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International Renewable Energy Agency

A Quality Infrastructure Roadmap **for green hydrogen**

In partnership with:

Physikalisch-Technische Bundesanstalt
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About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation; a centre of excellence; a repository of policy, technology, resource, and financial knowledge; and a driver of action on the ground to advance the transformation of the global energy system. A global intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy and geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security, and low-carbon economic growth and prosperity. www.irena.org

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Physikalisch-Technische Bundesanstalt (PTB) is the National Metrology Institute of Germany. PTB performs research in the field of metrology for the benefit of society, trade and industry, and the sciences, and advises the German federal government on all metrology issues. Internationally, PTB supports developing and emerging countries in the development and use of a needs-based and internationally recognised quality infrastructure.

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Disclaimer

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Abbreviations

ANM	Agence Nationale de Métrologie (Tunisia)
BIPM	Bureau international des poids et mesures
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung
CMC	calibration and measurement capacities
CO_2	carbon dioxide
CRTEn	Center for Energy Research and Technology (Tunisia)
DEF-NAT	Laboratoire de métrologie du Ministère de la Défense Nationale (Tunisia)
EURAMET	European Association of National Metrology Institutes
GHG	greenhouse gas
Gt	gigatonne
GW	gigawatt
INRAP	National Institute of Research and Physical and Chemical Analysis
IRENA	International Renewable Energy Agency
IAF	International Accreditation Forum
IEC	International Electrotechnical Commission
IECEE	IEC System of Conformity Assessment Schemes for Electrotechnical Equipment
IECEx	International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres
ILAC	International Laboratory Accreditation Cooperation
INetQI	International Network on Quality Infrastructure
INNORPI	Institut National de la Normalisation et de la Propriété Industrielle (Tunisia)
INSPIRE	International Standards and Patents in Renewable Energy
ISO	International Organization for Standardization
LCAE	Central Laboratory for Analysis and Testing (Tunisia)
MIME	Ministry of Mines, Industry and Energy (Ministère de l'Industrie, des Mines et de l'Energie)
MRA	mutual recognition arrangement
Mt	million tonnes
NMI	National Metrology Institute
OIML	International Organization of Legal Metrology (Organisation Internationale de Métrologie Légale)
PTB	Physikalisch-Technische Bundesanstalt
PV	photovoltaic
R&D	research and development
QI	quality infrastructure
TC	technical committee
WTO	World Trade Organization

Executive summary

Due to the global climate crisis, there is an urgency for all sectors of the global economy to be decarbonised - following a net-zero compatible pathway – by or around 2050. While most industries and applications can rely on electrification with renewable power, some hard-to-abate sectors need more than electrification alone, and require the use of hydrogen, or hydrogen derived commodities like ammonia, methanol or direct reduced iron (DRI) steel to achieve net-zero emissions. According to IRENA's 1.5°C scenario, green and blue hydrogen production would need to increase to 125 million tonnes per year (Mtpa) by 2030 and 523 Mtpa by 2050. This brings both opportunities for development, as well as challenges for scaling and adapting the production, infrastructure and end-use value chains required. The existence and further development of a robust Quality Infrastructure - defined as a system comprised of organisations, policies, legal framework, and practices required to assure quality, safety and sustainability of products and services – for green hydrogen is a key pillar for enabling this transition.

To raise awareness on the importance of quality infrastructure for the green hydrogen value chain and in order to provide recommendations on the development of the related services, IRENA together with Physikalisch-Technische Bundesanstalt (Germany's national metrology institute - PTB) and with financial support from Germany's Federal Ministry of Economic Cooperation and Development (BMZ) implemented a project entitled "Quality Infrastructure for Green Hydrogen: Technical standards and quality control for the production and trade of renewable hydrogen". This report presents the findings of this work.

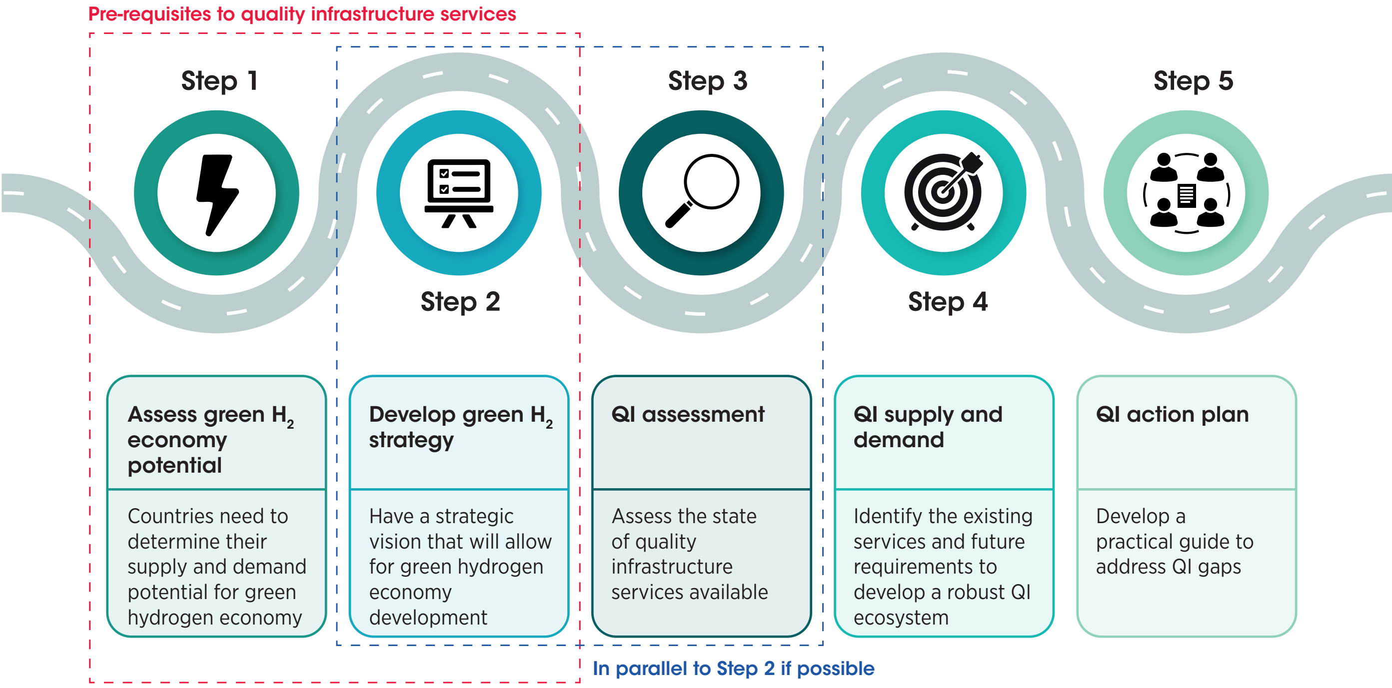
Quality infrastructure provides instruments and services to reduce safety, financial and reputational risks in the sector, while supporting the achievement of the intended positive sustainability impacts of investments. This report includes an overview of the main considerations and good practices for the key elements that underpin the quality infrastructure ecosystem, namely standardisation, metrology, conformity assessment (testing, certification, inspection, verification and validation) and accreditation as well as technical regulations that are relevant for the hydrogen sector.

A key output of this project is a general roadmap on how countries can develop their quality infrastructure to effectively support the green hydrogen sector – with particular focus on the hydrogen production and distribution segments of the value chain. The five steps that have been included in this roadmap approach are:

1. Assessing the green hydrogen potential
2. Development of a national hydrogen strategy
3. Assessment of the national quality infrastructure ecosystem
4. Assessment of quality infrastructure service offering and demand
5. Quality infrastructure development action plan

The roadmap steps provide guidance on key considerations for developing the hydrogen sector and the required quality infrastructure in parallel. The application of these roadmap steps was piloted in a Tunisia case study developed together with the Ministry of Industry, Mines and Energy. It is available as a PowerPoint slide deck on the IRENA webpage where this report is hosted.

Figure S1 Roadmap for green hydrogen quality infrastructure



Note: QI = quality infrastructure.

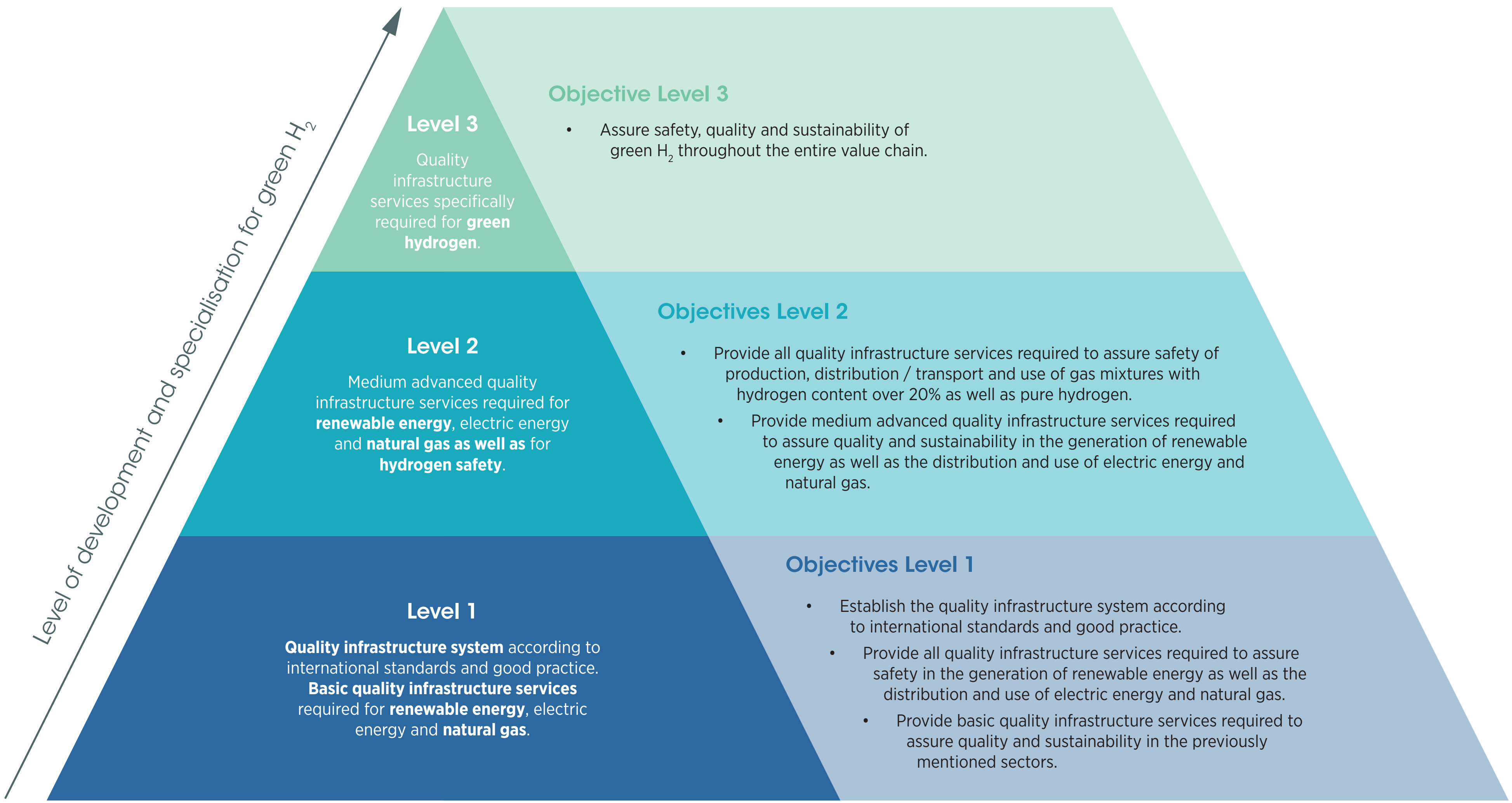
A three-level model is proposed which defines the required quality infrastructure services at different levels of development of the green hydrogen sector.

- The first level encompasses basic services that are essential to ensuring quality and safety of renewable energy generation, as well as in the distribution and use of electricity and gas (especially natural gas), covering the quality of components and safety of installation and operation. Most countries already have a fairly robust quality infrastructure in place at this level. It represents and creates a foundation for the integration of green hydrogen as innovative energy carrier into the existing energy system.
- The second level focuses on medium advanced quality infrastructure services, required to assure quality and sustainability in the generation, transport and distribution of renewable energy and gas (especially natural gas). The requirements at this level encompass and extend to hydrogen and blended mixtures with hydrogen content above 20%. In many countries, especially in developing and emerging economies, these services are currently not offered, or the existing offering does not fulfil the requirements defined in the applicable international standards.
- The third level includes advanced quality infrastructure services specifically required to assure safety, quality and sustainability of the production, transport, distribution, trade and use of green hydrogen. This includes for example certification of compliance with criteria related to the carbon intensity of the products and characteristics of the sourced energy generation. Many of the specific services for the quality infrastructure at this level are still under development or non-existent in most countries.

A checklist of services for each quality infrastructure pillar is provided, that can be used by policymakers and industry stakeholders to ensure that key services are in place from basic services to specialised requirements for green hydrogen. A database, comprising of a **non-exhaustive list** of available and upcoming quality infrastructure standards and technical regulations for hydrogen is also provided as an annex on the IRENA webpage where this report is hosted.

This publication applies the comprehensive knowledge and systemic approach of quality infrastructure to the emerging green hydrogen economy which the international community is actively exploring to catalyse energy transition efforts. The roadmap provides a structured method and tools for decision-makers and practitioners to apply when considering the vital role of quality infrastructure in supporting their energy transition efforts.

Figure S2 Development and specialisation of quality infrastructure services to support green hydrogen

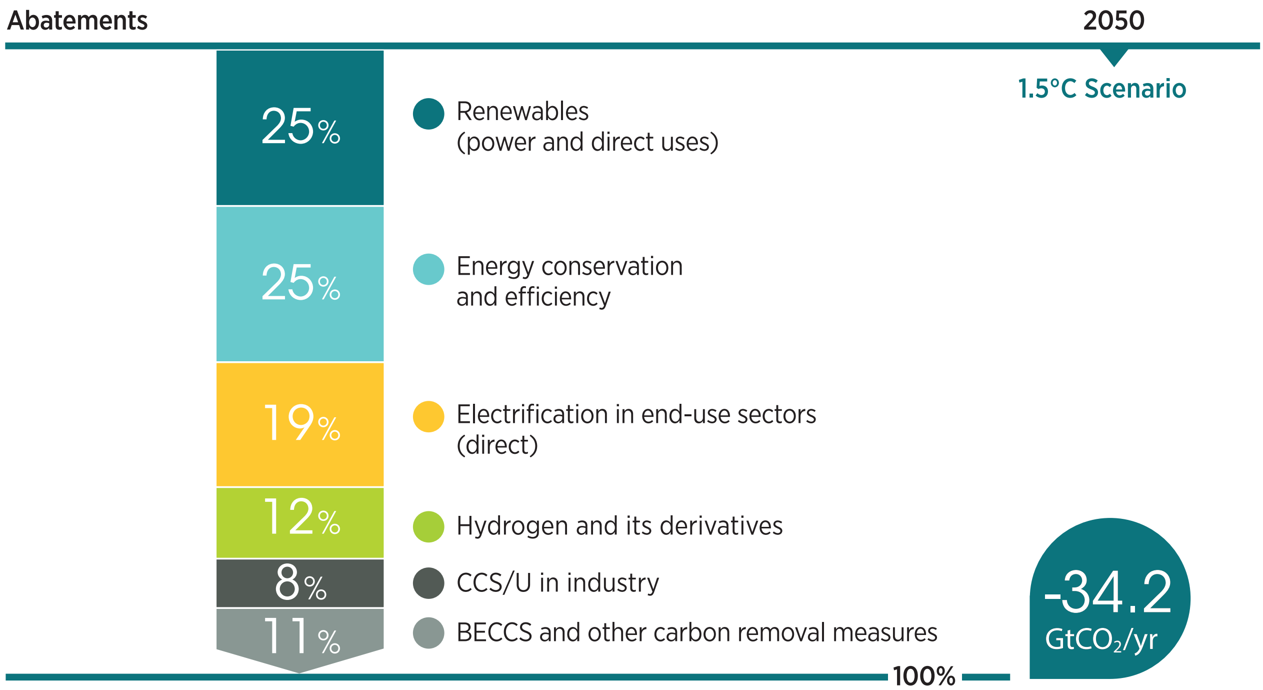


1. Introduction

The global transition to clean energy requires bold and innovative approaches to prevent greenhouse gas emissions from overshooting the agreed goals of the 1.5°C Scenario pathway (IRENA, 2024a). In addition to energy efficiency and direct electrification with renewables, green hydrogen produced from renewable-energy-powered water electrolysis, and its associated derivatives, is needed to reach net-zero emissions, particularly in sectors where emissions are hard to abate (Hydrogen Council and McKinsey & Company, 2021; IEA, 2024a; IRENA, 2023a, 2024b).

In the IRENA 1.5°C Scenario, by 2050, green hydrogen and its derivatives could reduce global emissions by 12%, as shown in Figure 1 (IRENA, 2023a, 2024b).

Figure 1 Emission abatements required by 2050 – 1.5°C Scenario



Source: (IRENA, 2023a).

Note: BECCS = bioenergy with carbon capture and storage; CCS/U = carbon capture and storage/utilisation; $GtCO_2$/yr = gigatonnes of carbon dioxide per year.

There is great opportunity for the use of green hydrogen to accelerate decarbonisation across sectors in developed economies and simultaneously open a path to accelerate the energy transition in emerging and developing economies. The international community is continuing its exploration of the viability of the hydrogen economy in making a sustainable energy transition successful. However, this will require strong demand signals, robust public policies and active private sector participation. Pursuit of this path will also result in the development of value chains, with a possible shift to producer countries that have abundant renewable energy resources (IRENA, 2024b).

Amid the focus on green hydrogen projects and associated infrastructure, an often-overlooked requirement is robust and resilient quality infrastructure[1] (QI). This trend is largely due to a lack of knowledge of quality infrastructure as well as its associated benefits for hydrogen stakeholders. The successful development of green hydrogen at scale, especially with due consideration to quality, sustainability and safety, must rely on a robust QI system. Well-functioning quality infrastructure also enables innovation, since reliable measurements and control are at the heart of technological improvements in hydrogen production processes. The establishment of a QI system for green hydrogen starts with information on, and awareness of, the system's importance, the required QI services and the priority areas for intervention. Then, the required QI services, which in part might still be missing, need to be implemented through co-ordination and co-operation among key national, regional and global stakeholders. It is also worth emphasising that expansion of quality infrastructure will be required across the hydrogen value chain (regardless of production avenue) along with exploration of quality developments for other decarbonisation pathways such as carbon capture, storage and utilisation.

To address this need, IRENA, together with Physikalisch-Technische Bundesanstalt (PTB)[2] and with financial support from Germany's Federal Ministry of Economic Co-operation and Development (BMZ), implemented a project titled "**Quality infrastructure for green hydrogen: technical standards and quality control for the production and trade of renewable hydrogen**", whose objective was to analyse the role of QI services as a key instrument for the successful global production and use of green hydrogen and selected derivatives. To fulfil this objective, two core outputs from this project were:

- **Output 1:** A roadmap on the development of the quality infrastructure to overcome existing quality, sustainability and safety challenges in green hydrogen production and trade.
- **Output 2:** For at least one selected country, recommendations for an action plan, resulting from a national stakeholder engagement process and geared towards overcoming existing quality, sustainability and safety challenges in green hydrogen production and trade.

This publication provides a **general roadmap** for quality infrastructure for green hydrogen and was developed in consultation with a broad stakeholder group. The roadmap has been prepared to guide policy makers and green hydrogen players on the key considerations to be followed in developing a robust QI system. It highlights key QI services (in the form of checklists and a tabular database annex), from a basic to an advanced level, that should be available for the green hydrogen sector in any national context.

The publication is organised as follows:

- Chapter 2 provides a brief overview of the latest developments in green hydrogen, looking into market developments, trade potential and sustainability.
- Chapter 3 defines quality infrastructure as well as the associated pillars supporting this system.
- Chapter 4 outlines the global landscape of QI services for green hydrogen, based on desk research as well as expert stakeholder consultations.
- Chapter 5 explains five roadmap steps to ensure the availability of relevant QI services.
- Chapter 6 offers key recommendations for decision makers to promote quality infrastructure at an industrial scale for green hydrogen development.

[1] *Chapter 3 of this report provides a comprehensive definition of what quality infrastructure entails.*

[2] *PTB is the national metrology institute of Germany.*

The application of this roadmap was undertaken as a **case study** for Tunisia (presentation available via the report landing page). Tunisia was chosen for several reasons, including the country's recent publication of an ambitious hydrogen strategy, which includes targets for local use and export of hydrogen. Another factor is Tunisia's close co-operation with PTB in the development of the country's QI services through dedicated bilateral projects. A link has thus been created between this IRENA project and the PTB-Tunisia project "**Renforcement de l'infrastructure qualité pour un développement économique durable en Tunisie**" (IQ.DED) and the project "**Renforcement de l'infrastructure qualité pour l'hydrogène vert en Tunisie**" launched in October 2024.

