1. Hydrogen content 2. Methane content 3. Other hydrocarbon content - Ethane - C3 and higher - C6 and higher 1. Total unsaturated HC 2. Total impurities content - Water - Sulphur	---

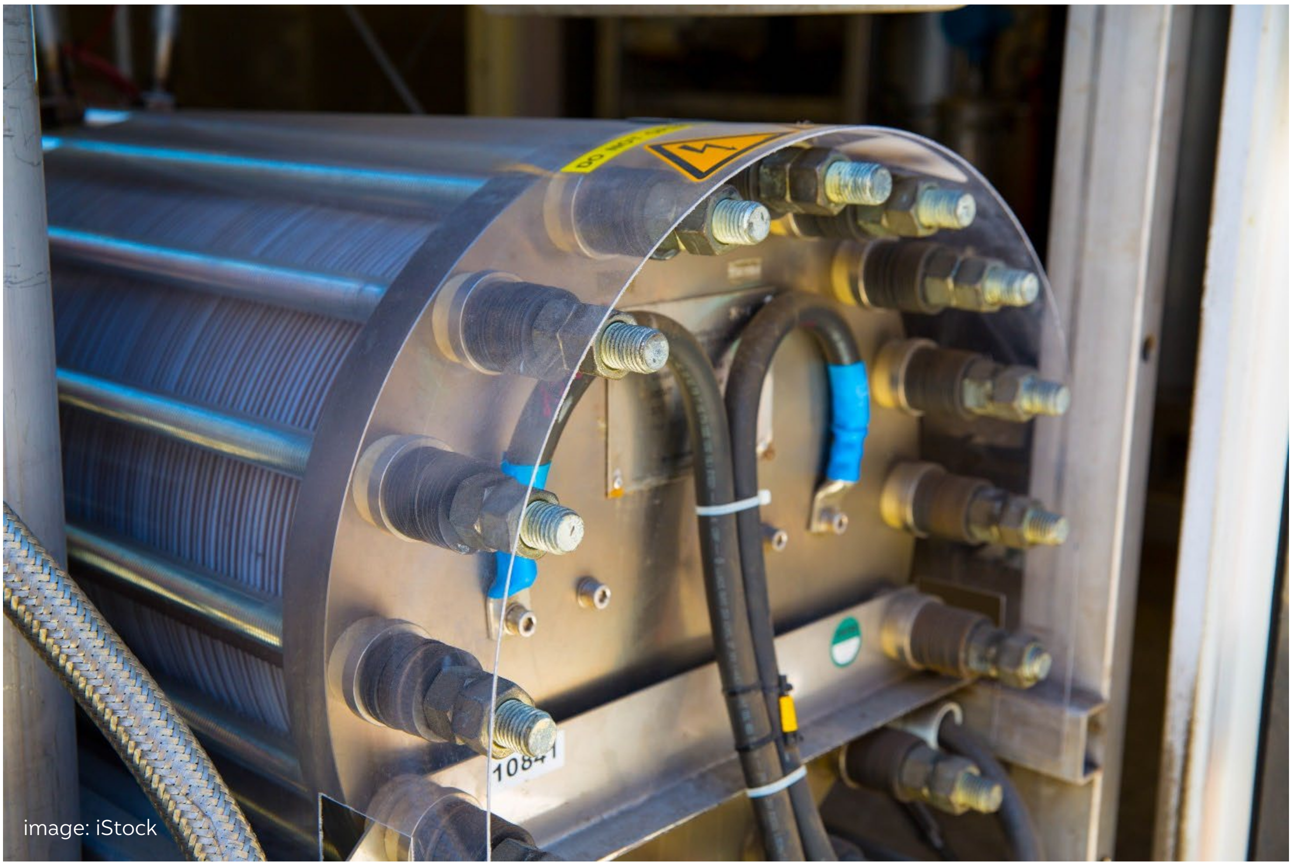
			- Oxygen - Carbon dioxide - Carbon monoxide	
35	IS/ISO 13985: 2006	Liquid hydrogen: Land vehicles fuel tanks.	1. Load during the pressure test 2. Design loads 3. Quality plan 4. Production control test plates 5. Non-destructive testing 6. Rectification 7. Pressure testing	---
36	IS/ISO 12619	Compressed gaseous hydrogen (CGH_2) and hydrogen/natural gas blended fuel system components	1. Impact test 2. Tensile test 3. Sustained load cracking test 4. Corrosion test 5. Ultraviolet resistance test 6. Shear strength test 7. Glass transition temperature test 8. Tensile test 9. Softening temperature test 10. Tensile test	---
After NGHM				
37	IS 18538 (Part 1,3,5, and 8)	Gaseous hydrogen fuelling stations: General requirements, dispenser hoses, hose assemblies, valves, and fuel quality control.	Part 1: 1. Pressure test 2. Leak test 3. Electrical testing 4. Fuelling safety and performance functional test 5. Fuelling protocol test Part 3: 1. Hydrogen gas pressure cycle test 2. External leakage test 3. Internal leakage test 4. Worst case fault pressure cycle test 5. Proof pressure test 6. Hydrostatic strength test 7. Excess torque resistance test 8. Bending moment test 9. Non-metallic materials test 10. Cold gas in warm valve test 11. Operation cycle test 12. Operation test 13. Pressure impulse test 14. Operation test under full pressure load 15. Electrical conductivity 16. Containment of/controlled relieving of hydrogen when uncoupled 17. Separation test 18. Impact test 19. Drop test 20. Twisting test 21. Maximum flow shut-off 22. Excess torque operation 23. Seat leakage test	---