Box 1 provides a list of IRENA's most recent hydrogen-themed publications; they can be viewed as complementary readings to this publication.

Box 1 Recent IRENA publications on hydrogen

This report follows prior relevant work published by IRENA on the subject of green hydrogen and its derivatives. Readers may consult these further references if interested:

Global trade in green hydrogen derivatives: Trends in regulation, standardisation and certification (IRENA, 2024).

Green hydrogen strategy: A guide to design (IRENA, 2024).

Shaping sustainable international hydrogen value chains (IRENA, 2024).

Green hydrogen auctions: A guide to design (IRENA, 2024).

International trade and green hydrogen: Supporting the global transition to a low-carbon economy (IRENA-WTO, 2023).

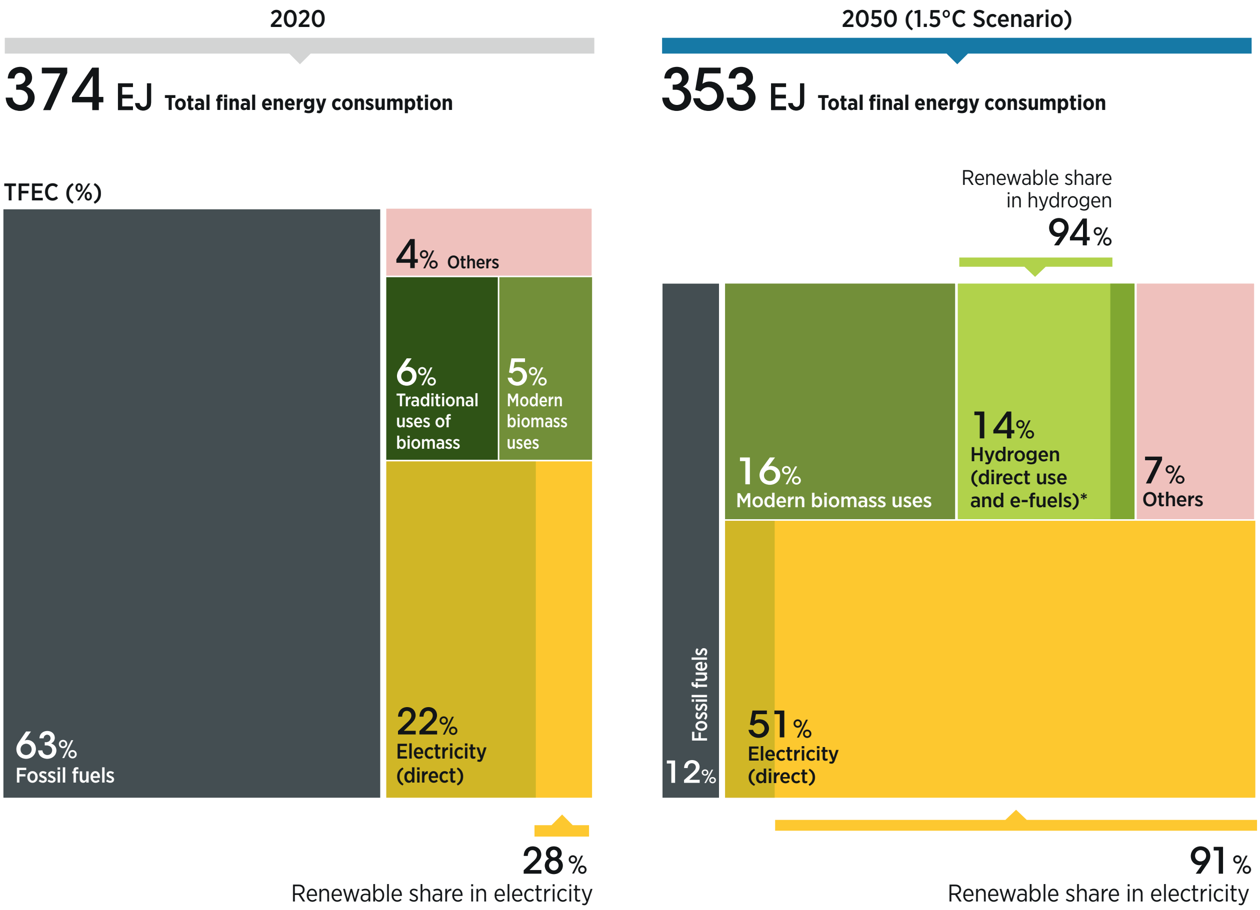
Global hydrogen trade to meet the 1.5°C climate goal: Trade outlook for 2050 and way forward (IRENA, 2022).

2. Developments in the global hydrogen market

Transitioning to a sustainable energy system and limiting the global average surface temperature increase to 1.5°C requires cross-sectoral decarbonisation. While hydrogen is used in fertilisers, chemicals and refineries, its production releases substantial carbon dioxide (CO_2) emissions because its origin is in natural gas or coal. This hydrogen needs to be replaced with clean hydrogen. In addition to existing uses, some sectors that do not use hydrogen today, namely, shipping, aviation, iron and steel, chemicals and petrochemicals, are particularly hard to decarbonise. While elements of these sectors can be electrified with renewable electricity, a significant portion could shift to sustainably produced hydrogen, either directly or in the form of hydrogen derivatives like ammonia, methanol and e-fuels. In the 1.5°C Scenario, by 2050, 14% of the world's final energy consumption will stem from the indirect electrification of these sectors using low-carbon hydrogen (refer to Figure 2).

This will require annual renewable hydrogen production of 125 million tonnes (Mt) by 2030 and 523 Mt by 2050, with green hydrogen dominating in the long term (rising from 40% in 2030 to 94% by 2050), and an installed electrolyser capacity of 428 gigawatts (GW) by 2030 and 5 722 GW by 2050 (IRENA, 2023b), from less than 3 GW in 2023 (IEA, 2024b).

Figure 2 Energy mix in 2050 in the 1.5°C Scenario



Source: (IRENA, 2023a).
Note: EJ = exajoule; TFEC = total final energy consumption.

Meanwhile, the higher production costs of green hydrogen relative to those of its dominant fossil-fuel-derived counterpart limit its contribution to the energy transition. The costs for green hydrogen are mainly driven by the cost of renewable electricity; the cost of the electrolysis plant; consisting of electrolysers and balance of plant (BoP); and, depending on the final use, the cost of transport, storage and distribution. IRENA's analysis shows that the cost for renewable power generation is declining quite rapidly, with the average costs for solar photovoltaics–based generation, and on-shore and off-shore wind generation having dropped by almost 90%, 69% and 59%, respectively, over 2010-2022. Today, solar and wind are the cheapest forms of new power generation in many regions of the world, and costs will likely continue to decline as these technologies continue to mature (IRENA, 2023c). On the cost for electrolysers, IRENA's analysis suggests that, if deployment volumes increase in the next years, the effects of "learning by doing" and economies of scale would lead to significant cost reductions of 40% in the short term and 80% in the long term (IRENA, 2022a).

As of May 2024, more than 50 countries had published national hydrogen strategies, setting targets for a projected electrolyser capacity of 113.5 GW by 2030 and 287 GW by 2050 (IRENA, 2024c). The global technical potential of green hydrogen is sufficient to meet their expected energy demand. However, some regions boast a competitive advantage in terms of resources (solar, wind, but also land, labour *etc*.) and therefore plan to become (net) exporters, whereas others may not be able to meet all of the demand and may require imports to complement their domestic production. IRENA estimates that about a quarter of all hydrogen consumed will be traded internationally by 2050 (in line with the 1.5°C Scenario), and approximately 55% of this hydrogen would be transported via pipelines, while the remaining 45% would be shipped, mainly as ammonia, which would predominantly be used directly as a synthetic fuel for international shipping or as a feedstock for the fertiliser and chemical industry (IRENA, 2022a).

Achieving these goals requires massive investments from the public and private sectors. Just as quality assurance has proven to be indispensable for establishing an enabling environment for the rapid deployment of renewable power technologies (IRENA, 2015a), developing a solid quality infrastructure for sustainable hydrogen supply chains will be key to gaining and maintaining the trust of investors and the public alike, in order to attract capital and maintain a license to operate.

2.1 Hydrogen trade

Today, almost all hydrogen is produced from fossil fuels, mostly at the location of its use, and the demand for trade is low. To achieve net-zero targets, hydrogen production must grow five-fold by 2050; to achieve this growth, regions with abundant renewable energy sources, due to lower production costs, along with factors such as access to capital, land and water, will deploy a substantial share of production facilities. This geographic separation of supply and demand creates a need for trade, allowing different regions to participate in the hydrogen economy (IRENA, 2022a: 1; IRENA and WTO, 2023).

International hydrogen trade will occur partly via pipelines, but also in the form of hydrogen-derived products like ammonia and methanol. A global low-carbon economy will require significant infrastructure investments, technology improvements and international co-operation to scale green hydrogen and meet the rising demand.

Trade in hydrogen (from different production pathways) occurs at a small scale today, and mainly between neighbouring economies, because the costs of transporting hydrogen over long distances is high and natural-gas-based blue hydrogen continues to be used mainly to produce fertiliser and refine oil, the main sources of current demand.

Global hydrogen imports amounted to USD 240 million in 2023; over 60% was traded between pairs of neighbouring countries (*e.g*. Canada to the United States, and Belgium to the Netherlands) (IRENA *et al*., 2023).

2.2 Ammonia

Ammonia is an essential commodity, which is used globally in the production of synthetic nitrogen fertilisers (85%). Ammonia production accounts for the emission of about 0.5 gigatonnes (Gt) of CO_2 annually, which is 1% of global CO_2 emissions. It is also ranks second in hydrogen consumption; about 45% of global hydrogen is used in the production of ammonia. A transition to green-hydrogen-based renewable ammonia is key to decarbonising the chemical industry. By 2050, the global ammonia market could reach 688 Mt, driven by the use of renewable ammonia in agriculture, as a maritime fuel and as a hydrogen carrier (IRENA, 2022b).

Despite its high initial costs, renewable ammonia could become cost competitive by 2030 with the right policies, including carbon pricing and contracts for difference (IRENA, 2022b). The shipping sector is projected to need 197 Mt of ammonia by 2050, representing a significant share of the demand for renewable ammonia, and indirectly for green hydrogen, while international trade of ammonia as a hydrogen carrier is expected to grow to 127 Mt annually (IRENA *et al*., 2022).

The global ammonia trade is more diversified and less regionalised than the global hydrogen trade, reflecting its global commodity nature (IRENA *et al*., 2023). Global ammonia imports amounted to USD 10.4 billion in 2023, 43 times the value of hydrogen trade. Trinidad and Tobago and Saudi Arabia are the main exporters, while the United States, the European Union, India and Morocco are the main importers (IRENA *et al*., 2023). It is expected that green ammonia shipped overseas would address about 40% of the global hydrogen demand by 2050 (IRENA *et al*., 2023). Just as for hydrogen, countries with significant renewable energy sources can develop a green ammonia export industry or produce green ammonia for their own fertiliser industry.

2.3 Methanol

Methanol is a key commodity in the chemical industry; it is used to produce different types of chemicals, for example, formaldehyde and plastics. Today, approximately 98 Mt of methanol are produced annually, from fossil fuels, releasing about 0.3 Gt of CO_2 emissions every year. Renewable methanol can be produced from biomass, as bio-methanol, or as green e-methanol from renewable CO_2 and green hydrogen. However, renewable methanol production is just starting to develop, with annual production of less than 0.2 Mt (IRENA and Institute Methanol, 2021), but there is a pipeline of announced projects that could lead to the production of over 29 Mt of renewable methanol by 2030 (Methanol Institute, 2024).

The value of global methanol imports amounted to USD 13.9 billion in 2023; supply was dominated by natural gas producers including Trinidad and Tobago, Oman, Saudi Arabia and the United States. The main market for methanol is China, which accounted for about 30% of the global methanol imports in 2023. Other major importers of methanol are the European Union, India, Brazil, the Republic of Korea and Japan (IRENA *et al*., 2023).

While renewable methanol is compatible with existing methanol distribution infrastructure, which is its advantage, its higher costs compared with fossil-fuel-based methanol, which is its disadvantage, continue to hinder its widespread adoption. Appropriate support mechanisms, clear certification schemes and production scale-up could help lower the production costs of renewable methanol and make it competitive with fossil-fuel-based methanol in the future (IRENA *et al*., 2021).

3. Quality infrastructure: Creating the basis for the sustainable development of the green hydrogen sector

The International Network on Quality Infrastructure (INetQI) formally defined quality infrastructure (QI) in 2017 as the national system of organisations, policies, legal framework and practices required to assure products and services are safe and sustainable. It serves as a fundamental element in the smooth functioning of domestic markets and facilitates international market access (INetQI, 2024). It also plays a pivotal role in fostering economic development and promoting environmental and social well-being (BIPM, 2017; Kellermann, 2019).

3.1 Elements of the quality infrastructure system

Quality infrastructure includes metrology, standardisation, accreditation, conformity assessment (including testing, certification, verification/validation and inspection)[3] and market surveillance as its components (INetQI, 2024). A cross-cutting aspect is technical regulation. Technical regulations define mandatory requirements to safeguard human health, safety and the environment. Standards can specify, and conformity assessments may verify, whether such requirements are met. Also, laws and technical regulations define the legal framework required for the national QI system. The purpose of this subchapter is to provide a brief overview of the elements of a QI system.

Standardisation

- **Standardisation** provides the technical requirements and specifications to ensure that products, processes and services are fit for their purpose. The process of standardisation involves creating and distributing standards, as well as informing interested parties about them. Developing standards is a process based on consensus as well as the contributions of interested parties. Standards establish a reference framework between suppliers and their customers, in turn facilitating trade, technology transfer and efficiency improvements (Sanetra and Marban, 2007). While the utilisation of standards is generally voluntary, they may become mandatory if referenced in legislation. The national standardisation body is responsible for developing standards, for the adoption and adaptation of international standards, and for raising awareness and providing the related information (IRENA, 2015b, 2017, 2020).

[3] *Conformity assessment bodies can be accredited under the related international standards: ISO/IEC 17020:2012, ISO/IEC 17021-1:2015, ISO/IEC 17024:2012, ISO/IEC 17025_2017, ISO/IEC 17065:2012, ISO 14065:2020 and ISO/IEC 17029:2019.*

Metrology

- **Metrology** is the science of measurement. It is used in legal matters, industry and science. The national metrology institute or a designated institute is responsible for developing and maintaining primary measurement standards (IRENA, 2017, 2020). The key service offered through metrology is the calibration or verification of measurement devices, wherein an instrument for measurement is compared to a measurement standard representing a higher hierarchy (IRENA, 2015b; JGCM, 2012). Metrology represents a fundamental pillar of quality infrastructure, as it supports standardisation, the regulatory framework, certification methods and testing regimes, among others.[4]

- **Calibration** is an operation that, under specified conditions, "*in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication*" (BIPM, n.d.). Calibration laboratories are frequently affiliated with universities, research centres or private enterprises, and offer calibration services for a wide range of measuring equipment or help ensure traceability with certified reference materials – by comparing the measurement values delivered by a device with the values for a calibration standard of known accuracy as established by the national metrology institute.

Accreditation

- Accreditation, provided by a national accreditation body or co-ordinated through a national focal point for accreditation, is a "third-party attestation related to a conformity assessment body conveying formal demonstration of its competence to carry out specific conformity assessment tasks" (ISO and IEC, 2020). The accreditation process entails a rigorous evaluation of an organisation's capabilities and its adherence to recognised standards. Testing and calibration laboratories, and certified reference material producers, along with certification, inspection, validation and verification bodies, seek accreditation to demonstrate organisations' reliability and competence in delivering services that fulfil established quality criteria. Accreditation boosts confidence in the services provided by accredited organisations and creates trust among stakeholders, including customers, regulatory bodies and other interested parties. Based on mutual recognition agreements, accreditation assures the international recognition of conformity assessment bodies.

Conformity assessment: Testing, certification, inspection, validation and verification

- **Testing** allows the characteristics or performance of a product or process to be determined following a specific procedure. It involves evaluating one or more properties of an object or product against the specifications outlined in a standard. This process is typically conducted by a testing laboratory. Standards often outline not only the specifications for the tested product but also the system requirements for the testing laboratory (as stated in ISO/IEC 17025:2005) and the testing processes (or guidelines) (IRENA, 2015b, 2017, 2020).

[4] *Service delivery and technical competency regarding metrology are demonstrated by the availability of measurement standards and the number and breadth of calibration and measurement capacities in any area required by, and provided to, the calibration laboratories. International recognition of metrology is achieved through participation in the Consultative Committees of the International Committee for Weights and Measures (CIPM), membership in the Bureau international des poids et mesures (BIPM) and Organisation Internationale de Métrologie Légale (OIML), and participation in key and supplementary comparisons.*

- **Certification** is the provision of written assurance (a certificate) that a product, service, process, person or system fulfils certain requirements. Product certification is based on testing to ensure that the products fulfil the criteria that are typically defined in a standard. Product and system certification requires periodic audits or inspections to verify that the products and systems conform to the specified standards (IRENA, 2015b, 2017, 2020).
- **Inspection** can be used to determine whether a product or process complies with certain requirements, and involves the examination of the respective sites, equipment or processes. Inspection bodies conduct the assessments on behalf of government agencies, parent companies or private clients (IRENA, 2015b, 2017, 2020).
- **Validation and verification** are *"understood to be a confirmation of the reliability of the information declared in claims. The activities are distinct according to the timeline of the assessed claim. Validation is applied to claims regarding an intended future use or projected outcome (confirmation of plausibility), while verification is applied to claims regarding events that have already occurred or results that have already been obtained (confirmation of truthfulness)"* (ISO *et al*., 2023).[5]

Market surveillance

- Market surveillance refers to the activities of authorities that involve monitoring and enforcing compliance with regulatory requirements, standards and specifications for the products or services. It relates to the identification of non-compliant products or to activities to safeguard customers, uphold fair competition and preserve the integrity of the market.

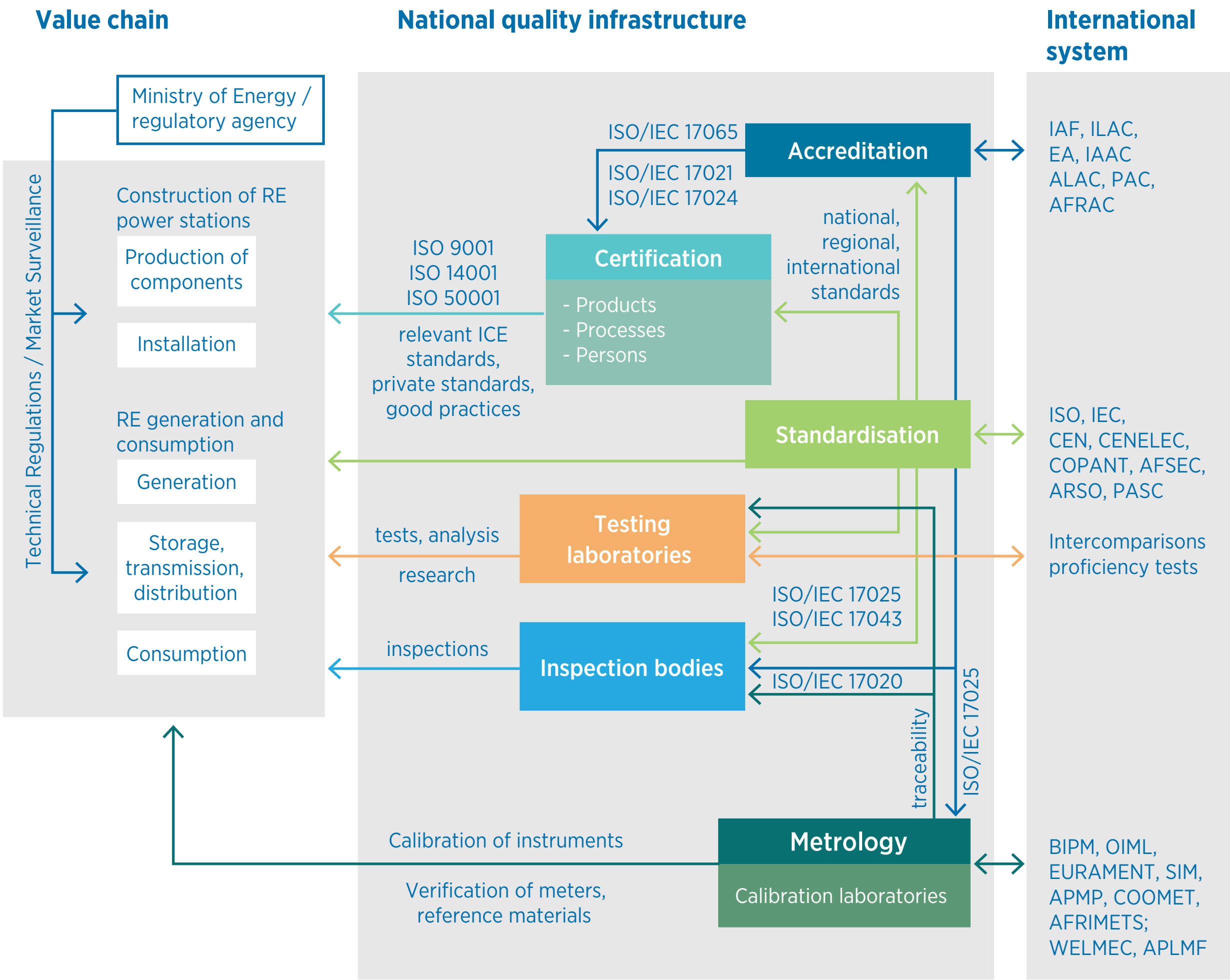
3.2 National quality infrastructure system and its international relations

National quality infrastructure system

The national QI system functions as a system of inter-related complementary components. The components described in the previous section must complement each other to be coherent and functional. The national policy environment and pertinent public and private institutions should be considered integral components of the extended quality infrastructure. They lay the groundwork for various services by establishing the necessary framework and guidelines. For instance, a ministry may choose to incorporate a standard into a technical regulation, thereby rendering the voluntary requirements outlined in that standard legally binding to safeguard environmental protection, health, safety and security. Public authorities or private service providers can evaluate the compliance of a product or a process with such requirements specified in a standard or technical regulation, depending on the context. Figure 3 provides a graphical overview of this system in a national context.