			Part 5: 1. Leakage test 2. Proof pressure test 3. Ultimate strength 4. Hydrostatic strength test 5. Electrical conductivity test 6. Tensile test 7. Vertical load strength test 8. Torsion strength test 9. Pressure cycle test (hydraulic-pressure impulse test) 10. hydrogen impulse test 11. Corrosion test 12. Hose permeation test 13. Ultraviolet light and water exposure test 14. Crush test 15. Abrasion resistance test 16. Marking material legibility test 17. Lining material test Part 8: NA	
To be considered for Development				
38	ISO 21266-1: 2018	Road vehicles: Compressed gaseous hydrogen (CGH_2) and hydrogen/natural gas blends fuel systems. Part 1: Safety requirements	1. Design 1.1. General 1.2. Components 2. Refuelling connection 2.1. General 2.2. Receptacle location 2.3. Receptacle mounting 2.4. Minimum receptacle clearance 3. Leakage control 4. Mounting of the cylinder(s) 5. Heat protection 6. Minimising the risk of gas ignition 7. Venting system	---
39	ISO 21266-2: 2018	Road vehicles: Compressed gaseous hydrogen (CGH_2) and hydrogen/natural gas blends fuel systems. Part 2: Test methods.	1. Cylinder mounting strength tests. 2. Leak test 3. Functional test 4. Receptacle mounting tests 5.	---

Table 10 lists the testing infrastructure required for hydrogen storage as identified by PESO. The tests pertaining to gas cylinders are carried out by the gas cylinder manufacturers as per the design standard during proto type testing and batch testing by BIS or any other third party inspection agency (TPIA) approved for that standards. Composite cylinders testing facilities have been incorporated in the recent gas cylinder amendment rules,2024 (PESO 2024). The cryogenic cylinders and containers testing is also carried out by the manufacturers through inhouse testing facilities in the presence of TPIA. Metallurgical laboratories that are approved by NABL are existing in India for material testing and chemical analysis. Laboratories for periodic testing of gas cylinders, approved by Chief Controller of Explosives, are doing testing as per the BIS standards. There is a need to sensitise NABL accredited labs to scale up for developing infrastructure for testing.

Table 10 Testing standards developed by PESO for hydrogen storage and transportation

Sr. no.	Code	Standard title	Tests to be conducted	Labs accredited for the standard
To be considered for Development				
1	ISO 11623	Gas cylinders: Composite construction, periodic inspection and testing.	1. External and internal inspection 2. Hydrostatic proof pressure test 3. Leak test.	---
2	ISO 19078	Gas cylinders: Inspection of the cylinder installation and requalification of high-pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles.	1. External and internal inspection 2. Hydrostatic proof pressure test 3. Leak test.	---



Performance evaluation of electrolysers and fuel cells are critical for green hydrogen production and application

Key factors to consider for the electrolyser testing involves tests on performance, durability, adaptability to VRE, characteristics, and purity.

image: iStock

3. Testing infrastructure for performance evaluation

Testing the performance of electrolysers and fuel cells is vital to guarantee the efficiency, durability, adaptability, and safety of hydrogen production systems. The following parameters for performance testing are necessary for the development, adoption, and scalability of these technologies. Figure 7 illustrates the sequence of the tests across various categories, discussed below:

1. Performance. Performance parameters such as specific energy consumption (kWh/kg H_2), stack efficiency, system efficiency, and plant efficiency at peak load and optimal operating points should be tested and certified by the testing laboratories. The degradation rate, which measures the loss of efficiency over time, is also crucial in determining the system's long-term performance and should be measured in the testing laboratory.

2. Durability. Durability testing involves the lifespan of the electrolyser and its components, such as electrodes, membranes, etc. Electrode and membrane life impact the overall cost and operational stability. The shorter the replacement interval of these components, the better the performance, which in turn influences maintenance costs and system downtime, which are critical for the commercial viability and scaling of these technologies.

3. Adaptability to variable renewable energy. Given that green hydrogen production often relies on VRE sources such as wind or solar, the ability of electrolysers to adapt to these fluctuations is crucial. This parameter is measured in terms of cold start-up time, hot start-up time, and shutdown time. How quickly the electrolysers can respond to the availability of renewable energy, need to be determined to optimise their operation in alignment with the energy supply.

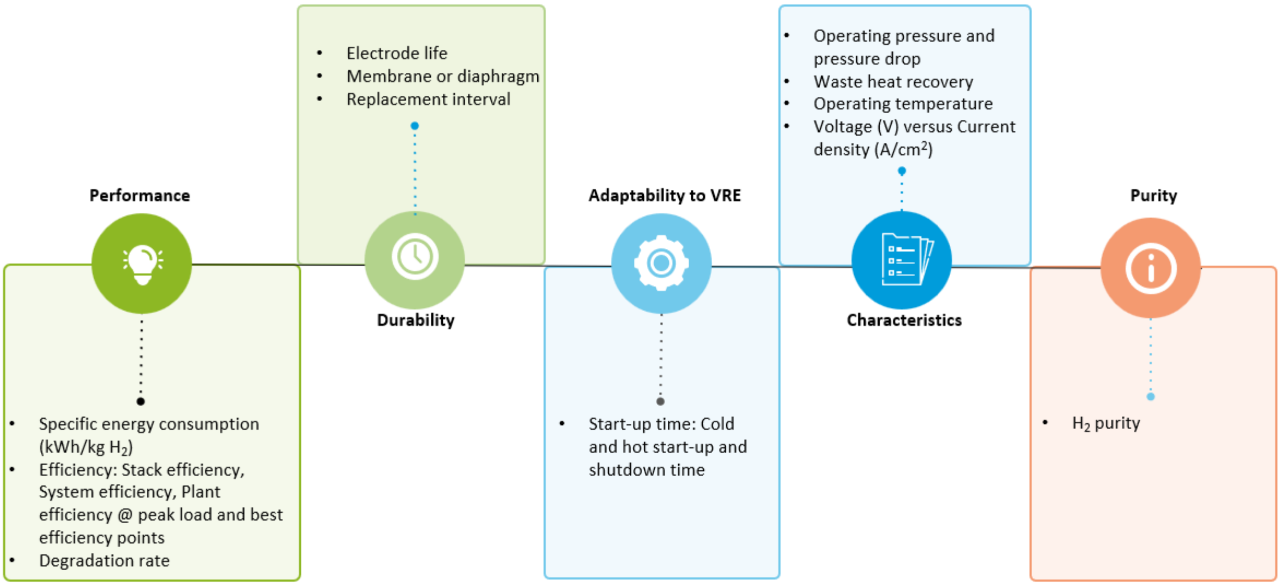
4. Characteristics. The operating characteristics of electrolysers and fuel cells, such as pressure, temperature, and the relationship between voltage (V) and current density (A/cm^2), are crucial for the efficiency and size of the hydrogen production systems. These parameters also influence the design and material selection for these technologies. Furthermore, measuring the operating pressure and pressure drop, and determining the waste heat generated from operating the electrolyser above the thermo-neutral voltage is essential.

5. Material analysis. Exposure to hydrogen, especially at high pressure, can lead to degradation, cracks, and failure. Consequently, hydrogen embrittlement is one of the main safety concerns affecting the whole value chain. Since the most common way to transport hydrogen includes pipelines, tanks, and vessels, these must undergo thorough and strict material safety measures. Some crucial factors in material analysis involve material composition, fatigue, and stress testing.