[5] *Important accreditation schemes for validation are as follows: ISO 14065:2020 – General principles and requirements for bodies validating and verifying environmental information; ISO/IEC 17029:2019 – Conformity assessment: General principles and requirements for validation and verification bodies.*

Figure 3 Overview of the quality infrastructure ecosystem



Source: (IRENA, 2015a, 2024d).

Notes: AFRAC = African Accreditation Cooperation; AFRIMETS = Intra-Africa Metrology System; AFSEC = African Electrotechnical Standardization Commission; APAC = Asia Pacific Accreditation Cooperation; APLMF = Asia-Pacific Legal Metrology Forum; APMP = Asia Pacific Metrology Programme; ARSO = African Organisation for Standardisation; BIPM = International Bureau of Weights and Measures; CEN = European Committee for Standardization; CENELEC = European Committee for Electrotechnical Standardization; COOMET = Euro-Asian Metrology Cooperation; COPANT = Comisión Panamericana de Normas Técnicas; EA = European Accreditation; EURAMET = European Association of National Metrology Institutes; IAAC = Inter American Accreditation Cooperation; IAF = International Accreditation Forum; IEC = International Electrotechnical Commission; ILAC = International Laboratory Accreditation Cooperation; ISO = International Organisation for Standardization; OIML = International Organization of Legal Metrology; PAC = Pennsylvania Accreditation Centre; PASC = Pacific Area Standards Congress; RE = renewable energy; SIM = Inter-American Metrology System; WELMEC = European Cooperation in Legal Metrology.

Global integration of the national quality infrastructure system

Building a national QI system requires integrating it with the global system, forging connections with essential international entities including:

- The International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and the International Telecommunication Union (for digital standards) for standardisation and certification;[6]
- The International Bureau of Weights and Measures (BIPM) and the International Organization of Legal Metrology (OIML) for scientific/industrial and legal metrology; and
- The International Accreditation Forum (IAF) and the International Laboratory Accreditation Cooperation (ILAC) for accreditation.

Only through this inter-connectedness is it possible to ensure international traceability; inter-operability; comparability; and recognition for local products, processes or services, and to benefit fully from the national QI system (Sanetra *et al*., 2007).

To promote quality infrastructure globally, there is a strong case for strengthening the links between these international bodies and the respective regional organisations, for example:

- For the Americas, the Inter-American Metrology System (SIM), the Pan American Standards Commission (COPANT), Inter-American Accreditation Cooperation (IAAC) and the Quality Infrastructure Council for the Americas (QICA).
- For Africa, the Intra-Africa Metrology System (AFRIMETS), African Organisation for Standardisation (ARSO), African Electrotechnical Standardization Commission (AFSEC), African Accreditation Cooperation (AFRAC) and Pan African Quality Infrastructure (PAQI); and
- For Europe, the European Association of National Metrology Institutes (EURAMET) and the European Committee for Standardization (CEN) / European Committee for Electrotechnical Standardization (CENELEC).

[6] *Dedicated international organisations such as the Versailles Project on Advanced Materials and Standards (VAMAS) co-ordinate standards development around specific themes – VAMAS, for example, provides the technical basis for drafting codes of practice and specifications for advanced materials as the precursor to standards (ISO, n.d.).*

4. Quality infrastructure services for green hydrogen

Global hydrogen demand was 94 Mt in 2021. This demand was mainly covered by fossil-fuel-based hydrogen production, which was approximately 77 Mt. Of the total hydrogen production, over one-sixth was by-products (approximately 16.5 Mt), mainly from the petrochemical industry. (IEA, 2024a). Hydrogen is produced, transported, distributed and utilised globally. In the existing value chain, hydrogen is mostly used as an industrial feedstock and is handled by specialised and safety-conscious personnel within industrial sites. Effective quality infrastructure (QI) services are implemented across the value chain to guarantee safe operation and the required gas quality.

However, the planned expansion of the green hydrogen sector requires a wider provision of QI services as more countries participate in the generation, distribution and use of this energy carrier. The physical and chemical properties of hydrogen are unique and more challenging than those of natural gas, for which well-established QI services exist in most countries. Green hydrogen thus requires many specific QI services. Also, a substantial increase of renewable energy generation is required for its production.

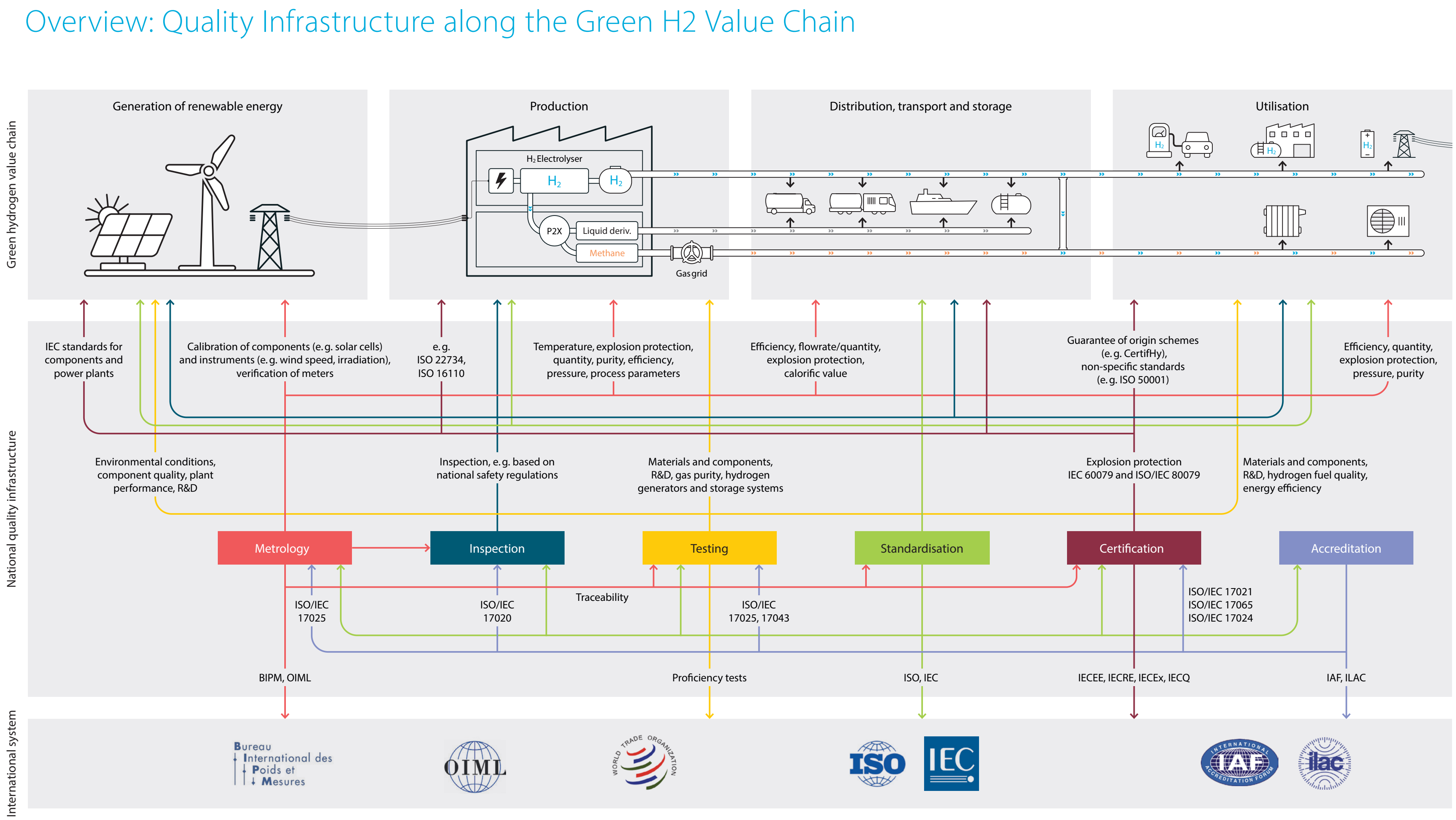
Based on an overview of quality infrastructure along the green hydrogen value chain, this chapter describes a model to differentiate the QI services according to their level of development and specialisation. The model can be used to analyse and plan the development of QI for the green hydrogen sector.

4.1 Overview of quality infrastructure along the green hydrogen value chain

Figure 4 summarises the green hydrogen value chain, example services provided by quality infrastructure and the relations among the organisations involved.

The section on top of the figure shows the green hydrogen value chain, which begins at renewable energy generation and proceeds through hydrogen production (via water electrolysis), distribution and transport, and ends with its utilisation. The section in the middle shows the components described in the previous chapter, with examples of the QI services provided at different steps of the value chain. This section also indicates the links between the components of the quality infrastructure. The section at the bottom summarises the links between the national quality infrastructure and international organisations.

Figure 4 Quality infrastructure along the green hydrogen value chain



Source: (Ferdinand, 2023).

Note: BIPM = Bureau International des Poids et Mesures (International Bureau of Weights and Measures); H_2 = hydrogen; IEC = International Electrotechnical Commission; IECEE = IEC System of Conformity Assessment Schemes for Electrotechnical Equipment; IECQ = IEC's Quality Assessment System; IECEx = International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres; ISO = International Organization for Standardization; OIML = International Organization of Legal Metrology; R&D = research and development.

4.2 Levels of quality infrastructure development and specialisation for the green hydrogen sector

A pyramid model (shown in Figure 5) differentiates the levels of the QI services required for the green hydrogen sector. The model defines three levels with increasing development and specialisation from bottom to top.

The pyramid model considers that QI services specific to green hydrogen will only be demanded in the long term in most countries. Different to that, QI services to assure safety, quality and sustainability in sectors complementing the green hydrogen value chain are demanded already today. As shown in Table 1, such sectors include renewable energy, as well as electric energy and gas (especially natural gas) derived from non-renewable sources. The national priorities in the development of such services must consider the concrete demand, for example, whether natural gas is distributed via a gas network or to what extent "grey" hydrogen is used. The generation of non-renewable energy (*e.g.* the generation of natural gas or "grey" hydrogen) is excluded from the analysis of the QI service requirements as part of this publication, since it is not compatible with the green hydrogen value chain.

Figure 5 Levels of development and specialisation of quality infrastructure services to support the green hydrogen sector

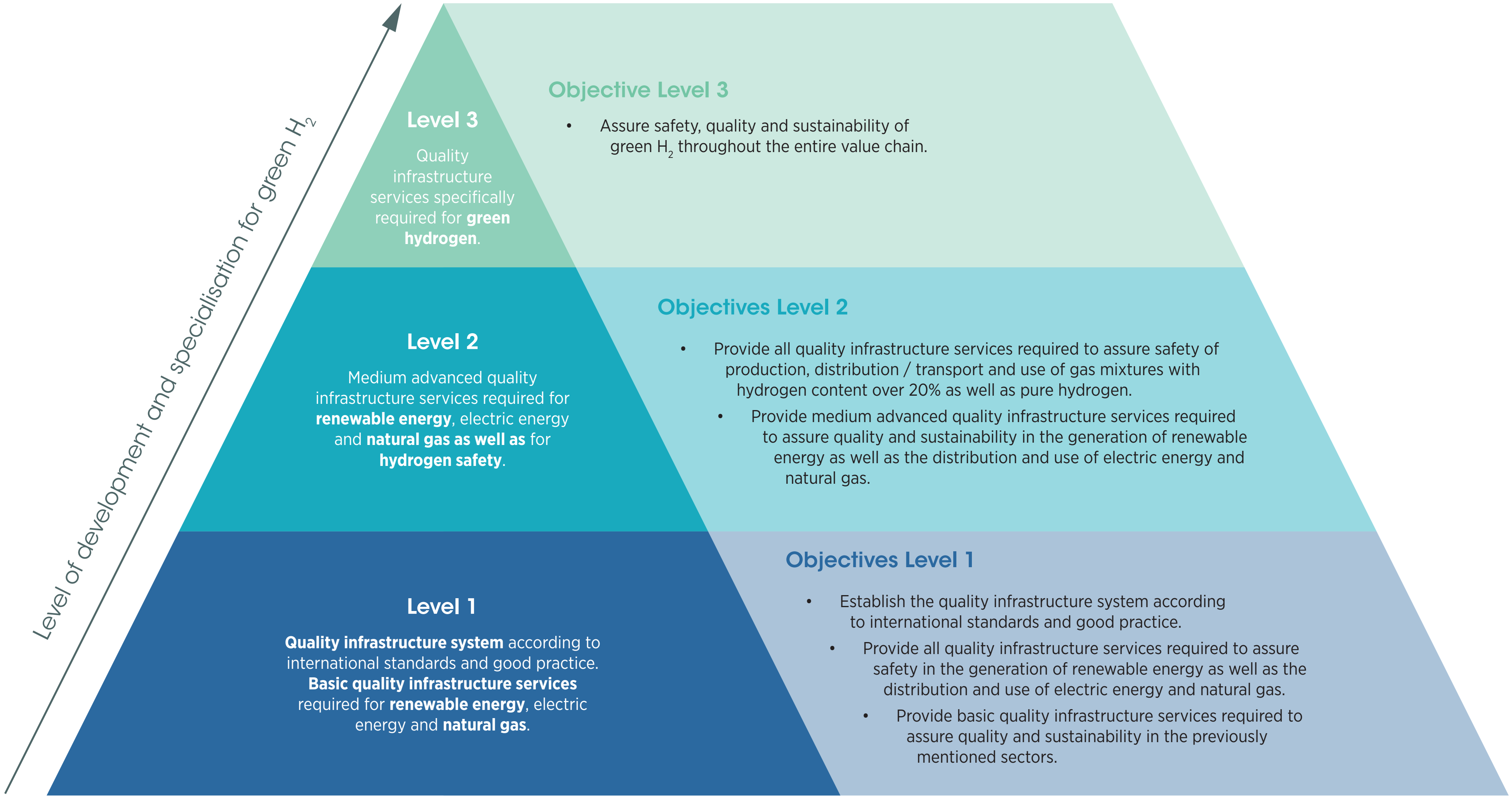


Table 1 Sector-specific requirements considered at the three levels of the pyramid model

	Sector				
	Renewable energy	Electric energy derived from non-renewable sources	Gas (especially natural gas)	Hydrogen derived from non-renewable sources	Green hydrogen
Consideration of sector-specific quality infrastructure services for:					
Assurance of safety	Level 1	Level 1	Level 1	Level 2	Level 2
Assurance of quality and sustainability	Levels 1+2+3	Levels 1+2	Levels 1+2	Level 2	Level 3
Value chain section					
Generation	Included	Not included	Not included	Not included	Included
Distribution		Included	Included	Included	
Use					

The three levels are described in more detail in the following section.

Level 1

Level 1 establishes the foundation for more specific services for the green hydrogen sector, which are included in the middle and top levels of the pyramid (Levels 2 and 3 of Figure 5).

The foundation requires a QI system that is set up in accordance with international standards and good practices. Especially the standards published by the International Organization for Standardization Committee for Conformity Assessment (ISO CASCO) must be considered with this regard. Further criteria and good practices are defined in the rapid diagnostic tool jointly developed by Physikalisch-Technische Bundesanstalt (PTB) and the World Bank Group.

Regarding specific QI services, Level 1 includes services defined as “basic” because they are already available or in demand in most countries. These services are essential not only for assuring quality and sustainability of renewable energy generation, but also of the distribution and use of electricity and gas (especially natural gas).

For instance, they ensure that renewable energy power plants are appropriately installed and that imported components meet the required quality, safety and sustainability standards. Level 1 also includes all services related to assuring safety within these sectors.[7]

The related QI services form the basis for any (future) development of green hydrogen as they help assure quality, safe and sustainable operations of the technologies, products, processes and services that are foundational for the hydrogen value chain. They are required in any country,[8] independent of the (future) demand for specific services in the green hydrogen sector.

Level 2

Level 2 includes medium advanced QI services required for assuring quality and sustainability in renewable energy generation as well as the distribution and use of electric energy and gas (especially natural gas). Such services are defined as "medium advanced" because they are currently not offered in many countries, especially developing and emerging economies, or the existing offering does not fulfil the requirements defined in the applicable international standards.

Level 2 also includes all QI services required to assure safe production, distribution/transport and use of gas mixtures with more than 20% hydrogen content, as well as pure hydrogen.

The Level 2 QI services are required in all countries planning to develop the green hydrogen sector.

Level 3

Level 3 includes advanced QI services specifically required to assure safe, quality and sustainable production, distribution/transport, trade and use of green hydrogen. Since green hydrogen is still an evolving sector, many of these specific QI services are still being developed.

Level 3 also includes advanced services related to assuring quality and sustainability of renewable energy. Such services are required, among others, for trade with renewable energy components and to fulfil sustainability criteria (*e.g.* carbon dioxide [CO_2] emissions related to energy generation).

[7] *It should be noted that QI services applied to natural gas are gradually also being applied for hydrogen. In particular, many standards for natural gas applications have been modified to account for the needs of the green hydrogen value chain. For example, the European Clean Hydrogen Alliance's Road Map on Hydrogen Standardization (published by the European Clean Hydrogen Alliance) lists many standards for all types of applications and components in the natural gas value chain that have been modified or remain to be adapted to include requirements for the use of hydrogen. The testing and calibration requirements are being specified accordingly (EU Commission, 2023).*

[8] *This is the case for countries where natural gas is distributed and used. The assurance of safety, quality and sustainability in the distribution and use of natural gas is essential for the development of the green hydrogen sector since the majority of the infrastructure can be used to distribute and use mixtures with hydrogen (up to a certain percentage).*

4.3 Fulfilling the demand for quality infrastructure nationally or by using services from other countries

It is worth noting that the development of the QI services essential for green hydrogen is both time and resource intensive. Such resources are to be provided not just once (*e.g*. for the equipment required in a testing laboratory) but also in the long term, as part of operational expenditure, for example, for rental, staff, training, calibrations and auditing/accreditation. Such substantial costs must result in the services generating equivalent benefits, for example, the income generated and/or macroeconomic benefits for the sector's development.

In this context, it is recommended to elaborate business plans for the development of specific required QI services. As explained above, Level 1 services are labelled "basic" since they have current demand. At the same time, such services are required in multiple sectors, since they are related to assuring basic safety and quality aspects. This means that in most countries, there should be sufficient demand to justify the development of the related services nationally.

However, especially for developing and emerging economies and for the services indicated for Levels 2 and 3, it may be advisable to assure access to the required services through co-operation with other QI organisations – in neighbouring countries, in the region or internationally. This can make it possible to quickly meet the demand of the national sector using the services of foreign QI organisations experienced and internationally recognised in the field.

For example, the metrology services included at Level 2 for renewable energy, irradiance level and spectral irradiance of the light source, wind speed, and the calibration of photovoltaic (PV) reference cells and modules require important investments in national metrology institutes (NMIs) and secondary metrology laboratories. In many national cases, co-operation with foreign NMIs and calibration laboratories to provide access to PV reference cells (especially primary calibrated cells) and modules is the economically and politically better approach.

4.4 Standardisation

Standardisation establishes commonly accepted criteria for products (or components), practices and services required along the green hydrogen value chain. Standards provide the basis for efficient, safe and sustainable interactions between market players, businesses and organisations in the hydrogen value chain. It also establishes agreed terms for market access and international trade.

As described in Chapter 3, standardisation involves creating and distributing standards, as well as informing interested parties about them. Because of that, enabling green hydrogen development requires national standardisation bodies to:

- Participate in relevant international technical committees (TCs),
- Participate in regional standardisation organisations,
- Establish related national mirror committees, and
- Adopt or adapt relevant international standards.

A. Participation in relevant international technical committees

National standardisation bodies must ensure they actively participate in international standardisation organisations relevant for the green hydrogen sector (Level 3) and for the complementing sectors described in the previous section. This includes mainly ISO and the International Electrotechnical Commission (IEC), as well as in their TCs. The participation of national standardisation bodies in these organisations facilitates:

- **Alignment with global standards.** Participation ensures that national standards are aligned with international standards. This facilitates global trade and ensures compatibility with international markets.
- **Influence and representation.** Participation in international committees can enable national bodies to represent their countries' interests. This contributes to the development of standards that reflect national priorities and needs.
- **Knowledge sharing and expertise.** Active involvement enables national bodies to stay updated on the latest technical developments and best practices. This facilitates knowledge and expertise transfer.