6. Gas quality testing. Gas purity is a critical aspect of hydrogen production, as it can seriously impact the system's performance, especially for fuel cell applications where a purity of 99.99 per cent is required for hydrogen. Key contaminants include O_2, CO, and N_2, which must be monitored and controlled within the limits set by standards such as ISO 14687 (hydrogen fuel quality and product specification). These contaminants act as poison for the catalyst, thus reducing the system's efficiency.

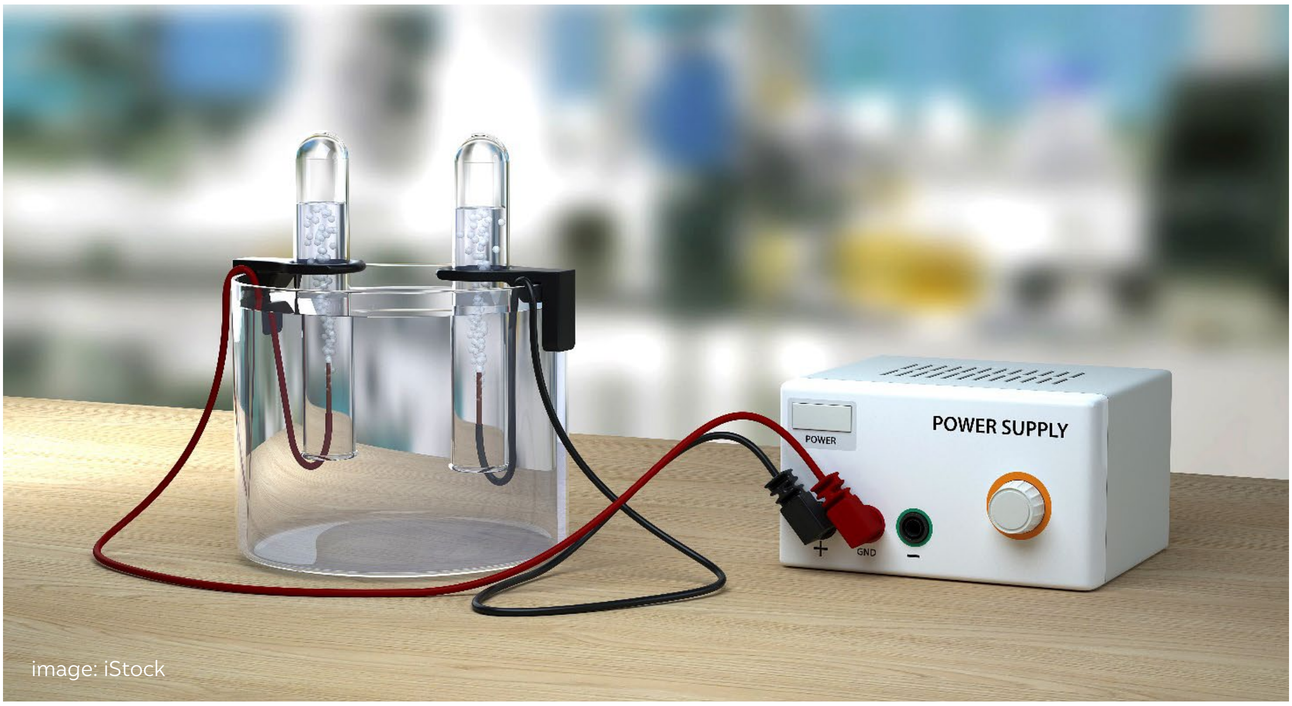
7. Purity. Hydrogen purity is a critical parameter, especially for applications such as fuel cells that require ultra-pure hydrogen (>99.99 per cent) to function effectively. Testing for hydrogen purity typically involves gas chromatography, which ensures that the hydrogen produced meets the required purity standards for various applications.

Figure 7 Factors to consider at different points in the hydrogen value chain



Source: Authors' analysis

Note: *VRE*-Variable Renewable Energy



Strengthening India's green hydrogen testing infrastructure is crucial to align with global standards, ensuring safety, performance reliability, and fostering confidence in the evolving hydrogen ecosystem.

Both the government and private sector need to play an active role in developing a robust testing infrastructure in India.

image: iStock

4. Role of government and private sector in testing infrastructure

Creating a robust green hydrogen testing infrastructure demands a concerted partnership between the government and the private sector to facilitate its widespread adoption in a safe and efficient manner. This section outlines the pivotal roles the government and the private sector can play in developing the testing infrastructure across the green hydrogen value chain in India.