Considering the above, the QI checklist developed as part of this publication describes the most relevant international TCs concerning the three development and specification levels of the pyramid model. Since participation in international standardisation activities requires substantial resources, countries applying the checklist must determine which international TCs are a priority in the country context.

B. Participation in relevant regional standardisation organisations

Regional standardisation organisations are bodies established to develop and harmonise standards across specific regions.[9] They have a fundamental role in aligning national, regional and international standards relevant for the green hydrogen sector within their regions. Because of that, national certification bodies should participate in relevant regional organisations, in addition to participating in international standardisation organisations and their TCs.[10]

C. Establishment of related national mirror committees

National mirror committees help adopt or adapt international standards into national standards guidelines or technical specifications. This ensures stakeholder engagement, consistency and smooth implementation at the national level.

Because of that, national standardisation bodies should also establish national mirror committees for the international TCs identified as relevant in the country context.

[9] *Examples of important regional standardisation organisations include the European Committee for Standardization (CEN), African Organisation for Standardisation (ARSO), Pan American Standards Commission (COPANT) and the Pacific Area Standards Congress (PASC), which coordinates standardisation efforts in the Pacific region.*

[10] *In specific cases, it can be sufficient for national certification bodies to participate only in regional standardisation activities, for example, if a topic is already well covered and an exchange with international TCs is assured.*

D. Adoption or adaptation of relevant international standards

To ensure global compatibility, promote best practices, simplify compliance and facilitate innovation, international standards relevant for the development of green hydrogen must be adopted or adapted[11] into the national standards system.

An annex was developed, as part of this publication, to facilitate the identification of relevant standards. The annex describes the standards required for the three development and specification levels of the pyramid model. The checklist for the QI development for standardisation (see below) refers to this database.

Since the standards required for **renewable energy** are highly sector specific, they are not included in the database created as part of this publication. Depending on the specific focus of their national renewable energy policies, countries amongst others can refer IRENA's International Standards and Patents in Renewable Energy (**INSPIRE**) database which has a compendium of relevant standards for different renewable energy technologies that can be searched via technology and sub-technology (IRENA, 2024).

The standardisation checklist summarises the standardisation requirements at the three development and specification levels. The requirements are further described in the section below.

Table 2 Standardisation checklist

	Renewable energy generation	Production			Distribution and transport	Utilisation
		Electrolysis	Conversion into derivatives	Storage		
Level 1	• Adopt international standards in the national standard system as defined in the database for Level 1. • At least "observer" status in international TCs and establishment of the related national mirror committees in the following areas: IEC TC 31 – Explosive atmospheres and related subcommittees (*i.e.* SC 31J, SC 31M), IECEx (acceptance of international certificates of conformity), ISO/TC 180 – Solar energy, IEC TC 82 – Solar photovoltaic energy systems, IEC TC 88 – Wind energy generation systems, ISO/TC 161 – Controls and protective devices for gaseous and liquid fuels, ISO/TC 22/SC 32 – Electrical and electronic components and general system aspects, ISO/TC 301 – Energy management and energy savings, ISO/TC 58 – Gas cylinders. • Adopt relevant ISO CASCO – Standards related to the national quality infrastructure system.					
Level 2	• Adopt international standards into the national standard system as defined in the database for Level 2. • Full participating member in international TCs and establishment of national mirror committees in the following areas: TCs mentioned for Level 1 with "observer status" previously, IECEx and IECEE (Member Body), ISO/TC 197 – Hydrogen technologies. • At least "observer" status in international TCs and national mirror committees in the following areas: ISO/TC 207 – Environmental management (*i.e.* SC 7 Greenhouse gas and climate change management and related activities), ISO/TC 158 – Analysis of gases, ISO/TC 161/WG 5 – High-pressure controls, ISO/TC 193 – Natural gas.					
Level 3	• Adopt international standards into the national standard system as defined in the database for Level 3. • Full participating member in international TCs and national mirror committees in the following areas: TCs mentioned for Level 2 with "observer status" previously, IEC/TC 105 – Fuel cells, IECRE (Member Body).					

Note: CASCO = Committee for Conformity Assessment; IECEE = IEC System of Conformity Assessment Schemes for Electrotechnical Equipment; IECEx = International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres; IECRE = IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy; ISO = International Organization for Standardization; TC = technical committee.

[11] *Adoption refers to the direct use of an international standard without modification. The national body fully accepts the international standard as it is. Adaptation involves modifying an international standard to suit specific national needs or conditions.*

Standardisation requirements at Level 1

Level 1 covers standardisation related to assuring quality and sustainability in renewable energy as well as the distribution and use of electric energy and gas (especially natural gas).

Level 1 also includes standardisation required to assure safety in the sectors mentioned before:

- Countries should adapt or adopt the following specific standards into their national standard system: international standards related to safety in the energy and gas sectors, which include, among others, the IEC and ISO standards on risk management, hazard identification and analysis as well as process safety (including safety instrumented systems, pressure containment, fire safety, explosive atmospheres, electrical components and, if required, natural gas). Countries should additionally adapt or adopt relevant safety and quality standards for renewable energies, depending on the specific national focus. The specific standards required can be found in the standard database created as part of this publication.
- Regarding participation in relevant international TCs, depending on their specific national contexts at this level, countries should consider at least "observer" status in the committees described in the checklist and establish the related national mirror committees. Among others, this includes the IEC System for Certification to Standards relating to equipment for use in explosive atmospheres (IECEx System) and the related IEC TC 31 equipment for explosive atmospheres, as they are vital for supporting the development of the required safety standards.

Standardisation requirements at Level 2

Level 2 includes standardisation required to assure quality and sustainability in renewable energy generation as well as the distribution and use of electric energy and gas, especially natural gas. Level 2 also includes standardisation needed to assure safe production, distribution/transport and use of gas mixtures with more than 20% hydrogen content as well as pure hydrogen. The related requirements are mentioned in Table 2 and can be summarised as follows:

- National adoption or adaptation of international standards related to hydrogen safety, quality (*e.g.* purity specification) and sustainability (*e.g.* greenhouse gas [GHG] emissions). Additionally, national adoption or adaptation of quality requirements for the gas sector (if nationally relevant), gas analysis, extended requirements for explosion protection and, depending on national priorities, sustainability aspects in renewable energies (see the standard database for a detailed list of the international standards suggested to be considered).
- Participation in the related international TCs of IEC and ISO as described in the standardisation checklist (*e.g.* ISO TC/197 – Hydrogen technologies) and establishment of national mirror committees. National standardisation organisations should have "full participating membership" status in ISO/TC 197 as well as the TCs with "observer" status at Level 1. Additionally, "Member Body" status in the IEC System of Conformity Assessment Schemes for Electrotechnical Equipment (IECEE) is advisable.

Standardisation requirements at Level 3

Level 3 includes standardisation requirements related to safety, quality and sustainability of the production, distribution/transport, trade and use of green hydrogen. This includes:

- National adoption or adaptation of international standards defining sustainability and quality requirements specifically for the green hydrogen sector, including, for example, ISO/TS 19870:2023 – Hydrogen technologies. Among others, the methodology for determining GHG emissions associated with the production, conditioning and transport of hydrogen to consumption must be defined (for further standards required at this level, see the list of international standards in the standards database annex).

- Active role in international TCs as full participating member and, if required nationally, establishment of the related national mirror committees on the use of hydrogen (*i.e.* IEC TC Fuel Cells 105). Additionally, an active role in the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy (IECRE) is important. Also, national standardisation organisations should have "full participating membership" status in the TCs with "observer" status at Level 2.

International requirements for standardisation

While safety-related international standardisation for hydrogen production is already relatively well developed, standards for other parts of the value chain and standards related to quality and sustainability still need to be developed.

The development of commonly accepted criteria to facilitate international green hydrogen trade requires harmonising requirements and establishing minimum quality criteria. Such requirements should be defined in the standards developed by internationally recognised organisations (*i.e.* ISO and IEC), which apply good standardisation practices based on the principles of consensus, balance, transparency and stakeholder engagement. Additionally, convergence of national and regional standards and international standards is fundamental.

The following are the main areas identified as being required for agile and fit-for-purpose standardisation for green hydrogen:

- Since material and equipment must be fit for purpose to tolerate higher or 100% hydrogen content in storage, transport and distribution, new standards are required (*i.e.* for storing equipment), and the requirements established by existing standards must be adapted or updated.
- International standards must specify safety-related criteria applicable to the components relevant for the hydrogen sector, for example, requirements for protection against electric shock from electrolysers (DIN *et al.*, 2024).
- Criteria must be defined for classifying hydrogen and its explosion characteristics: (1) above atmospheric conditions and (2) for mixtures with other gases or substances. Also, methods to determine these characteristics must be developed (amongst others, this is relevant for metrology and testing).
- Hydrogen purification is associated with considerable costs, and not all applications require hydrogen of high purity. Existing hydrogen quality standards must be adapted, or quality standards must be specified (*i.e.* ISO 14687 and CEN/TS 17977) as part of the expansion of the hydrogen sector.
- Liquid hydrogen and derivatives, such as synthetic fuels, are currently not sufficiently covered by international standards. The same applies for emergency response procedures and comprehensive management frameworks to ensure safe operations in an expanded green hydrogen sector.
- Internationally recognised criteria are also required for life cycle assessments (LCA). LCAs amongst others are important to estimate emissions and other unintended environmental impacts generated in the hydrogen value chain. Especially fugitive emissions of hydrogen must be considered, since the gas has high indirect global warming potential due to its interference with atmospheric chemistry (Sand *et al.*, 2023).

- Requirements for guarantee of origin certification (see also the certification section below) for green hydrogen must be defined, specifying, among others, the traceability of renewable energy sources and criteria for reporting carbon emissions (including CO_2 emissions released by ancillary processes, particularly transport).
- Further, "whole of system" standards to assess the sustainability impacts of green hydrogen along the value chain are required. Such standards are especially important to promote a just transition (BMWK, n.d.), which refers to a fair and inclusive transition towards a sustainable economy, ensuring equitable distribution of the benefits and burdens of the energy transition. This is especially important in preventing adverse impacts on vulnerable communities, for example, impacts related to the use of water, competition for renewable energy resources (*i.e.* lack of additionality) or the creation of new dependencies on hydrogen exports among developing countries.

Standardisation is an iterative process, which relies on contributions from industry and other stakeholders to define fit-for-purpose, technically rigorous criteria and guidance. Broad and active stakeholder engagement is essential to ensure international standards remain technically coherent, technologically agnostic and broadly representative of the global consensus on the best practices.

In this context, it must be noted that new standards or updated criteria must be supported by other components of the quality infrastructure. Standards must refer to metrology and conformity assessment services, which in some areas still need to be developed and validated. Due this requirement, it is crucial that the representatives of the different QI components are involved in the relevant TCs.

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4.5 Metrology

Metrology is required to guarantee accuracy and traceability in green hydrogen. Metrology is the "science of measurement and its application, including all theoretical and practical aspects of measurement". The term "metrology service" in the context of this publication is understood as the provision of all key elements of metrology relevant for the green hydrogen sector, including determining uncertainty (quantifying uncertainty or variability in measurement results), establishing traceability (ensuring measurement results are linked to references through an unbroken chain of comparisons, usually to international or national standards) and calibration (comparing a measurement instrument or system to a known reference to verify its accuracy and performance) (JGCM, 2012; Standards Alliance, 2022a). Such metrology services are provided by NMIs[12] as well as secondary and tertiary calibration laboratories.

Metrology services assure safe operations along the green hydrogen value chain. They are also crucial for reducing environmental risks, making production and use more efficient, assuring high gas quality and enabling correct billing (including custody transfer, where hydrogen is transferred between two parties).

International measurement systems are built on consensus, which is established among global NMIs. Mutual equivalence among measurements and improved measurement capabilities requires comparison of national measurements through the NMIs. For countries to be able to participate in global green hydrogen trade and reduce technical barriers to trade, NMIs have the important role of establishing this mutual equivalence among national measurement standards and calibration capacity relevant for green hydrogen (Standards Alliance, 2022a, 2022b).

In this context, all the services summarised in the checklist below require measurement standards and calibration and measurement capacities of NMIs. For NMIs to effectively contribute to the sector's development, they must participate in the CIPM Consultative Committees (expert committees advising the International Committee for Weights and Measures [CIPM]) (Krietsch and Werhahn, 2024), have active membership in the Bureau International des Poids et Mesures (BIPM) and the International Organization of Legal Metrology (OIML), and participate in key and supplementary comparisons related to the services required for the green hydrogen sector.

The checklist below summarises the metrology services needed for green hydrogen at the three development and specification levels of the pyramid model as well as in the different parts of the value chain. These services are further described in the section that follows.

[12] *An NMI is an organisation responsible for developing, maintaining and disseminating national measurement standards; ensuring their traceability to the International System of Units (SI); and providing calibration services and expertise to support accurate measurements in science, industry and commerce (NPL, 2024).*

Table 3 Metrology checklist

Overview of the metrology services required for the development of the green hydrogen sector

<table>
<tr><th></th><th>Renewable energy generation</th><th colspan="3">Production</th><th>Distribution and transport</th><th>Utilisation</th></tr>
<tr><th></th><th></th><th>Electrolysis</th><th>Conversion into derivatives</th><th>Storage</th><th></th><th></th></tr>
<tr><td>Level 1</td><td>• Electrical characteristics: Current and voltage
• Temperature
• Humidity
• Conductivity
• Force and torque
• Verification of electricity meters</td><td colspan="5">• Reduced temperature range (-40°C to 100°C)
• Pressure (up to 200 bar)
• Calibration of gas detectors</td></tr>
<tr><td>Level 2</td><td>• Irradiance level and spectral irradiance of light source
• Wind speed
• Calibration of photovoltaic reference cells and modules
• Verification of smart/digital electricity meters
• Frequency
• Harmonic distortion</td><td colspan="5">• Expanded temperature range (-260°C to 100°C)
• Pressure (up to 800 bar)
• Gas flow rate
• Mass (e.g. for the production of reference gas)
• Density (liquid)
• Chemical composition and purity of gases
• Calorific value
• Gas standards and certified reference gas mixtures</td></tr>
<tr><td rowspan="3">Level 3</td><td rowspan="2">• Acoustics</td><td colspan="3">• Efficiency of hydrogen generators
• Water purity</td><td></td><td>• Efficiency of hydrogen utilisation</td></tr>
<tr><td colspan="5">• Chemical composition of hydrogen derivatives
• Very high pressure (up to 1 000 bar)
• Volume</td></tr>
<tr><td colspan="6">Modelling of green hydrogen systems</td></tr>
</table>

Metrology services required at Level 1

Several basic metrology services are required to assure safety and explosion protection,[13] quality and efficiency in the sectors related to green hydrogen. These includes services in the following areas:

- Among others, measurement of electrical characteristics, temperature, humidity, conductivity, force, torque and verification of electricity meters are required in the renewable energy sector.
- Reduced temperature ranges (-40°C to 100°C), pressure up to 200 bar and calibration of gas detectors are especially required to ensure safety in the gas sector.

Metrology services required at Level 2

The following are the medium advanced metrology services required to ensure safety, quality and efficiency in the sectors related to green hydrogen:

- In the renewable energy sector, especially wind and PV, the following metrology services are demanded to assure quality of components and power plants as well as appropriate grid management: irradiance level and spectral irradiance, wind speed, calibration of PV cells and modules, and verification of smart/digital electricity meters. Measurements of frequency and harmonic distortion, among others, are relevant for the integration of renewable energy into the grid and for grid management.
- An expanded temperature range (-260°C to 100°C), pressure up to 800 bar, gas flow rate, mass, density, chemical composition and purity of gases, and calorific value are crucial for assuring quality in the gas sector, at the same time creating the basis for safely operating gas infrastructure with high percentages of hydrogen. Access to gas standards and the provision of traceable and certified reference gas mixtures amongst others are relevant for the analysis of gas quality and the determination of gas properties for product control and billing purposes.

Metrology services required at Level 3

Advanced NMIs and designated institutes[14] already offer many services relevant for green hydrogen. Such services typically exist for pressure, temperature, density or efficiency. However, certain specific metrology services relevant for green hydrogen are offered by only a few institutes worldwide, while they are being developed by others. The following is a list of such services:

- Measurement of very high pressures with small measurement uncertainties. These measurements, for example, are required for tests of equipment durability and for leak detection during the generation, distribution and storage of hydrogen. (IRENA *et al.*, 2023)
- Many advanced NMIs are developing metrology services for determining the hydrogen gas quantity and gas flow required for gas meters. Calibrated gas meters are important for correct billing for end users. Flow measurement with very high accuracy is required for precise monitoring of gas flow across all segments of the value chain. Measuring high flow ranges (*e.g.* required by hydrogen transmission and distribution

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[13] *In this context, it is important to take note of the United Nations' past extensive study, UNECE WP6, to arrive at the Common Regulatory Objective, which acknowledges the concerns of explosion protection and supports the international standards issued by ISO and IEC with support from international certification through the IECEx. Refer to the United Nations Economic Commission for Europe publication "A Common Regulatory Framework for Equipment Used in Environments with an Explosive Atmosphere: ECE/TRADE/391".*

[14] *A designated institute is an institute that has been officially recognised by a government or national authority to perform specific metrological functions, which may not fall under the responsibility of the country's NMI.*

operators, or at refuelling stations for heavy-duty vehicles, which have conditions of extreme pressure and temperature), and different gas mixtures is a metrological challenge.

- Reference measurement methods and gas standards, among others, aid in measuring the purity of water in the electrolysis process and trace impurities in hydrogen and its derivatives. The same applies to hydrogen content variations in mixtures with natural gas that affect the calorific value and the safety of appliances.
- Currently, only a few advanced NMIs and calibration laboratories offer measurement of the chemical composition of hydrogen and its derivatives, the modelling of entire green hydrogen systems[15] and the validation of procedures to determine calorific value – important if hydrogen is mixed with natural gas (Ferdinand, 2023).
- For process management and controlling hydrogen quality, it is crucial to calibrate online/real-time sensors (*e.g*. moisture and oxygen content, ancillaries such as temperature and pressure). Such calibration services are currently still under development.
- Metrological services related to the efficiency of electrolysis plants and applications using hydrogen are lacking in most countries. Especially the determination of the efficiency of electrolysis plants over time needs to be investigated more.

Metrological standards[16] and methods to be developed internationally

Several metrological standards and methods still need to be developed internationally to fulfil the current and future demand of the emerging green hydrogen sector, and major efforts are needed to advance metrology accordingly. The following is a list of such areas[17]:

- Standards and methods that allow the traceable validation and performance evaluation of gas quality (EURAMET, 2022). Among others, this is important to guarantee high hydrogen purity for applications such as fuel cells and for determining the hydrogen production method at the end of the value chain.
- Improved methods for evaluating measurement uncertainty along the green hydrogen value chain (EURAMET, 2022). Such methods are required to correctly interpret measurement results and further improve their precision.
- The international recommendations of the OIML, which establish the metrological characteristics of measuring instruments and specify methods and equipment to assessing their conformity, must be adapted to cover the specific characteristics of hydrogen. This is especially the case for OIML R 140 on measurement systems for gaseous fuel and for OIML R 139-1 on measurement systems for compressed gaseous fuel for vehicles.
- Measurement standards for calibrating and validating flow metering equipment must be developed internationally to guarantee precise determination of the hydrogen quantity in pipelines (EURAMET, 2022; PA Consulting, 2020). Measurement devices need to be adapted and validated to ensure accuracy is maintained even when the gas composition fluctuates (DIN *et al*., 2024).
- New measurement methods are also required for determining hydrogen release from leaks (fugitive emissions).

[15] *The modelling of a green hydrogen system means a systemic consideration of the characteristic values of all production processes combined by modelling facilities. Such modelling is crucial for further process improvements (Ferdinand, 2023).*

[16] *A metrological standard is an object or system with a defined relationship with a unit of measurement of a physical quantity. Metrological standards are the fundamental reference for a system of weights and measures, against which all other measuring devices are compared (Ostwald and Muñoz, 1997).*

[17] *Further areas that are currently being developed are defined in the Strategic Research Agenda of the European Metrology Network (Version 2.0 (09/2022)) (EURAMET, 2022).*

4.6 Testing

Testing laboratories, whether public or private, have played a crucial role in ensuring safety of the operations in the hydrogen industry over decades. One example of an essential service offered by testing laboratories is the examination of storage tanks, which must demonstrate robustness to be considered safe and effective. Rigorous standards and regulations establish stringent criteria for these tanks and their components; this in turn necessitates a diversity of tests conducted under extreme conditions.

With rapid expansion of the green hydrogen sector, there arises a need for increasingly stringent requirements accompanied by additional and new testing. For instance, the purity of hydrogen must now be scrutinised at refuelling stations, especially because fuel cell vehicles are much more sensitive to impurities. Moreover, testing conducted as part of research and development initiatives supports amongst others the development of more efficient electrolysers or dependable remote sensing systems for storage and distribution.