4.1. Role of government

1. Establish regulatory frameworks. Governments are responsible for creating and enforcing regulations that govern testing infrastructure. They must establish a regulatory framework that encourages the development of green hydrogen infrastructure, such as setting safety, quality, and interoperability standards.

2. Provide incentives and promote innovation. Many governments provide financial support for the development of testing infrastructure. These include grants, subsidies, and public-private partnerships to build and upgrade testing facilities. Such investments are crucial for fostering innovation and ensuring testing capabilities keep pace with technological advancements in green hydrogen.

3. Foster international collaboration. International partnerships facilitate the sharing of knowledge and best practices in green hydrogen testing and production. This collaboration helps to harmonise standards and testing protocols across borders, encouraging global trade and technology transfer in the sector.

4. Coordinate between industry and government. Public-private partnerships facilitate collaborations between government and private entities to share resources, expertise, and risks. Bolstering this partnership will ensure that testing infrastructure aligns with industry needs and regulatory requirements, facilitating smoother implementation.

5. Boost market creation. The government should stimulate the demand for green hydrogen by creating uses in various sectors, including transportation, energy storage, and industrial processes. This market development should be accompanied by the need for robust testing infrastructure to guarantee that products adhere to quality and safety standards.

4.2. Role of private sector

The private sector has been instrumental in developing the testing infrastructure for the solar power sector. It is poised to play an equally pivotal role in the emerging green hydrogen economy. To facilitate this, the private sector should:

1. Leverage existing knowledge from the PV sector. Existing expertise and experience from established industries such as solar photovoltaics (PV) must be leveraged to develop comprehensive standards for module safety (e.g., IS 61730 Part 1), performance testing, and recognised laboratories for conducting these tests with regard to green hydrogen.

2. Commercialise and scale up. Similar to the solar sector, private companies are well-positioned to develop and commercialise advanced testing tools. These capabilities must be integrated in the value chain.

3. Establish industry-academia partnerships. Private companies must collaborate with academic and research institutions to access cutting-edge research and contribute to developing technologies and best practices.

4. Invest in training and workforce development. The private sector must invest in training programs and certifications for engineers, technicians, and other professionals involved in the testing value chain. This will ensure that the workforce has the skills to operate, maintain, and test hydrogen systems effectively.

5. Action items

This report discusses the status of testing infrastructure globally and in India. It identifies the gaps that must be addressed to augment India's testing capabilities to international standards. The following actions are required to strengthen testing infrastructure in India:

- Expedite standards development and identification of testing requirements. MNRE should collaborate with relevant standard-setting bodies to streamline the process and accelerate the adoption of standards currently under development and those identified for development. Further, MNRE should also work with relevant bodies to identify appropriate testing requirements and accrediting labs that can conduct these tests.

- Develop a priority list of testing infrastructure requirements and estimate the budget needed. There are over 200 standards related to the safety of green hydrogen. Each standard has multiple testing requirements. Therefore, MNRE should collaborate with relevant bodies and industry stakeholders to develop a priority list of standards for developing testing infrastructure in India. For example, there is an urgent need to develop testing infrastructure for type 1 to type 4 cylinders for hydrogen storage and transportation. MNRE should also estimate the budgetary requirements for various testing laboratories.

- Identify and develop performance testing infrastructure for critical components. Having reliable data on the performance of key components such as electrolysers and fuel cells is crucial for developing investors' confidence in the hydrogen economy. Therefore, MNRE should focus on developing infrastructure for performance testing of electrolysers and other key technologies.

- Foster international collaboration. Developed countries in North America and Europe have significant experience in the hydrogen value chain. India can benefit from collaborating with these countries to leverage their knowledge. Additionally, international collaboration aids in promoting interoperability in testing procedures with partnering nations and enhancing India's testing capabilities and integration into global supply chains.

- Incentivise private sector participation. To advance the testing infrastructure in emerging sectors such as green hydrogen, private-sector investments and participation is crucial. Similar to the solar sector, the MNRE should facilitate private-sector participation in developing testing infrastructure for green hydrogen technologies.