Table 4 Testing checklist

	Renewable energy generation	Production			Distribution and transport	Utilisation
		Electrolysis	Conversion into derivatives	Storage		
Level 1	Environmental conditions: • Air salinity	• Explosion protection and safety of gas pipelines, valves and storage devices (*e.g.* durability, mechanical/hydraulic, chemical, insulation) • Electrical safety • Detection of gas leakages				
Level 2	Environmental conditions: • Irradiance • Wind speed Plant performance and safety (field testing): • Power (IV curves, current, voltage) • Sound power • Structural analysis • Electroluminescence imaging • Insulation testing • Infrared imaging • Cables/connector boxes	• Component resistance to corrosion (including in ammoniacal atmosphere) and hydrogen embrittlement • Hydrogen permeation in metals • Gas composition, purity • Calorific value (*i.e.* of gas mixtures) • IECEx and IECEE approved testing of equipment for use in explosive atmospheres and electrotechnical components				
Level 3	Testing of renewable energy components according to ISO/IEC standards, *i.e.* • Photovoltaic modules • Inverters • Wind turbines	• Water purity • Efficiency of hydrogen generators				• Efficiency of hydrogen utilisation
		• Component quality according to applicable standards for hydrogen generators, as well as components for hydrogen distribution and transport				

Note: IEC = International Electrotechnical Commission; IECEE = IEC System of Conformity Assessment Schemes for Electrotechnical Equipment; IECEx = International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres; ISO = International Organization for Standardization.

Testing requirements along the green hydrogen value chain can be summarised as follows.

Testing services required at Level 1

Basic testing services required to assure the quality and sustainability of renewable energy include the monitoring of environmental conditions:

- Temperature and humidity tests, offered in all countries, are not included in the checklist.
- The testing of air salinity (in the environment and in climate chambers) is to be considered in the design of renewable energy power plants and is not offered in all countries. Considering this, it is included as a Level 1 service in the checklist.

In the gas (especially natural gas) and electricity sectors, tests in the following areas are required to assure safe operations:

- Explosion protection and safety of gas pipelines, valves and storage devices (*e.g.* durability, mechanical/ hydraulic, chemical, insulation)
- Electrical safety
- Detection of gas leakages

Testing services required at Level 2

Services at Level 2 include the following tests that are crucial for the correct design of renewable energy plants and for the determination of their performance:

- Irradiance tests using pyranometers are conducted in all countries, but are often not performed correctly (*e.g.* due to incorrectly installed pyranometers).
- Wind speed can be considered as a basic test, but the related data are often insufficient (*e.g.* due to inappropriate anemometer placement and measurement duration).

Additionally, on this level important field-testing services and tests related to the safety of renewable energy plants are required. This includes the following:

- For most renewable energy installations, testing of electric parameters, structural elements, cables and connector boxes, as well as insulation.
- For wind power plants, sound power tests in the field.
- To analyse the quality of PV modules, electroluminescence and infrared imaging.

Testing services on this level also include those required to assure quality and sustainability in the distribution and use of electric energy and gas, especially natural gas. Additionally, all testing services required to assure safety of production, distribution / transport and use of gas mixtures with hydrogen content over 20% as well as pure hydrogen are included at this level.

Such services include:

- Tests to determine the component resistance to corrosion and the hydrogen enhanced degradation of materials' properties are fundamental to guarantee safe operation of equipment, especially with higher percentages of hydrogen. Understanding the impact of hydrogen on materials is crucial across various applications, including hydrogen storage, equipment and pipelines. While significant research has been conducted on hydrogen's effects on pipeline materials, limited information is available on its impact on other types of equipment materials.
- As hydrogen is frequently mixed with other gases, such as natural gas, for distribution and transport, it is increasingly important to test the gas composition and purity of these blends. In this context, highly selective and sensitive analysis of hydrogen purity and its trace contaminants is required. Specifically, the adsorptive properties of trace impurities like sulphur compounds, ammonia or water present challenges. For these tests, traceability to certified reference materials or reference methods must be ensured (see the metrology section above) (DVGW, 2023; Holger *et al*., 2023).
- Hydraulic cycle and hydraulic burst tests are critical for evaluating whether the materials and designs of pipelines, storage tanks and transportation vehicles are suitable for the high pressures at which hydrogen is often stored and transported.
- Furthermore, tests of equipment for use in explosive atmospheres and electrotechnical components, conducted by approved laboratories under the IECEx and IECEE schemes, are also included at this level.

Testing services required at Level 3

Advanced testing requirements for the renewable energy sector include the assessment of components according to ISO/IEC standards. These tests are vital for market surveillance and enforcing technical regulations related to components as well as ensuring the quality of national production. The following components are among those subject to testing at this level:

- PV modules
- Inverters
- Wind turbines

In particular for the production, distribution/transport, and utilisation of hydrogen generated via electrolysis, the following tests are necessary:

- Water purity to ensure the appropriate quality as input for electrolysis.
- Efficiency of hydrogen generators and hydrogen applications.
- Component quality, including endurance and reliability, in accordance with applicable standards for hydrogen generators as well as components used in hydrogen distribution and transport.

International development of testing services

Testing laboratories must further develop their services, in line with the growth of the green hydrogen sector. Testing services to be developed internationally include the following:

- Tests for large-scale hydrogen generators and related equipment, such as hydrogen compressors, heat exchangers, liquid hydrogen pumps and valves.
- High-precision tests of gas purity, including the relevant sampling procedures and protocols. These tests are particularly crucial for fuel cell vehicles, which are highly sensitive to impurities.
- Testing of hydrogen emissions to support related regulatory frameworks.
- Evaluation of cryogenic components, which are utilised for the storage and distribution of hydrogen in liquid form at approximately -253°C. Cryogenic storage allows for hydrogen to be stored in small volumes, offering higher energy density; however, it may lead to damage to materials due to embrittlement. It is essential to test the resistance of materials over time to ensure safe operation. In this context, reliability testing of systems and components is required, such as environmental simulation, fatigue, accelerated stress and environmental endurance tests.
- Development of easy applicable tests to investigate the restrictions of materials for hydrogen application.
- Alongside slow and time-consuming laboratory tests, there is a need for fast and simple online analysis. In this regard, significant research projects are underway that focus on online analysis for ultrapure hydrogen (DIN *et al.*, 2024).
- Advanced testing services to support research and development, among others, to support the development of highly efficient electrolysers or to establish reliable remote sensing systems for storage and distribution.

The new services developed by testing laboratories also create additional requirements for metrological services, ensuring traceability and enabling accurate testing results. These requirements are summarised in the previous chapter.

4.7 Certification, inspection, verification and validation

The global trade in green hydrogen demands not only internationally recognised standards but also robust and efficient conformity assessment based on these standards. In this context, certification and inspection schemes play a crucial role in reducing trade barriers. Globally harmonised certification and inspection promote the consistent application of commonly accepted criteria. Internationally recognised schemes enhance efficiency and reliability, as personnel, products or systems (such as an installer of a hydrogen fuelling station, green hydrogen produced in an exporting nation or the management systems of an electrolysis plant) need to undergo testing and certification only once to achieve international acceptance.

Table 5 Certification, inspection, validation and verification checklist

	Renewable energy generation	Production			Distribution and transport	Utilisation
		Electrolysis	Conversion into derivatives	Storage		
Level 1	• Acceptance of international certificates of conformity based on the IECEE and the IECEx					
Level 1	• Market surveillance of the most relevant renewable energy components, including sample testing, certification and inspection, *i.e.* PV modules and inverters • Personnel certification: Certification of renewable energy plant installers (including, *e.g.* welding personnel)	• System certification: Quality management, environmental management, energy efficiency management, occupational health and safety • Inspection and certification of safety aspects based on national technical regulations aligned, *i.e.* with EU Directives Pressure Equipment Directive (PED), and equipment for potentially explosive atmospheres (ATEX)				
Level 2	• Membership in IECEx and IECEE with the related certification and approval systems (*i.e.* approved certification bodies and testing laboratories according to the schemes), including IECEx Certified Equipment Scheme, IECEx Certified Service Facilities Scheme and IECEx Certification of Personnel Competencies					
Level 2	• Renewable energy plant inspection during construction and commissioning • Product certification: renewable energy plant components related to safety, *i.e.* cables/ connector boxes, mounting structures, wind turbines	• Product certification: Components for hydrogen production, distribution and transport according to international standards • System certification: Hydrogen production systems • Renewable gas guarantee of origin, *e.g.* based on European Renewable Gas Registry (ERGaR)				
Level 3	• Certification according to the IECEE and IECRE certification schemes (by accepted national certification bodies)					
Level 3	• Product certification: Certification of the most relevant renewable energy plant components, *i.e.* PV modules, inverters • System certification of renewable energy component manufacturing • Guarantee of origin and carbon dioxide emissions certification for renewable energy	• Product certification: Equipment for hydrogen utilisation, hydrogen and derivate quality • Certification, validation and verification of green hydrogen according to international standards, including carbon footprint, renewable content, use of land/water, social impacts				

Note: EU = European Union; IECEE = IEC System of Conformity Assessment Schemes for Electrotechnical Equipment; IECEx = International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres; IECRE = IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy; PV = photovoltaic.

Certification, inspection, verification and validation services required at Level 1

Basic services required to assure quality, safety and sustainability in the generation of renewable energy include the following:

- Recognition of certificates based on the IECEE certification scheme for renewable energy components to enable imports based on commonly accepted quality and safety criteria.
- Establishment of an effective market surveillance system for the most relevant renewable energy components, that is, PV modules, inverters and wind turbines (depending on the specific national priorities). Such a system includes, among others, the certification and inspection of compliance with applicable standards and technical regulations.
- Product certification of renewable energy plant components related to safety, that is, cables/connector boxes, mounting structures (*e.g*. IEC 62930 – Electric cables for PV systems).
- Implementation of personnel certification schemes for renewable energy plant installers (including, *e.g*. welding personnel) to assure the required levels of professional training for the correct installation.

For the assurance of safety, quality and sustainability in the distribution, transport, and utilisation of gas and electric energy, the following basic services are required:

- Acceptance of international certificates of conformity based on the IECEE and the IECEx certification schemes. This is essential to assure that electrotechnical components and equipment used in explosive atmospheres can be safely used.
- Implementation of system certification schemes for the management of quality, environmental aspects, energy efficiency, risk management, as well as occupational health and safety (including the labour standards set by the International Labour Organisation, *e.g*. SA8000 or ISO 45001).
- Inspection and certification of safety aspects that are defined in national technical regulations (*i.e*. EU Directives Pressure Equipment Directive [PED], Equipment for potentially explosive atmospheres [ATEX]).

Certification, inspection, verification and validation services required at Level 2

- Medium advanced services include the inspection of renewable energy plants during the construction and commissioning, to assure the fulfilment of quality and safety criteria defined in the applicable standards (*e.g.* for PV: IEC 62548:2023 – PV arrays – Design requirements; for wind energy: IEC 61400 – Wind turbines).
- Product certification services are required to assure quality and safety of components used for hydrogen production, distribution and transport according to international standards (*e.g.* ISO 22734:2019 – Hydrogen generators using water electrolysis, ISO 16111:2018 – Hydrogen – Fuel tanks for stationary and mobile applications).
- Membership in IECEx and IECEE with the related certification and approval systems (*i.e.* approved certification bodies and testing laboratories according to the schemes), including IECEx Certified Equipment Scheme, IECEx Certified Service Facilities Scheme and IECEx Certification of Personnel Competencies.
- At this level, the certification of the guarantee of origin of renewable gas can be required as an intermediate step in the development of the green hydrogen sector, for example, based on the standard EN 16325 – Guarantees of origin related to energy – Guarantees of origin for electricity, gas and hydrogen.

Certification, inspection, verification and validation services required at Level 3

Advanced services are especially relevant to assure the quality and safety of components produced nationally, including PV modules and inverters.

Also, system certification schemes are required for the manufacturing of components at this level. Furthermore, certification is required at this level for the following products:

- Equipment used for the utilisation of hydrogen (*e.g.* based on ISO 19880 Series – Gaseous hydrogen – Fuelling stations or IEC 62282 Series – Fuel cell technologies).
- Hydrogen quality (*e.g.* based on ISO 14687:2019 – Hydrogen fuel quality).
- Hydrogen derivates (*e.g.* based on ISO 14671:2013 – Ammonia used as a refrigerant – Product specifications).

To assure the intended positive sustainability impacts of the development of green hydrogen, specific certification, verification and validation schemes based on international standards are required, especially regarding carbon footprint, renewable energy content, social impacts, as well as the use of land and water. As indicated in the chapter on standardisation, such international standards are still under development. Existing approaches have to evolve to enable the mutual recognition and inter-operability required for cross-border trade of green hydrogen (IRENA, 2023d, 2024e).[18]

[18] *The UK government is working on a green hydrogen supply chain certification scheme, which is likely to be underpinned by accreditation.*

4.8 Accreditation

Internationally recognised accreditation of testing, calibration, certification, verification, validation and inspection services is crucial to foster the transborder trade of green hydrogen and infrastructure components required along the value chain.

In less developed QI systems, often the accreditation bodies are not internationally recognised. National accreditation bodies are internationally recognised through mutual recognition arrangements (MRAs) with organisations like the International Accreditation Forum and the International Laboratory Accreditation Cooperation. These MRAs ensure that accreditation bodies operate in accordance with globally accepted standards, such as ISO/IEC 17011, for conformity assessment. By signing these agreements, national accreditation bodies demonstrate their competence and trustworthiness, enabling certificates and reports issued by accredited entities to be accepted across borders, thereby facilitating global trade and reducing the need for duplicate assessments.[19, 20]

Some accreditation services required for the development of green hydrogen are rarely demanded in most countries (*e.g.* tests of wind turbines performed in specialised laboratories). In other areas, newly developed assessment schemes must be included into the accreditation portfolio, requiring their evaluation by national accreditation bodies or international bodies such as the European Cooperation for Accreditation. This applies, for example, to new certification schemes for GHG emissions in the green hydrogen value chain.

Considering this, countries fostering the development of green hydrogen should make sure that frequently demanded accreditation services are offered by the national accreditation body (or bodies) based on MRAs covering the relevant scopes (as defined in ISO/IEC 17011, Clause 1. Scope).[21] Other, more specific and less frequently demanded services may be offered by accreditation bodies from other countries.

Table 6 lists which accreditation services should be made available at the three levels, either nationally or by agreement with foreign accreditation bodies.

19 Accreditation bodies in developing economies often co-operate with advanced accreditation bodies and international accreditation organisations with the aim of fulfilling the requirements for international recognition. Organisations such as PTB or the United Nations Industrial Development Organization support such co-operation.

20 For example, see the International Accreditation Forum Multilateral Recognition Arrangement process and requirements: https://iaf.nu/en/about-iaf-mla.

21 Testing and calibration (based on ISO/IEC 17025), Certification (based on ISO/IEC 17021 for management systems, ISO/IEC 17065 for products, ISO/IEC 17024 for personnel), Inspection (based on ISO/IEC 17020), Proficiency tests (based on ISO/IEC 17043).

Table 6 Accreditation checklist

	Renewable energy generation	Production			Distribution and transport	Utilisation
		Electrolysis	Conversion into derivatives	Storage		
Level 1	• Testing and calibration laboratories (services according to the checklists for metrology and testing, Level 1) • Certification, inspection, validation and verification bodies (services according to checklist, Level 1) • Evaluators and experts with technical expertise in the conformity assessment services required, especially related to safety					
Level 2	• Proficiency test providers • Testing and calibration laboratories (services according to the checklists for metrology and testing, Level 2) • Certification, inspection, validation and verification bodies (services according to checklist, Level 2) • Evaluators and experts with technical expertise in proficiency tests and conformity assessment, especially related to hydrogen					
Level 3	• Testing and calibration laboratories (services according to the checklists for metrology and testing, Level 3) • Certification, inspection, validation and verification bodies (services according to checklist, Level 3) • Evaluators and experts with technical expertise in proficiency tests and conformity assessment, especially related to green hydrogen					

Note: All services should be offered by internationally recognised accreditation bodies.

Accreditation services required at Level 1

This level includes "basic" metrology and conformity assessment services required in most countries to control and increase quality and sustainability in renewable energy generation, as well as in the distribution and use of electricity and gas. All services related to assuring safety in these sectors are also included at this level.

Considering the existing demand in most countries and the relevance of safety, internationally recognised accreditation services should be provided by national accreditation bodies in the following areas:

- Accreditation of the testing, calibration, certification, inspection, validation and verification services as defined in the previous chapters (see Level 1 in the related checklists).
- All services provided must utilise trained evaluators and experts with the required technical expertise (as defined in ISO/IEC 17011:2017 Conformity assessment – Requirements for accreditation bodies accrediting conformity assessment bodies).

Accreditation services required at Level 2

Accreditation services required at this level include those in the following areas:

- Accreditation of testing, calibration, certification, inspection, validation and verification as defined in the previous chapters (see Level 2 in the related checklists); one example is the accreditation of inspection bodies for renewable energy plants.
- Accreditation of proficiency test providers offering services for the testing of laboratories operating in the renewable energy, electricity, as well as gas and hydrogen sectors.
- The provided services must be based on trained evaluators and experts with the required technical expertise, including conformity assessment in the hydrogen sector.

As the related accreditation services are more specific and (at least currently) in less demand in many countries, they may be covered either by national accreditation bodies that are internationally recognised or by foreign accreditation bodies.

Accreditation services required at Level 3

Advanced QI systems normally have internationally recognised accreditation bodies, but such organisations must expand their services to fulfil the newly developing requirements to assure quality and sustainability in the green hydrogen sector. This includes all testing, calibration, certification, inspection, validation and verification services as defined in the previous chapters for Level 3. Evaluators and experts involved in the related processes require technical expertise specific to green hydrogen.

Also, new assessment schemes must be included in the accreditation portfolio at this level, including certification schemes for GHG emissions across the green hydrogen value chain.

4.9 Technical regulation

Regulations are created to guarantee safety and integrity along the value chains of the gas, electricity, and in more advanced systems, of the green hydrogen sector. They are also intended to protect the customer, set minimum standards for the quality of services delivered and to prevent possible negative environmental effects. In this context, national and supranational regulators (*e.g.* the European Commission in the revised Renewable Energy Directive) have in recent years published new and updated legal requirements that are especially relevant for the hydrogen sector. Such regulations as well as the related standards, effective procedures and governance structures must be implemented nationally.

The use of standards and technical rules is usually voluntary. However, they can be made binding by referencing them in a law or in a contract. In many cases, the mandatory QI services of metrology, testing, inspection and certification are derived from technical regulations.

Standards and technical rules also play an important role as instruments for supporting and implementing legal regulations and provisions. The legislator often cites national rule setting institutions directly in laws. Thus, in Germany, for example, the German Association for Gas and Water (DVGW) is the legally recognised rule setting institution for gas and hydrogen within the meaning of the Energy Industry Act (EnWG). The standards and technical rules set by a gas sector technical body may specify how hydrogen production plants may operate, and how hydrogen may be handled within gas pipelines, for example. Furthermore, in the German case, as an example, the German Technical-Scientific Association (VDE) is responsible for setting technical rules in the electricity sector under this Act. These rules may specify how a hydrogen producer may safely connect their electrolyser to a power source. Further examples are detailed in the sections which follow. For further information on the regulations applicable in Germany see the RCS Database.

In this context, national and supranational regulators have in recent years published new and updated legal requirements that are especially relevant for the gas and hydrogen sectors (EU Commission, 2021). Such regulations as well as the related standards, effective procedures and governance structures must be implemented nationally according to local legislative frameworks and divisions of regulatory competence.

Table 7 Technical regulation checklist

<table>
<tr><th></th><th>Renewable energy generation</th><th colspan="3">Production</th><th>Distribution and transport</th><th>Utilisation</th></tr>
<tr><td></td><td></td><td>Electrolysis</td><td>Conversion into derivatives</td><td>Storage</td><td></td><td></td></tr>
<tr><td>Level 1</td><td>• Grid codes covering renewable energy connection
• Regulation of renewable energy power plant safety and environmental aspects</td><td colspan="5">Regulation on occupational safety
• For example, safety and health protection of workers potentially at risk from explosive atmosphere, 1999/92/EC
Regulation on environmental aspects in gas production, distribution, transport and utilisation
Regulation on product safety, for example,
• Equipment for potentially explosive atmospheres (e.g. ATEX Directive 2014/34/EU, Pressure Equipment Directive (e.g. PED Directive 2014/68/EU)
• Machinery Directive 2006/42/EU and Regulation (EU) 2023/1230</td></tr>
<tr><td rowspan="2">Level 2 and 3</td><td></td><td colspan="3">Regulation on safe production of hydrogen, for example,
• Control of major accident hazards (e.g. Directive 2012/18/EU SEVESO III)
Regulation on sustainable production of hydrogen
• For example, EU RED II and delegated acts
• US Inflation Reduction Act (Section 45V and Guidance from the Internal Revenue Service)</td><td colspan="2">Regulation of distribution and transport of hydrogen, for example,
• Control of major accident hazards (e.g. Directive 2012/18/EU SEVESO III)
• Control of transport of hydrogen in liquified or gaseous cylinders or pipelines (e.g. EU 2021/535)
• Control of transportation of hazardous materials (e.g. 49 CFR Part 192)
Regulation on end uses in new sectors, for example,
• Hydrogen refuelling stations (e.g. OIML R139, PED or TPED, AFIR)
• Fuel cell vehicles (e.g. UN Regulations No. 134,146, 153)</td></tr>
<tr><td></td><td colspan="5">Regulation on product safety, for example,
• Pressure equipment (e.g. Directive 2014/68/EU)
• Measuring instruments (e.g. Directive 2014/32/EU)</td></tr>
</table>

Note: AFIR = Alternative Fuels Infrastructure Regulation; ATEX = Equipment for potentially explosive atmospheres; OIML = International Organization of Legal Metrology; PED = Pressure Equipment Directive; UN = United Nations.