Green hydrogen ecosystem needs to adopt policies similar to that of solar sector to achieve scale and smooth transition.

image: iStock

Acronym

AHTC	Advanced Hydrogen Technology Center
AIST	National Institute of Advanced Industrial Science and Technology
ANSI	American National Standards Institute
ARAI	Automotive Research Association of India
AVL	Anstalt für Verbrennungskraftmaschinen List
BIS	Bureau of Indian Standards
CIPET	Central Institute of Petrochemicals Engineering and Technology
CSA	Canadian Standards Association
CSIR	Council of Scientific and Industrial Research
DGC	Danish Gas Technology Center
DNV	Det Norske Veritas
GASTEF	High Pressure Gas Testing Facility
GB/T	Guobiao Standards (Chinese National Standards)
GTI	Gas Technology Institute
H2 IIS SIDER S.R.L.	Hydrogen Italian Institute of Welding and SIDER Test
HATIC	Hydrogen Appliance Test & Inspection Center
IEC	International Electrotechnical Commission
IFE	Institute for Energy Technology
IS	Indian Standard
ISO	International Organization for Standardization
KGS	Korea Gas Safety Corporation
MNRE	Ministry of New and Renewable Energy
MoRTH	Ministry of Road Transport and Highways
NABL	National Accreditation Board for Testing and Calibration Laboratories
NASA	National Aeronautics and Space Administration
NCL	National Chemical Laboratory
NDT	Non-Destructive Testing
NFCTEC	National Fuel Cell Technology Evaluation Centre
NGHM	National Green Hydrogen Mission

NHPQITC	National Hydrogen Power Quality Inspection and Testing Centre
OISD	Oil Industry Safety Directorate
PESO	Petroleum and Explosives Safety Organization
RDW	Dutch Vehicle Authority
SAE	Society of Automotive Engineers
TesTneT	Testing Network (by UL Solutions)
TÜV SÜD	Technischer Überwachungsverein Süd
UL	Underwriters Laboratories
UN GTR	United Nations Global Technical Regulation
UNECE	United Nations Economic Commission for Europe
UUT	Unit Under Test

Reference

Aerospace Technology Institute. 2024. *Hydrogen Capability Network – the test infrastructure landscape.* June. https://www.ati.org.uk/news/hydrogen-capability-network-the-test-infrastructure-landscape/.

AIST. n.d. *AIST:H2 and Heat Utilization System Team, Renewable Energy Research Center.* https://www.aist.go.jp/fukushima/en/unit/HHUS_e.html.

ARAI. 2023. "Leading the Path towards safer and sustainable mobility solutions."

AVL. n.d. *Electrolyzer Testing.* https://www.avl.com/en-in/testing-solutions/fuel-cell-testing/electrolyzer-testing.

BIS. n.d. *Bureau of Indian Standards.* https://www.bis.gov.in/ .

Bureau Veritas. n.d. *Hydrogen.* https://group.bureauveritas.com/markets-services/power-utilities/hydrogen .

Busch, Julian. 2024. *KGS plans two New Hydrogen Safety Inspection Facilities.* MPR International GmbH.

Clara Venture Labs. n.d. *Clara Venture Labs.* https://sustainableenergy.no/en/facilities/.

CSIR - CECRI . n.d. *CSIR-Central Electrochemical Reserach Institute.* https://www.cecri.res.in/OutreachCentres/Chennai.aspx?menuitem=Infrastructure.

CSIR. n.d. *Council of Scientific and Industrial Research .* https://www.csir.res.in/ .

CSIR-NPL. n.d. *Centre for Calibration & Testing (CFCT).* https://www.nplindia.org/index.php/commercial-services/calibration-testing/.

Dekra. 2023. *Full Range of Testing Services for Hydrogen Refueling Stations.* 6 November. https://www.dekra.com/en/full-range-of-testing-services-for-hydrogen-refueling-stations/.

Deloitte. 2023. *Green hydrogen: Energizing the path to net zero, Deloitte's 2023 global green hydrogen outlook.* Deloitte.

Destinus. n.d. *Introducing the First European Private Hydrogen Testing Site.* https://www.destinus.com/post/introducing-the-first-european-private-hydrogen-testing-site.

DNV. n.d. *Hydrogen Exposure Testing.* https://www.dnv.com/services/hydrogen-exposure-testing-210546/#:~:text=At%20DNV%20we%20have%20a,fracture%20and%20%20fatigue%20performance%20%20evaluation .

Element. n.d. *Element.* https://www.element.com/energy/hydrogen.

Energy House. n.d. *Energy House (By The Switch).* https://sustainableenergy.no/wp-content/uploads/2021/01/220119_EnergyHouse_-Datasheet.pdf.

ENTRANCE energy. n.d. *HYDROHUB MEGAWATT TEST CENTRE.* https://www.entrance.eu/kennis/projecten/hydrohub-megawatt-test-centre/.

EU Science Hub. n.d. *Electrolyser Testing Facility.* https://joint-research-centre.ec.europa.eu/laboratories-z/electrolyser-testing-facility_en .

Force Tehnology. n.d. *The hydrogen technology testing centre benefits businesses undergoing green transformation.* https://forcetechnology.com/en/all-industry-facilities/products-and-structures-testing/hydrogen-technology-testing-centre-facility-consultancy .

Fraunhofer hydrogen labs. n.d. *Supporting the market scale-up of green hydrogen for a CO2-neutral industry.* https://www.hydrogen-labs.fraunhofer.de/en.html.

GASTEF. n.d. *High Pressure Gas Testing Facility.* https://joint-research-centre.ec.europa.eu/laboratories-z/high-pressure-gas-testing-facility_en.

Greenlight Innovation. n.d. *Greenlight Innovation.* https://www.greenlightinnovation.com/ .

GTI Energy. n.d. *Hydrogen Technology Center.* https://www.gti.energy/hydrogen-technology-center/labs/ .

H2 IIS SIDER. n.d. *H2 IIS SIDER S.R.L.* https://www.h2iis-sider.it/?lang=en.

Hexagon Purus. n.d. *Hydrogen high-pressure Type 4 cylinders.* https://hexagonpurus.com/our-solutions/hydrogen-type-4-cylinders .

Horiba Fuelcon. n.d. *Test Systems for Electrolyzers.* https://www.horiba-fuelcon.com/en/electrolyzer-testing.

Hynergy. n.d. *Advanced Hydrogen Technology Center in Baoding, North China.* https://www.hynergy.de/en/advanced-hydrogen-technology-center-in-baoding-north-china/.

HYNOR. n.d. *IFE Hynor Hydrogen Technology Center (IFE Hynor).* https://ife.no/en/laboratory/ife-hynor-hydrogen-technology-center-ife-hynor/.

InterTek. n.d. *Intertek Hydrogen.* https://www.intertek.com/hydrogen/.

Kiwa. n.d. *Kiwa Hydrogen laboratory.* https://www.kiwa.com/en/service2/certification/hydrogen-laboratory/.

Leigh, Collins. 2023. *HydrogenInsight.* January. https://www.hydrogeninsight.com/transport/china-starts-operations-at-new-74m-national-hydrogen-fuel-cell-vehicle-testing-facility-in-chongqing/2-1-1385779.

Lucideon. n.d. *Hydrogen Fired Kilns.* https://www.lucideon.com/technologies/hydrogen-fired-kilns.

Ministry of New and Renewable Energy. 2023. "National Green Hydrogen Mission." New Delhi.

Ministry of New and Renewable Energy. 2024. "Scheme Guidelines for funding of testing facilities, infrastructure, and institutional support for development of Standards and Regulatory framework under the National Green Hydrogen Mission."

Mitsubishi Heavy Industries Group. n.d. *Accelerating Decarbonization: Takasago Hydrogen Park.* https://solutions.mhi.com/power/decarbonization-technology/accelerating-decarbonization-takasago-hydrogen-park/.

MNRE and CEEW. 2024. *Green Hydrogen Standards and Approval Systems in India: Streamlining the Green Hydrogen Ecosystem for Accelerated Implementation of the National Green Hydrogen Mission.* New Delhi: Ministryu of New and Renewable Energy.

MoRTH. n.d. *Ministry of Road Transport and Highways* . https://morth.nic.in/ .

NABL. n.d. *National Accreditation Board for Testing and Calibration Laboratories* . https://nabl-india.org/ .

NASA. n.d. *Fuel Cell Testing Laboratory.* https://www1.grc.nasa.gov/facilities/fctl/ .

NCL. n.d. *National Chemical Laboratory.* https://www.ncl-india.org/ .

NITI Aayog, RMI. 2022. *Harnessing Green Hydrogen* . June.

NREL. n.d. *National Fuel Cell Technology Evaluation Center.* https://www.nrel.gov/hydrogen/nfctec.html.