Technical regulation required at Level 1

Renewable energy generation assets

Basic technical regulation for the renewable energy sector includes grid codes for the connection of renewable energy power plants. Also, the safety and environmental aspects of such plants must be regulated.

Occupational health and safety

For the production, distribution and transport as well as utilisation phases of the gas and electricity sector, regulations on occupational health and safety must be in place.

In the European Union, such aspects are covered, among others, in the following regulations:

- Safety and health protection of workers potentially at risk from explosive atmospheres, 1999/92/EC.
- ATEX Directive 2014/34/EU (also known as "ATEX 114" or "the ATEX Equipment Directive") on the approximation of the laws of Members States concerning equipment and protective systems intended for use in potentially explosive atmospheres.
- ATEX 153 "workplace" Directive 1999/92/EC – Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.
- Directive 99/92/EC (also known as "ATEX 137" or the "ATEX Workplace Directive") on minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres.
- Directive 94/9/EC ATEX 100, which concerns explosive atmospheres.

For products, these risks are covered by the Machinery Directive 2006/42/EU. From 20 January 2027, the directive will be replaced by Regulation (EU) 2023/1230.

In the United States, the production of hydrogen is governed by 40 CFR Part 98 Subpart P – Hydrogen Production. The Environmental Protection Agency regulates the release of pollutants into the environment, including hydrogen. It sets standards for emissions from hydrogen production facilities and may also be involved in permitting and compliance monitoring.

IRENA's Alliance for Industrial Decarbonization recommends that countries refer to IEC/TC 31 International Standards within National and Regional Regulations with regards to regulating equipment for explosive atmospheres.

Technical regulation required at Levels 2 and 3

More advanced technical regulations include regulation on the safe production of hydrogen and of product safety for both pressure equipment and measurement instruments.

High-pressure use of hydrogen

When using hydrogen in new applications, and with the stated aim of reducing emissions over its life cycle, new risks appear that are related to higher pressure, new environments where hydrogen could leak, new products that are derived from hydrogen and indirect environmental impacts of electrolysers on power grids.

In the European Union, such aspects are covered, among others, in the following regulations:

- Control of major accident hazards (*e.g*. Directive 2012/18/EU SEVESO III)
- Pressure equipment (*e.g*. Directive 2014/68/EU)
- Measuring instruments (*e.g*. Directive 2014/32/EU)

The area of **occupational safety** is covered by Directive 89/391/EEC (Occupational Safety and Health Framework Directive). The regulations include:

- Special protective measures against physical and chemical effects, in particular against fire and explosion hazards;
- Activities involving explosive substances; measures in the event of operational disruptions, accidents and emergencies, information and instruction of employees.

In the United States, the Occupational Safety and Health Administration sets standards for workplace safety, including those related to hydrogen production and handling. These standards cover topics such as personal protective equipment, ventilation and emergency procedures.

Electricity generation for electrolysers

When the use of green hydrogen is aimed at reducing emissions (in substituting a fossil source), it is important to guarantee that the electricity used does not lead to direct or indirect emissions. If existing renewable energy assets are used to power electrolysers, there is a risk that this power will be compensated by fossil assets, in grids that are not completely decarbonised. This is an indirect negative effect.

To address this risk, the EU RED II (EU Commission, 2021) and its delegated acts outline requirements for the green hydrogen producers to demonstrate the additionality the renewable power consumed, including requirements on time matching (demonstrate that the renewable electricity is generated at the same time as it is consumed) and be physically connected to the same grid the electrolyser is connected to. In the United States, the Inflation Reduction Act introduces clean hydrogen production tax credits (under Section 45V), while guidance on demonstrating additionality, time matching and geographic matching is provided by the US Treasury Department and Internal Revenue Service.[22]

[22] *Currently only available in a draft document.*

IRENA's Alliance for Industrial Decarbonization recommends that countries and stakeholders refer to ISO/TC 197 for the regulation of GHG emissions over the life cycle of hydrogen.

Hydrogen storage and transport

Hydrogen storage needs to be regulated for stationary storage in gaseous, liquid or in metal hydride form. This will entail including hydrogen considerations in land use planning and permitting including zone prohibition, environmental and risk assessments, and safety requirements such as safety distances.

The EU's Regulation (EU) 2021/535 covers safety requirements for liquefied (535a) and compressed (535b) hydrogen storage systems.

The road transport of hydrogen in gas tanks (tube trailers), metallic cylinders and composite vessels should be regulated for gaseous, liquid and hydride forms. This may entail road planning as well as allowed pressures and quantities to be transported over the road.

Road transport of hydrogen is regulated in the European Union through several directives:

- European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR): This agreement sets out the requirements for the transport of dangerous goods, including hydrogen, by road. It covers aspects such as packaging, labelling and vehicle requirements (Makka *et al*., 2019).
- Directive 2008/68/EC on the inland transport of dangerous goods (TDG): This directive incorporates the ADR into EU law and applies to the transport of dangerous goods by road, rail and inland waterways (Cenex, 2021).
- Transportable Pressure Equipment Directive (TPED) 2010/35/EU, which covers the design, manufacture and testing of transportable pressure equipment, including cylinders and tubes used for hydrogen transport.
- The Pressure Equipment Directive (PED) applies to the design, manufacture and conformity assessment of pressure equipment, including those used in hydrogen transport (Cenex, 2021).
- The Classification, Labelling and Packaging Regulation (CLP) – EC No 1272/2008 ensures that the hazards of chemicals, including hydrogen, are clearly communicated to workers and consumers through classification and labelling.
- Registration, Evaluation, Authorisation and Restriction of Chemicals Regulation (REACH), while primarily focused on chemical safety, also has implications for the transport of hydrogen (Wouteresen *et al*., 2018).

The UN Recommendations on the Transport of Dangerous Goods – Model Regulations form the basis for many international and EU transport regulations.

In the United States, the Department of Transportation (DOT) regulates the transportation of hazardous materials, including hydrogen. It sets standards for packaging, labelling and transportation of hydrogen cylinders, tanks and other containers. The Pipeline and Hazardous Materials Safety Administration is a part of the DOT and regulates the transportation of hazardous materials through pipelines, including hydrogen:

- 49 CFR Part 192: This part outlines the general design, construction, operation, maintenance and inspection requirements for gas pipelines, including hydrogen pipelines. It covers topics such as materials, welding, testing and emergency procedures.
- 49 CFR Part 199: This part establishes safety standards for the operation of gas pipelines, including requirements for personnel qualifications, emergency plans and record keeping.
- 49 CFR Part 194: This part governs the transportation of hazardous materials through pipelines, including hydrogen. It sets requirements for pipeline integrity management programmes, leak detection systems and emergency response procedures.

When injecting hydrogen into pipelines (either existing or newly built) rules should exist governing commercial and domestic end-user gas appliances that would utilise hydrogen gas blends, in both transmission and distribution.

The pipeline transport of hydrogen in the United States (like natural gas) is regulated at a state level, while the country still lacks a clear regulatory framework for inter-state hydrogen pipelines, with three regimes under consideration: the Federal Energy Regulatory Commission (FERC) Natural Gas Act, the FERC Interstate Commerce Act and the Surface Transportation Board Interstate Commerce Commission Termination Act.

Hydrogen refuelling stations

In addition to regulations that cover potentially explosive air (mentioned above), regulations are required to ensure that the installation and operation of hydrogen refuelling stations are conducted safely. This will require regulating the status of hydrogen as a fuel (and possible sustainability requirements), fuel quality and how fuel is delivered to the fuelling stations. The permitting process for setting up and operating a hydrogen refuelling station should cover safety, possible restrictions in placing these stations in particular locations, *etc*.

Examples of such regulations include ATEX, OIML R139, PED or Transportable Pressure Equipment Directive (TPED), and the Alternative Fuels Infrastructure Regulation (AFIR).

Fuel cell vehicles

Many categories of fuel cell vehicles exist, such as cars, buses, trucks but also motorcycles, boats and ships. Regulations for these vehicles should cover the requirements for maintenance and services (and who is allowed to provide these), registration processes, road and port infrastructure, as well as how these are included in potential support schemes.

Some aspects of fuel cell vehicles are covered by UN regulations, including UN Regulation No. 146 for hydrogen and fuel cell two- and three-wheelers, UN GTR No. 13 for hydrogen and fuel cell vehicles, UN Regulation No. 134 for hydrogen and fuel cell vehicles, and UN Regulation No. 153 for fuel system integrity and electric power train safety at rear-end collisions.

4.10 QI contributions to the development of green hydrogen

Quality infrastructure plays an essential role in supporting green hydrogen development; it provides the necessary technical foundations. In addition, QI aids in mitigating safety, financial and reputational risks within the sector, besides helping to realise positive sustainability outcomes from investments.

To establish green hydrogen as a significant component of the low-carbon economy, there is a pressing need for enhanced and expanded QI services. Many such services already exist and are applied to the production, distribution and use of hydrogen from non-renewable resources. The demand for such services is increasing as more hydrogen is produced, distributed and consumed. Establishing green hydrogen as a relevant part of the low-carbon economy requires additional and improved QI services. This also applies to the required increase in renewable energy generation capacity, where the supply and application of state-of-the-art QI services are now more important than ever (Ferdinand, 2023; Ferdinand *et al*., 2021).

In this context, the main contributions of quality infrastructure to the development of the green hydrogen sector can be summarised as follows.

Safety and risk reduction

Expansion of the green hydrogen sector requires ensuring safety across the value chain. The value chain has specific inherent risks, which must be mitigated continually. Given hydrogen lacks odour and colour, early (and standardised) detection of leaks or spills is crucial. Among others, this necessitates the use of detectors in production plants, storage/transportation facilities and refuelling stations. Further, hydrogen has the following important characteristics: it has a wide flammability range and very low minimum ignition energy and burns with high flame velocity. Hydrogen's low volumetric energy density means that it needs to be transported and stored under high pressure. This presents challenges, among others, in end-use applications such as fuel-cell-powered transportation. Moreover, hydrogen can contribute to damage to certain materials and components, causing them to degrade due to a combination of their micro-structure, mechanical stress, and hydrogen content – known as hydrogen embrittlement. Research and development (R&D) in appropriate infrastructure and close monitoring of material fatigue is thus essential.

QI services form the foundation for effective safety assurance, risk prevention and detection in the green hydrogen sector. **Standards** and **technical regulations** establish common baseline requirements for acceptable safety criteria to be met across the green hydrogen value chain. Standards have a voluntary character, but they are essential in complementing mandatory regulatory requirements to enhance the safety environment and provide additional safeguards for mitigating and managing risks. **Testing** provides vital information on the safety of materials and infrastructure; it helps detect potential **leaks**, for example. **Metrology** is required to increase measurement precision and establish traceability (and comparability), for example, of testing services. It supports reliable **inspection** and **certification** based on safety standards. Reliable measurements, for example, of pressure and temperature in production, storage, transport and use, are crucial to assure safe operations within this evolving sector.

Quality and sustainability

Green hydrogen must meet commonly recognised quality and sustainability criteria[23] (Nationaler Wasserstoffrat, 2021) to fulfil the requirements of international markets, mitigate reputational risks, ensure compliance with regulations (such as RED II) and attract investment via policy-backing initiatives (such as the US Inflation Reduction Act tax credits).

Quality and sustainability criteria are established through standards. In this context, standards that define criteria for the exclusive use of renewable energy in green hydrogen production and account for GHG emissions throughout the value chain (such as ISO/TS 19870) are especially relevant for the sector.

Conformity assessment services based on standards accredited by internationally recognised accreditation bodies lay the groundwork for global trade and a credible green hydrogen market.

Metrology services, among others, contribute to increasing purity of hydrogen gas during production and assure precise measurement of gas quantity during hydrogen transport, storage and utilisation. To support trade, metrology provides precise measurement of traded quantities in large pipelines via flow metering.

Efficiency, innovation, and research and development

Efficiency in renewable energy generation and its conversion into green hydrogen must be improved continuously to optimise available resources and drive down costs. Significant innovations are required to support the sector's expansion and address important engineering challenges that persist, for example, in the direct distribution of hydrogen to the end user and in making electrolysers more efficient.

Quality infrastructure contributes to both efficiency and innovation by providing reliable testing and precise calibration services for R&D programmes, or by establishing commonly recognised standards for energy-efficient production. By supporting evolving best practice through standardisation, testing and certification, functional quality infrastructure fosters trust in new technologies, services and products – a key success factor in the development and expansion of green hydrogen.

Quality infrastructure also aids in more effective information exchange as it supports the establishment of common criteria and terminologies and the development of new knowledge, which in turn forms the basis for further innovation. In this context, quality infrastructure catalyses collaborative development and speeds up technology development (BSI, 2021).

The development of efficient production processes (*e.g.* energy consumption) and the storage, transport and use of green hydrogen require metrology and standardisation considering composition, efficiency and safety aspects, along with improvement and development of measurement instruments and methods. Efficiency gains represent an outcome of robust R&D.

According to IRENA's 1.5°C Scenario by 2050, approximately 55% of the hydrogen will be traded via pipelines, whereas the remainder would be shipped as ammonia, to be used in the fertiliser and shipping industry (IRENA, 2022a). A narrative discussion on the importance of developing and implementing quality infrastructure protocols (particularly testing) for existing pipelines, especially in the context of hydrogen blending with natural gas is presented in Box 2 below.

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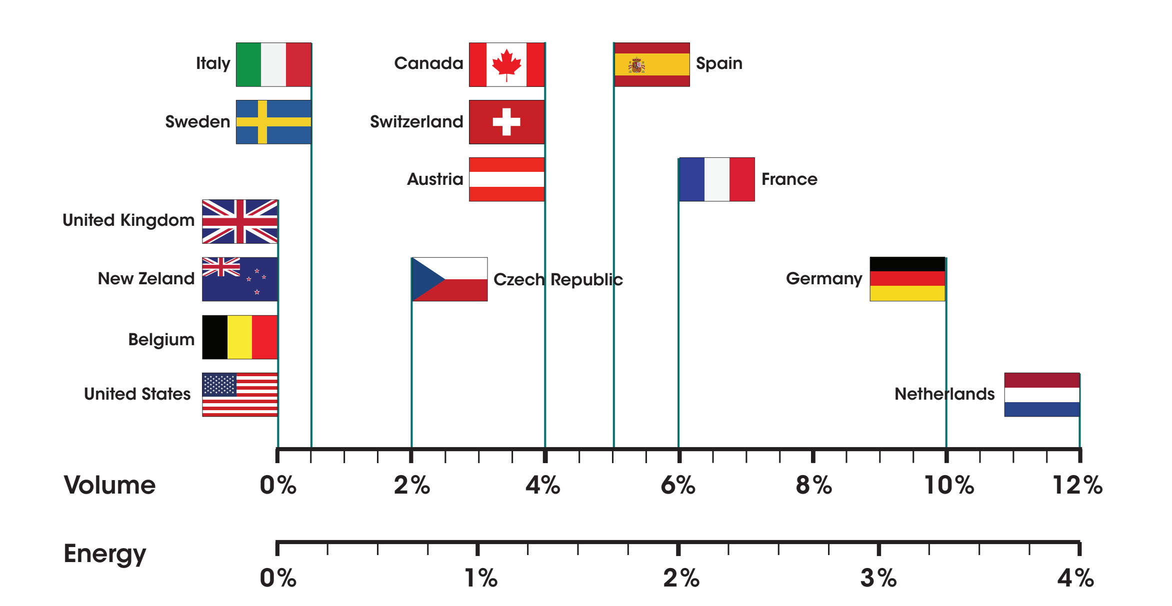
[23] *Germany's National Hydrogen Council defined the following sustainability criteria for hydrogen projects: certified CO_2 footprint along the entire value chain; overall reduction of CO_2 emissions; impact assessments; reduction of energy poverty; resolution of conflicts on land use; and avoidance of water conflicts – water supply must not be jeopardised (Nationaler Wasserstoffrat, 2021).*

Box 2 Quality Infrastructure considerations for pipeline utilisation for hydrogen transport

Blending hydrogen into existing natural gas pipelines and hydrogen transport is now being considered by several countries as part of the decarbonisation strategy (APA, 2023; DNV, 2023; ENTSOG *et al.*, 2021) – see figure below for perspective on hydrogen blending percentages in some countries.



Source: (Zemite *et al.*, 2023).

While gaseous hydrogen transport via existing gas pipelines is a low-cost option[24] for delivering large volumes of hydrogen, there is a serious threat of hydrogen damage, particularly for old-aged gas pipelines with corrosion and other mechanical damages, after future long-term blended or 100% hydrogen service (Popov *et al.*, 2018). A small volume percentage of gaseous hydrogen in a mixture (1% hydrogen) can lead to serious pipeline material deterioration and hydrogen embrittlement when combined with stress concentration conditions (Popov *et al.*, 2018).

Factors such as the material, stress condition, hydrogen pressure, and hydrogen concentration in steel – can potentially result in fatigue being accelerated by a magnitude of 10% and reduction of fracture resistance by greater than 50%. (Djukic, 2022; Popov *et al.*, 2018). Lower grade steel pipeline (characterized by lower strength and higher ductility) are not ideal conduits for hydrogen transportation as they are still susceptible to hydrogen embrittlement, depending on the microstructure, stress level, and age of the pipeline (CSA Group, 2024; Djukic, 2022; Popov *et al.*, 2018). On the latter, aged pipelines suffer from deteriorated mechanical properties, corrosion and mechanical damage, and poor-quality welds which significantly accelerate hydrogen embrittlement (Djukic, 2022; Popov *et al.*, 2018). It is important to note that despite the extensive research on the complex hydrogen-steel and hydrogen-deformation interactions during hydrogen embrittlement there is no agreement regarding the true nature and trigger for this phenomenon (Djukic *et al.*, 2019).

[24] *Approximately around 10% to 35 % of the construction costs for new dedicated hydrogen pipelines (ENTSOG et al., 2021)*

A selection of suitable materials for pipelines is critical for the safety of any hydrogen application. The permitted hydrogen-natural gas blending ratio (0-20% H2, or higher) is not a predefined parameter and is dependent on the operating conditions, material choice as well as age/condition of the existing gas pipeline (CSA Group, 2024; DNV, 2023; Djukic, 2022).

In consultation with scientific experts (via targeted survey's), areas that should be investigated further with regards to determining the viability of using pipelines for hydrogen transport/distribution include but not limited to:

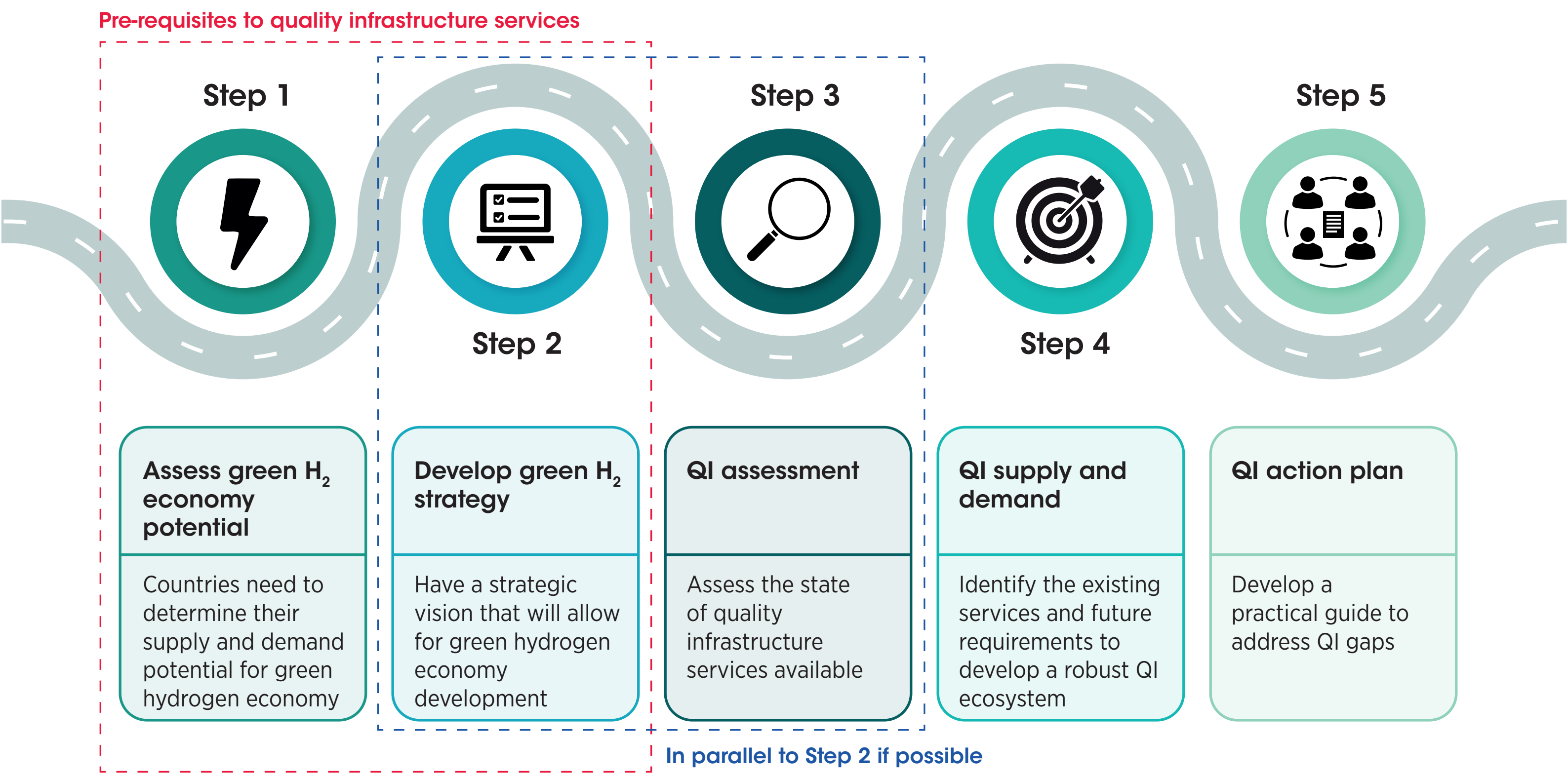
- Recommend and encouraging pipeline manufacturers and operators to follow and conform with industry standards such as ASME B31.12 (United States); IGEM/TD/1 Edition 6 supplement 2 (United Kingdom); and DVGW G 409 (Germany) (DNV, 2023; Djukic, 2022).
- Operationally to consider the following facets: a) defining optimal operating conditions for hydrogen blending and 100% H transport; b) defining allowable hydrogen concentration in natural gas depending on materials and age/condition of pipelines; and c) defining optimal operating conditions for hydrogen blending into "aged" pipelines.
- From a testing and maintenance perspective a) facilitating the implementation of structural health monitoring (SHM) systems in pipelines for hydrogen transport and b) undertaking inspection and mapping of internal corrosion/mechanical damages in "aged" gas pipelines via In-line inspection (ILI) tools. Comprehensive technical/scientific assessment programmes must be developed and applied to examine the suitability, integrity, and safety of the existing (aged) and new gas pipelines, for both hydrogen-blending and potentially 100% hydrogen transport conditions in the future. Key test that should be developed further include but not limited to: Slow strain rate tests; fatigue tests; hydrogen charging tests, autoclave testing; hollow specimens' techniques; and fractographic measurements
- Skills development in gaining knowledge on hydrogen embrittlement, mechanical testing, and fractographic analyses tools are crucial. Personnel in standardisation bodies, testing laboratories and certification bodies have a very little knowledge about hydrogen embrittlement of metallic materials and complex hydrogen-materials interrelations. Hydrogen embrittlement is a multidisciplinary and interdisciplinary science with multi-mechanism coordination, including the characteristics of many other disciplines, such as materials science, mechanics, electrochemistry and mechanical engineering.

Quality infrastructure facilitates international green hydrogen trade. It establishes internationally recognised criteria and evaluates compliance with them. Such criteria and specific services for the green hydrogen sector are still being developed in many areas. Among others, hydrogen exporters will have to demonstrate a reliable emission quantification along the entire green hydrogen value chain. Given the "physical or visual tangibility" of carbon content, new standards and conformity assessment services are required for the establishment of a well-functioning international green hydrogen market (DVGW, 2023; EURAMET, 2022; IRENA *et al*., 2023; PA Consulting, 2020).

5. Quality infrastructure roadmap for green hydrogen

The development of a hydrogen quality infrastructure (QI) roadmap should take place within the framework of an overarching green or low-carbon hydrogen strategy. Drawing on the QI green hydrogen landscape assessment conducted by this project as well as numerous discussions with QI experts from different organisations across the public and private spectrum, a representative roadmap (as shown in Figure 6) has been developed to illustrate **how a strategic vision for green hydrogen can be symbiotically intertwined with the associated QI requirements in any national context**. A description of each step is provided in the subsections below.

Figure 6 Roadmap for a green hydrogen quality infrastructure



Note: QI = quality infrastructure.

5.1 Step 1 – Assessing the potential for green hydrogen

The development of a national hydrogen strategy should begin with an assessment of the potential role of low-carbon hydrogen and its derivatives in a future, ideally fully decarbonised, energy system. This assessment lays the groundwork for future hydrogen demand. To meet this demand, an analysis of the supply side – whether through domestic production or imports – must be carried out. Key variables to consider in this assessment include (but are not limited to) the:

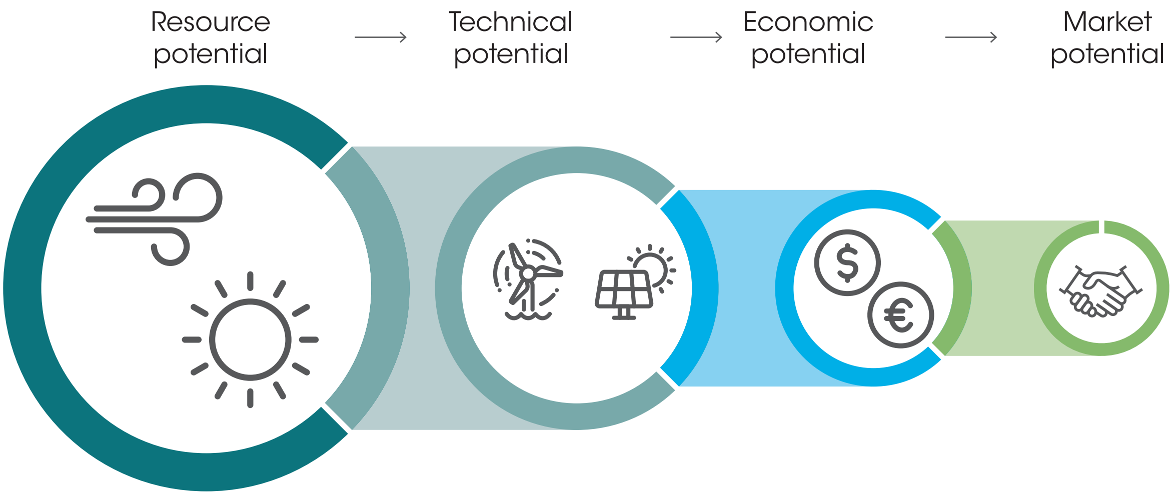
- **Techno-economic potential of renewable energy sources.** These sources primarily include solar and wind, but other renewables such as geothermal, hydroelectric, *etc*. are also considered if available. Renewable energy generation for green hydrogen can be either grid connected or operated in island mode. For grid-connected systems, the limitations in grid flexibility and the potential curtailment of renewable energy could provide a source of zero or low-cost electricity for electrolysers, which should be integrated into grid planning.
- **Long-term freshwater availability under low stress.** An evaluation of freshwater availability should consider national renewable water supply and demand. For green hydrogen projects, it is essential that water is available throughout the entire project life cycle. Countries with coastal access can explore the feasibility of seawater desalination.
- **Current and potential uses of low-carbon hydrogen in local industries.** Industries to be considered include fertilisers (ammonia), steel, petrochemicals, chemicals (methanol, olefins, *etc*.), transport (road freight, shipping), power generation, glass, food processing (hydrogenation of fats), *etc*.
- **Readiness of hydrogen transport and distribution infrastructure and potential demand or supply from neighbouring countries.** An assessment of existing infrastructure, including ports, terminals and gas pipelines, should be coupled with an analysis of the demand or supply of hydrogen that could be transported via pipelines from nearby regions, or shipped through deep-sea ports from more remote areas (*e.g*. ammonia).
- **Potential of hydrogen carriers.** Given the challenges related to repurposing existing assets (such as gas pipelines) due to high costs, safety concerns and low energy density, it could be worth exploring the potential of hydrogen carriers such as methanol and ammonia, along with their new or existing infrastructure.

5.2 Step 2 – Development of a national hydrogen strategy

As a second step, countries should, based on the assessments mentioned above and in consultation with all relevant stakeholders, determine the goals and outcomes they wish to achieve within their hydrogen economy. This may include identifying priority sectors. This step involves techno-economic modelling of potential scenarios with quantitative analysis, which establishes a robust foundation for setting priorities and developing policies by identifying and filtering out less viable pathways.

A comprehensive strategic analysis of available options will subsequently inform the financial indicators and economic justifications for the recommended policies. Stakeholder engagement and long-term energy scenarios provide a well-rounded approach to establishing strategic priorities within the hydrogen value chain, as they incorporate diverse perspectives and align policy development with national objectives. Figure 7 provides an overview of the types of renewable energy potentials that should be considered as strategic priorities in the development of hydrogen initiatives.

Figure 7 Types of renewable energy potential



- Theoretical physical potential
- Enegy content of resource

- System and topographic constraints
- Land-use constraints
- System performance

- Projected technology costs
- Available vs. required revenue for energy project

- Regional competition with other energy sources
- Policy implementation and impacts
- Regulatory limits
- Investor response

Source: (IRENA, 2024c).

This phase involves identifying the production pathways, transport systems and end-use applications to prioritise, based on an analysis of technological feasibility, economic factors and decarbonisation potential across various sectors. Once priorities are established, the next step is to define specific, well-informed targets, identify potential risks and outline strategies to mitigate these risks.

At this stage, tailored policy support measures can be developed to align with the country's specific opportunities and characteristics, laying the groundwork for implementing a hydrogen strategy. The most specific actions should be formulated in collaboration with the relevant stakeholders. While it may not be practical to define detailed measures for later stages of the strategy, it is essential to establish governance, standards and regulations early on, which requires active involvement from policy makers. The approval and structuring of the governance framework are critical for successful execution of the strategy.

IRENA and other institutions have published guidance documents in recent years to assist countries in developing hydrogen strategies. For further insights on key considerations, please refer to documents on **sustainable industrial hydrogen** (IRENA, UNIDO and IDOS, 2024), **enabling measures** (IRENA, 2021), **scaling green hydrogen for inclusive growth** (World Bank, 2023) and the **green hydrogen strategy** (IRENA, 2024c).

Box 3 summarises the key points included in Tunisia's forthcoming national hydrogen strategy. This case study was selected for the application of this roadmap due to Tunisia's strong ambition to integrate hydrogen into its energy transition efforts and its strong relationship with Physikalisch-Technische Bundesanstalt (PTB), the implementation partner within the IRENA project.

Box 3 Key points from Tunisia's national hydrogen strategy

Tunisia has prioritised the integration of hydrogen across various sectors to advance its energy transition efforts. On 26 May 2024, the country published a summary of its forthcoming national hydrogen strategy. Key targets and points outlined in the vision include:

- Tunisia aims to produce **8 Mt of green hydrogen** by 2050.
- The primary driver for developing Tunisia's hydrogen economy is the export of locally produced hydrogen to Europe, with a target of **6 Mt** to be exported by 2050.
- Green hydrogen is the preferred production route, with a goal of achieving **100 GW** renewable energy capacity by **2050**. This will be achieved through the expansion of solar photovoltaic and on-shore wind capacities in the south of the country. Desalinisation of seawater will serve as the primary water source for electrolysis, ensuring that no freshwater sources are utilised for green hydrogen production.
- The strategy includes three main implementation tools:
    1. **Establishment of a hydrogen task force** to oversee the overall development of the national hydrogen economy.
    2. **Creation of an EU co-operation framework** to align markets and attract investors to develop infrastructure needed for hydrogen production.
    3. **Development of a National Hydrogen Framework** to provide a regulatory framework that is conducive to the development of the hydrogen economy.
- Hydrogen will be transported locally as well as exported via pipelines, leveraging the existing and established gas infrastructure.
- The initial local demand for hydrogen will focus on the development of the **ammonia industry**, subsequently expanding to methanol, steel and synthetic fuels.

The strategy also highlights the necessity of **quality infrastructure** and identifies broad categories where standardisation is required.

For further insights into Tunisia's status regarding the availability of quality infrastructure services for green hydrogen, the national case study that complements this publication can be consulted.

Source: (Tunisia MIME, 2024).

5.3 Step 3 – Assessment of the national QI system

In Step 3, the overall status of the national QI system should be analysed to identify its strengths and areas that require further development. This analysis is not sector specific, but applies to all areas of public interest.

By leveraging existing strengths and systematically addressing gaps within the overall system, a solid foundation will be created for the development of concrete services relevant to the green hydrogen sector (→ Step 4).

The assessment of the national system should involve analysing the QI organisations and the relevant legal and institutional framework based on established criteria. These criteria are derived from related standards and international best practices in the following areas:

- Legal and institutional framework
- Administration and infrastructure
- Service delivery and technical competency
- External relations and recognition

The Rapid Diagnostic Tool, developed jointly by PTB and the World Bank, provides a valuable basis for conducting the necessary analysis. It is recommended that the checklists be completed in collaboration with QI organisations and national or international experts, as specific knowledge is essential for accurate application.

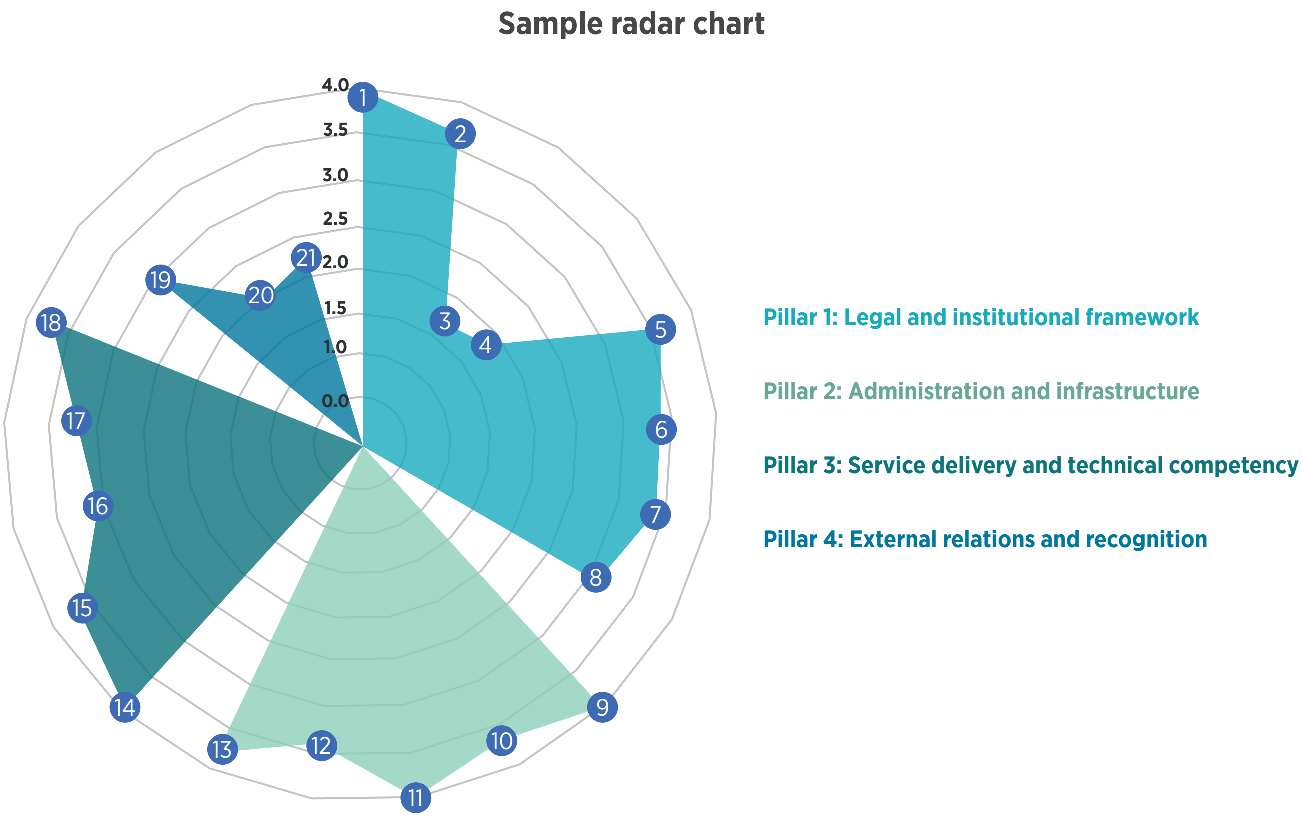
From a regulatory perspective, the Standards and public policy toolkit developed by ISO is a insightful document that provides guidance on how policy makers can utilise international standards to develop and implement technical regulations. The toolkit also offers actionable recommendations on how national standards bodies can effectively engage and collaborate with policymakers during the formulation of technical regulations (ISO, 2023).

An additional perspective gleaned from these QI assessment tools is the determination of the level of interaction and inter-dependence among all elements of the national QI system and the hydrogen/energy sector activities within a specific national context.

The gaps identified in the QI system should inform the development of a dedicated action plan (→ Step 5).

Figure 8 presents an example of the results from the general QI assessment in the area of testing.

Figure 8 Results of the PTB–World Bank Rapid Diagnostic Tool in the area of testing



1. Testing services strategy
2. Designated test laboratories
3. Test laboratories for export market
4. Test laboratories for the health sector
5. Legal entity
6. Governance
7. Testing services scope
8. Financial sustainability
9. Top management
10. Organisational structure
11. Management and personnel
12. Premises
13. Equiptment
14. Quality management system documentation
15. Proficiency testing
16. Preassessment for accreditation
17. Initial assessment for accreditation
18. Accreditation
19. Recognition at national level
20. Recognition at international level
21. Co-ordination within the QI

Source: (PTB, 2022).

Box 4 provides a brief overview of the status of quality infrastructure in Tunisia based on a case study, utilising the approach outlined in Step 3 of this roadmap.

Box 4 The status of Tunisia's quality infrastructure

In preparing the Tunisia case study and leveraging the Rapid Diagnostic Toolkit, it was observed that the country has an established history of QI, contributing to a general awareness of the importance of quality assurance across different sectors. Following are key findings from the assessment of Tunisia's QI ecosystem:

- **Legal and institutional framework.** The existing framework encompasses several aspects of quality infrastructure through different policies and decrees. It is strongly recommended that the country consider developing a national quality policy and a quality law to ensure a clear separation of functions and the required financial resources. Such a policy or law should provide a concrete overview of which institutions will lead the development of each QI pillar.
- **Co-ordination and human resources.** Many QI organisations in the country are co-ordinated by the Ministry of Mines, Industry and Energy (MIME) through a centralised model. It is recommended that efforts be directed towards strengthening intra co-ordination among QI organisations and private sector players engaged in green hydrogen development. Additionally, human resource capacities should be expanded by providing training on the implementation of international QI services within the country.
- **Standardisation.** Institut National de la Normalisation et de la Propriété Industrielle (INNORPI) is the national body responsible for overseeing the development of national and international standards for product and quality systems' certification, quality promotion and the protection of industrial/intellectual property. It is essential for this body to increase its participation in international technical committees and to strengthen national mirror committees to enhance alignment with international standards. This will ensure that national social and economic interests are adequately reflected in international standard-making processes. INNORPI is closely monitoring development in quality infrastructure at the international level to determine how national standards on safety, quality and environmental considerations in their established gas and emerging hydrogen sectors comply with international best practices.
- **Metrology.** Agence Nationale de Metrologie (ANM) has been established as the national metrology institute with several calibration and measurement capabilities by the designated institute, the Laboratoire de métrologie du Ministère de la Défense Nationale (DEF-NAT). It is recommended that an updated metrology law be developed to ensure broad acceptance of ANM as the national metrology institute for the country and to integrate the existing technical competences into the national metrological reference landscape, for example, by designation. It is however essential to stress that the role and remit of metrology institutes will vary across countries depending on how the national quality infrastructure is structured. Some organisations maintain core metrology capabilities, such as traceability to the international system of units, while others focus on certification or work closely with the industry and regulators. Each country thus has a metrology framework fingerprint that is unique to its QI set-up.
- **Testing.** Numerous testing laboratories offer the most in-demand accredited services for green hydrogen. It is advisable to develop a recognised testing strategy for green hydrogen that aligns with the public priorities. There is also a need to support the international accreditation of public laboratories and the co-operation between laboratories.

- **Certification/inspection.** Several certification bodies are accredited to provide the most sought-after services. It is strongly recommended that the legislation governing certification and inspection be updated to allow other certification bodies, in addition to INNORPI, to certify based on Tunisian product standards. Developing a national strategy for certification and inspection would facilitate the expansion of accreditation for public organisations offering conformity assessment services, as well as establish a notification system for inspection bodies and foreign certificates.
- **Accreditation:** The Conseil National d'Accréditation (TUNAC) is well established and internationally recognised for the most relevant scopes applicable to hydrogen. It would be beneficial to include proficiency test providers within the accreditation scope and to define an updated accreditation strategy.