Office of Energy Efficiency and Renewable Energy. n.d. *Hydrogen Shot.* https://www.energy.gov/eere/fuelcells/hydrogen-shot .

OISD. n.d. *Oil Industry Safety Directorate.* https://www.oisd.gov.in/ .

PESO. 2024. *Gas Cylinders (Amendment) Rules.* New Delhi: Petroleum & Explosives Safety Organization (PESO).

—. n.d. *Petroleum and Explosives Safety Organization* . https://peso.gov.in/web/ .

PIB. 2021. *English rendering of the text of PM's address from the Red Fort on 75th Independence Day.* 15 August. https://pib.gov.in/PressReleasePage.aspx?PRID=1746062.

—. 2021. *National Statement by Prime Minister Shri Narendra Modi at COP26 Summit in Glasgow.* 1 November. https://pib.gov.in/PressReleasePage.aspx?PRID=1768712.

Powertech labs. n.d. *HYDROGEN FUEL SYSTEMS TESTING.* https://powertechlabs.com/hydrogen-fuel-systems-testing/ .

SGS. 2022. *SGS's Shanghai Laboratory Expands into Full-Specification Hydrogen Analysis.* 07 March. https://www.sgs.com/en/news/2022/03/sgss-shanghai-laboratory-expands-into-full-specification-hydrogen-analysis.

TesTneT. n.d. *Testing Ensures Safety.* https://h2-test.net/ .

TUV SUD. n.d. *Hydrogen testing: components, fuel cells & storage systems.* https://www.tuvsud.com/en/industries/mobility-and-automotive/automotive-and-oem/hydrogen-mobility/component-testing.

UK Government. 2021. *UK Hydrogen Strategy.* August.

UL Solutions. n.d. *Fuel Cell Testing and Certification.* https://www.ul.com/services/fuel-cell-testing-and-certification.

Westcon's battery and hydrogen lab. n.d. *Westcon's battery and hydrogen lab.* https://sustainableenergy.no/en/facilities/.

ZwickRoell. n.d. *Mechanical materials testing in the hydrogen industry across the entire value chain.* https://www.zwickroell.com/industries/energy/.

The authors

Aditya Khator
aditya.khator@ceew.in

Aditya is a Research Analyst with the Industrial Sustainability team at The Council, focusing on developing an inventory for thermal equipment in Indian industries to reduce emissions. He also explores emerging sectors like green hydrogen and solid textile waste management, collaborating with key stakeholders to shape effective policies. Aditya is an engineer by education, having graduated from IIT Delhi with a dual degree (BTech + MTech) in Chemical Engineering.

Karthik Shetty
karthik.shetty@ceew.in

Karthik is a Consultant at The Council, with experience in chemical and agriculture equipment manufacturing industries. Here at the Council his focus is on decarbonisation of the steel sector in India. Karthik has a Bachelor's degree in Mechanical Engineering from RV College of Engineering, Bangalore and a master's degree in Energy Science, Technology and Policy from Carnegie Mellon University, Pittsburgh. Further, he is also a LEED BD+C (Leadership in Energy and Environmental Design, for building design and construction) accredited professional.

Rishabh Patidar
rishabh.patidar@ceew.in

Rishabh is a Chemical Engineer and a Research Analyst at CEEW. He has nearly three years of experience, and his current research focuses on the techno-economic assessment of pathways for CO_2 utilisation and green hydrogen technologies. Rishabh holds an MTech in Chemical Engineering from IIT Gandhinagar, Gujarat, and a bachelor’s degree in Chemical Engineering from Ujjain Engineering College, MP.

Deepak Yadav
deepak.yadav@ceew.in

Deepak is a Senior Programme Lead at CEEW and has expertise in green hydrogen, carbon capture and utilisation, and the steel sector. He has over eight years of experience in renewable energy, alternative fuels, and industrial sustainability. He is also a BEE-certified energy auditor and has published his research in leading international journals and conferences. Deepak holds a doctorate and a master’s degree from the Department of Energy Science and Engineering, IIT Bombay.

Scan to download the study

COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)

ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi - 110070, India
T: +91 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewIndia

MINISTRY OF NEW AND RENEWABLE ENERGY (MNRE)

Atal Akshay Urja Bhawan, Lodhi Road,
New Delhi - 110070, India

mnre.gov.in | @mnreindia | mnreministry