5.4 Step 4 – Quality infrastructure service offerings and demand assessment

Following the assessment of the national QI system (→ Step 3), concrete services required for the development of the green hydrogen sector should be analysed. This assessment should be based on the checklist included in Annex A, which was developed through desk research and stakeholder engagement. When applying the checklist, the following general aspects should be considered:

- The checklist considers the three levels of QI development introduced in section 4.2.
- Not all services included in the checklist need to be established at the national level. Based on current and future demand, access to existing services in other countries may be provided.
- Before developing new services, it is essential to evaluate existing services and enhance quality assurance measures (which may include the introduction of management systems, training, accreditation, calibrations and round robin tests, depending on the service).

Also, the specific focus of the national green hydrogen strategy should be considered when planning the development of the necessary QI services. Figure 9 illustrates three potential scenarios for the national green hydrogen strategy:[25]

A. Import of green hydrogen for national use

B. National green hydrogen production for export

C. National green hydrogen production, use and export

Depending on the focus of the national green hydrogen strategy, different priorities must be assigned to the QI services developed alongside the sector. For instance, **Scenarios "B" and "C"** must prioritise safety, quality and sustainability assurance in renewable energy generation. In contrast, **Scenario "A"** requires a focus on import control, market surveillance and the required conformity assessment. Additional QI services relevant to this scenario include electric safety, gas (particularly natural gas), as well as the distribution, transportation and utilisation of green hydrogen and its derivatives.

[25] *Also, others could exist, for example, focussing on the trade of green hydrogen.*

Figure 9 Quality infrastructure development aligned with the focus of the national green hydrogen strategy

Renewable energy generation	Production			Distribution and transport	Utilisation
	Electrolysis	Conversion into derivatives	Storage		

Scenario C: National production, use and export of green hydrogen

- Quality infrastructure (QI) services considering the results of the QI analysis for: renewable energy generation, electric safety, gas (especially natural gas) as well as production, distribution/transport and utilisation of green hydrogen and its derivatives.
- Technical regulation on safety, human health and environmental aspects along the entire value chain.

Scenario B: National green hydrogen production for export

- QI services considering the results of the QI analysis for: Renewable energy generation, electric safety, gas (especially natural gas) as well as production and distribution/transport of green hydrogen and its derivatives.
- Technical regulation on safety, human health and environmental aspects along the value chain, excepting use of green hydrogen.

Scenario A: Import of green hydrogen for national use

- QI services considering the results of the QI analysis for: electric safety, gas (especially natural gas) as well as distribution/transport and utilisation of green hydrogen and its derivatives.
- Technical regulation on safety, human health and environmental aspects with focus on import/market surveillance, distribution/transport and utilisation of green hydrogen and its derivatives.

5.5 Step 5 – Quality infrastructure development action plan

Based on the previous analysis, an action plan should be established to upgrade the QI system and its specific services to support green hydrogen. To ensure acceptance of the proposed activities, key stakeholders need to be engaged in the planning.

The plan must encompass the required activities for developing the QI system (Step 3) as well as the specific services identified in Step 4, addressing the three levels. It is advisable to focus on developing Level 1 services in the short term (1-3 years); Level 2 services in the medium term (5-7 years); and Level 3 services in the long term (8-10 years).

Concrete timelines should be aligned with the development steps defined in the national green hydrogen strategy.

Several overarching priorities to be factored into the action plan include the following:

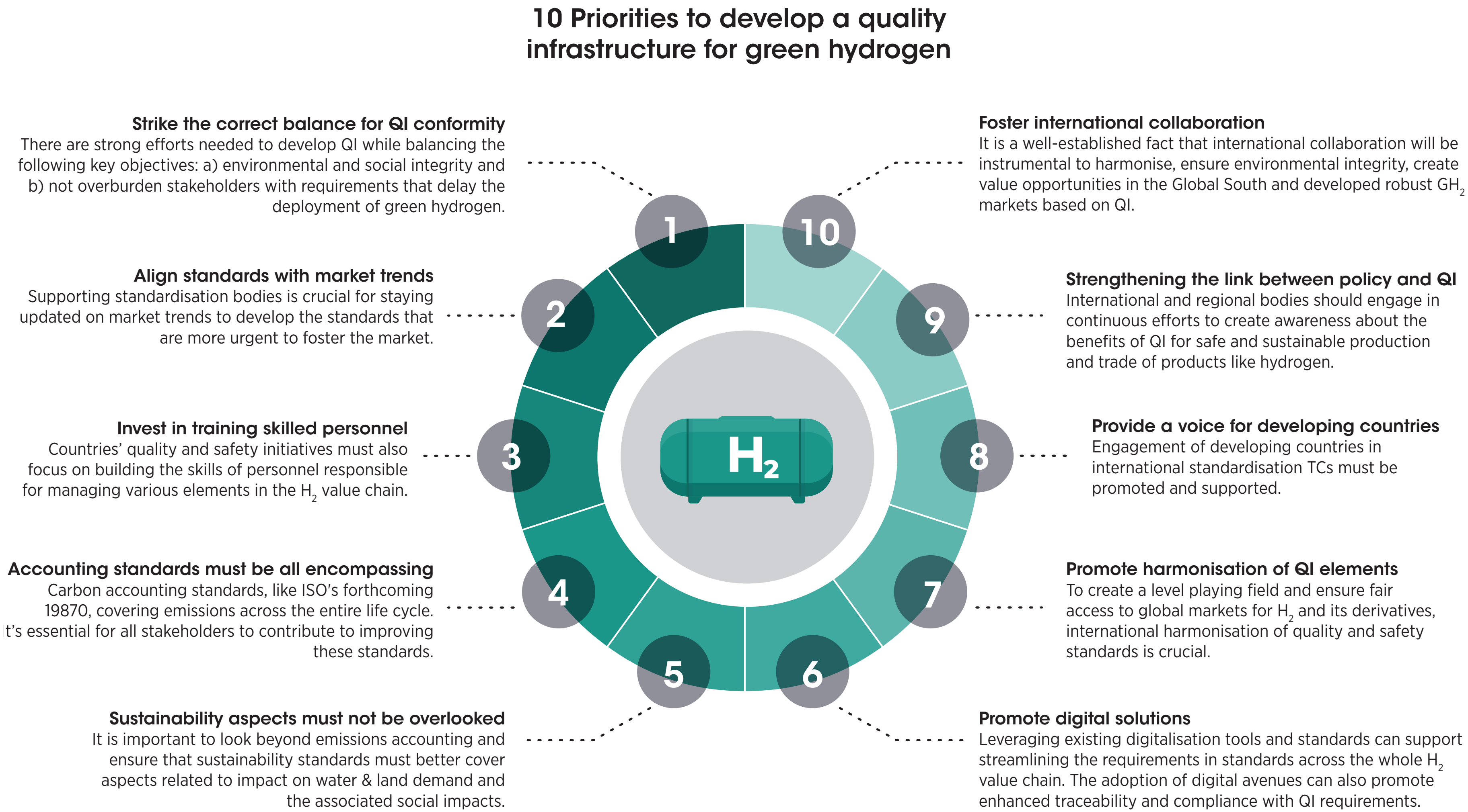
- When developing action plans, it is crucial to consult and actively engage all relevant stakeholders. This approach ensures a robust structure and assigns clear responsibilities to those who will lead efforts to address challenges identified during the national assessment on the QI ecosystem's readiness for the green hydrogen sector.
- To maximise resource efficiency, efforts should be made to explore how public and private stakeholders can collaborate, sharing their knowledge and capabilities to ensure the relevant QI services are effectively developed. Additionally, developing and/or strengthening regional capacities can be mutually beneficial for many countries and provides opportunities to establish harmonised frameworks.
- It is important to identify and/or invest in the qualification of trained staff within QI institutions as well as in the hydrogen sector and governance more broadly. This also opens avenues for collaboration with universities, technical colleges and vocational centres, ensuring that relevant training materials on quality infrastructure are included in their curricula.

Beyond these overarching requirements, key facets to consider when developing QI action plans, as discussed during the Quality Infrastructure for Green Hydrogen Symposium at IRENA's Innovation Week 2023, include the following:

1. **Strike the correct balance for QI conformity.** There are strong efforts needed to promote quality infrastructure, through identifying and resolving any gaps, while maintaining a balance between two key objectives: (a) ensuring environmental and social integrity and (b) avoiding overburdening stakeholders with requirements that could delay the deployment of green hydrogen.
2. **Align standards with market trends.** There is a pressing need to adopt an international approach to standardisation, rather than concentrating solely on national standards. Market trends indicate that economies of scale in green hydrogen can be best achieved with a single set of international standards and consistency in testing and certification. This globally harmonised approach eliminates the repeated testing and certification undertaken to comply with specific national standards. While a substantial market for hydrogen derivatives is anticipated, there is still a lack of QI services in these areas. Greater involvement by the international community is vital to develop these services.

3. **Invest in training skilled personnel.** Countries must ensure their QI efforts include the development of personnel who can oversee the installation, operation and maintenance of different components along the hydrogen value chain. For example, the International Electrotechnical Commission (IEC) has established the International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres (IECEx), which offers training and conformity assessment for equipment, facilities, services and personnel. This ensures that components operating in explosive environments, including those where hydrogen may be present, comply with international technical and safety standards.
4. **Ensure accounting standards are all encompassing.** It is essential that carbon accounting standards address emissions across the entire life cycle. The standards of the International Organization for Standardization (ISO) are a good starting point, but it is crucial that all stakeholders review and suggest improvements to their scope. The ISO 19870 standard offers a methodology for determining the greenhouse gas (GHG) emissions associated with the production, conditioning and transport of hydrogen to the consumption point. This standard accounts for comprehensive emissions, including those arising from upstream activities during raw material acquisition and transport. GHG emission contributions are expressed in terms of carbon dioxide equivalent.
5. **Non greenhouse gas sustainability aspects.** It is critical to look beyond mere emissions accounting and ensure that sustainability standards adequately address factors related to the impact on water and land demand, as well as the associated social implications.
6. **Promote digital solutions.** Leveraging existing digitalisation tools and standards can help streamline requirements across the entire hydrogen value chain. The adoption of digital approaches can also enhance traceability and demonstrate compliance with international QI requirements.
7. **Promote the harmonisation of QI elements.** To ensure that hydrogen and its derivatives have sustainable and equitable access to international markets, it is essential to pursue international harmonisation of quality infrastructure for green hydrogen, which will create a “level playing field” for all stakeholders in the industry. International QI organisations such as the ISO, Bureau international des poids et mesures (BIPM) and IEC can play a leading role in driving these efforts among national and regional QI bodies.
8. **Provide a voice for developing countries.** When updating existing QI services or developing new ones (such as new standards), it is vital to grant developing countries ample conduits to express their views as well as ensure that these services align with their development objectives. Their engagement in international standardisation technical committees must be promoted and supported.
9. **Strengthen the link between policy and quality infrastructure.** It is observed that international policy makers often fail to fully comprehend the concept of quality infrastructure and its significance. Therefore, it is necessary for international and regional QI bodies to undertake continuous awareness-raising efforts to educate these stakeholders on the necessity of quality infrastructure for the safe and sustainable production and trade of products such as hydrogen and its derivatives.
10. **Foster international collaboration.** International collaboration is vital in harmonising general concepts and conformity assessment, ensuring environmental integrity and safety, creating value addition opportunities in the Global South and developing robust green hydrogen markets based on quality infrastructure.

Figure 10 Quality considerations for preparing a tangible action plan



Source: IRENA Innovation Week 2023 – Quality Infrastructure for Green Hydrogen Symposium held on 27 September 2023.
Note: GH_2 = green hydrogen; H_2 = hydrogen; ISO = International Organization for Standardization; QI = quality infrastructure; TC = technical committee.

Table 8 presents an example of the metrology action plan (among other QI pillars) that IRENA and PTB developed as part of the Tunisia national case study. This plan is aligned with the timelines outlined in the national hydrogen strategy.

Table 8: Metrology short-, medium- and long-term action plans for Tunisia

 Financial resources  Knowledge  Political support

Short term (until 2026)

Activity	Leading organisation	Organisations to be involved	Resources required
Metrology			
• Development of an up-to-date **national metrology law and aligned national metrology strategy, including scientific, legal and industrial metrology**, assuring an **independent** development of the national metrology system and the recognition of the **National Metrology Institute (NMI)** by all relevant ministries and stakeholders.	• Ministère du Commerce • Ministère de l'Industrie, des Mines et de l'Energie (MIME)	• ANM, INRAP, DEF-NAT, LCAE, other metrology laboratories (CTMCCV, CETIME, CNCC, CRTEn, *etc.*)	
• Review of the current capacities and definition of specific activities to develop the metrological services relevant for gas pipelines and equipment for the chemical analysis of natural gas and hydrogen mixtures.	• Ministère du Commerce • MIME	• ANM, INRAP, DEF-NAT, LCAE, other metrology laboratories (CTMCCV, CETIME, CNCC, CRTEn, *etc.*)	  
• Improvement in the **existing services of the NMI and designated institutes** based on an analysis of the current status, including the required training, introduction of management systems, inter-comparisons and accreditation calibration and measurement capacities (CMCs); and electrical characteristics such as current and voltage, temperature, humidity, conductivity, force and torque, verification of electricity meters and medium temperature range (-40°C to 100°C).	• ANM, INRAP, DEF-NAT, LCAE, other metrology laboratories.	• Ministère du Commerce • MIME • International co-operation	
• Development of **new national metrology services** or access to foreign services, based on an assessment of specific current/future demand and business planning focused on the calibration of gas detectors.	• ANM, INRAP, DEF-NAT, LCAE, other metrology laboratories.	• Relevant ministries, international co-operation	

Medium term (until 2028)

Activity	Leading organisation	Organisations to be involved	Resources required
Metrology			
• Development of existing services of the NMI and designated institutes based on analysing the current status, which includes necessary training, introduction of management systems, intercomparisons and accreditation/CMCs. This should cover irradiance levels and spectral irradiance of light sources, wind speed, calibration of photovoltaic reference cells and modules, verification of smart/digital electricity meters, mass (*e.g.* for the production of reference gas), gas flow rate/calibration of gas meters, chemical composition and purity of gases, and calorific value.	• ANM, INRAP, DEF-NAT, LCAE, other metrology laboratories.	• Relevant ministries, international co-operation	
• Development of new national metrology services or access to foreign services, based on assessment of specific current/future demand and business planning: large temperature range (-260°C to 100°C), reference gases, and density.	• ANM, INRAP, DEF-NAT, LCAE, other metrology laboratories	• Relevant ministries, international co-operation	 
• Elaboration of measurement procedures and review of adequate technologies for flow measurement for higher hydrogen content in natural gas.	• DGETE	• STEG, LCAE, CRTEn, ANM	
• Recognition of measurement/calibration services for higher hydrogen content in natural gas by the legal metrology authorities.	• ANM	• All competent metrology service providers in Tunisia	

Long term (until 2030)

Activity	Leading organisation	Organisations to be involved	Resources required
Metrology			
• Development of the existing services of the NMI and designated institutes based on the analysis of the current status, including the required training, introduction of management systems, inter-comparisons and accreditation/CMCs for very high pressure and volume.	• ANM, INRAP, DEF-NAT, LCAE, other metrology laboratories.	• Relevant ministries, international co-operation	
• Development of new national metrology services or access to foreign services, based on assessment of current/future demand and business planning, specifically for the efficiency of hydrogen generators and utilisation, chemical composition of hydrogen derivatives, and modelling of green hydrogen systems.	• ANM, INRAP, DEF-NAT, LCAE, other metrology laboratories.	• Relevant ministries, international co-operation	 

Note: ANM = Agence Nationale de Métrologie; CETIME = Mechanical and Electrical Industries Technical Center; CNCC = Centre National du Cuir et de la Chaussure; CRTEn = Center for Energy Research and Technology; CTMCCV = Technical Center for Construction Materials, Ceramics and Glass; DEF-NAT = Laboratoire de métrologie du Ministère de la Défense Nationale; DGETE = Direction Générale de l'Electricité et de la Transition Energétique; INRAP = National Institute of Research and Physical and Chemical Analysis; LCAE = Central Laboratory for Analysis and Testing; STEG = Tunisian Company of Electricity and Gas.

6. Supporting quality infrastructure considering specific national conditions: General recommendations

The following key recommendations outline how policy makers and sector stakeholders can support quality infrastructure (QI) to effectively promote the development of the green hydrogen industry.

1. Develop an appropriate policy framework

Policy and regulatory frameworks are an integral part of the QI system and influence both the provision and application of QI services across the green hydrogen sector. Public policies and programmes should include objectives and criteria related to quality, safety and sustainability in the green hydrogen sector. Relevant requirements and standards, guided by international specifications and practices, should be specified in public tenders, contracts and government programmes to encourage their application. In the context of hydrogen, it is crucial to ensure that strategic choices are made concerning the use of equipment for potentially explosive atmospheres, which are compliant with reference directives such as ATmospheres EXplosibles (ATEX) in Europe, National Electric Code (NEC) in the United States and Canadian Electric Code (CEC) in Canada.

Policy makers and stakeholders need to develop rigorous international safety standards and regulatory frameworks tailored for hydrogen pipelines. Investment in advanced monitoring technologies, regular inspections and proactive maintenance is essential. Research and development would do well to focus on innovating safer pipeline materials and technologies. Establishing specialised training and certification for personnel ensures adherence to high safety standards. Strengthening emergency response plans ensures swift and effective mitigation of pipeline incidents, supporting the safe and sustainable transport of hydrogen.

At the same time, the inclusion of detailed quality criteria in technical regulations should be avoided. Mandatory requirements that go beyond safeguarding human health and safety or the environment do not align with international best practices and World Trade Organization Technical Barriers to Trade agreements. Moreover, experience indicates that such mandatory requirements often fail due to a lack of enforcement. In contrast, incorporating quality criteria into tenders, contracts and government programmes encourages industry stakeholders to demonstrate compliance proactively.

2. Support QI while developing the green hydrogen sector

Experience from rapidly developing sectors, such as photovoltaics, indicates that countries typically follow a learning curve: initial investment opportunities often lead to a surge in development. However, after this initial phase, quality, safety and sustainability issues crop up in installations and components. Such problems are particularly prevalent when a new sector is growing quickly and is staffed by inexperienced professionals. Recognising these issues fosters heightened awareness of quality and the improvement of quality assurance mechanisms in more mature sectors.

Policy makers and stakeholders can draw valuable lessons from this experience and incorporate essential quality infrastructure as an integral part of green hydrogen sector development. Systematically addressing quality infrastructure early on boosts the efficiency of investments, improves sustainability impacts, increases acceptance of this technology and reduces its risks. By establishing robust inter-connections between policy/regulatory frameworks and QI requirements, it is possible to create "market stability and safety" standards that can prevent negative incidents from potentially "poisoning the market", that is, create public resistance or opposition to the development of the green hydrogen sector. Recommended approaches on developing a green hydrogen roadmap can be found in IRENA's publication entitled "Green Hydrogen Strategy: A Guide to Design".[26] It is equally important that governments develop programmes and incentives to cultivate skilled personnel well versed in quality infrastructure and include such elements in vocational trainings.

3. Take a holistic approach to the development of quality infrastructure

National quality infrastructure is an inter-connected system in which the components complement each another. Therefore, the components should be developed collaboratively to ensure coherence and functionality. Furthermore, national quality infrastructure should not be isolated but rather integrated into the international system by establishing relationships with the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) including the IEC System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres (IECEx) and the IEC System of Conformity Assessment Schemes for Electrotechnical Equipment (IECEE) for standardisation; to Bureau international des poids et mesures (BIPM) and Organisation Internationale de Métrologie Légale (OIML) for metrology and legal metrology; to the International Accreditation Forum (IAF) and International Laboratory Accreditation Cooperation (ILAC) for accreditation; and to various regional organisations. Alignment with international standards, benchmarks and testing criteria should form the basis of a national QI system, enabling market access and harmonisation in terms of trade.

This holistic approach lays the groundwork for developing specific QI services required by the green hydrogen sector and their recognition in international markets.

4. Foster exchange and co-operation between the green hydrogen sector and QI organisations

It is essential to promote exchange and co-operation among the green hydrogen sector and QI stakeholders to raise awareness and jointly develop effective quality assurance approaches. Representatives from the relevant renewable energy sectors should be involved in this dialogue, as they are an essential part of the green hydrogen value chain. Broad engagement processes are standard practice, particularly in standardisation, where industry and QI stakeholders work together within the consensus-building frameworks of relevant ISO and IEC technical committees. Similar approaches are also necessary across all components of the quality infrastructure to facilitate the exchange of information about current and future supply and demand, align related programmes and strategies, encourage innovative solutions and establish productive, long-term relationships.

[26] *Access publication via this reference (IRENA, 2024c).*

A particular initiative that can be explored (complementary to the existing forums such as technical committees in several organisations) is the organisation of forums on quality infrastructure for hydrogen (both nationally and internationally). The purpose of such forums would be to have a platform where experts from different QI pillars can congregate and engage in the consultation of the activities of the other pillars. Such forums could prevent working in an isolated manner in specific areas of quality infrastructure but create a holistic approach towards knowledge exchange as well as service development. On the international level, the **International Network on Quality Infrastructure** is an existing platform that can potentially take the lead to co-ordinate such a forum and ensure different organisations are continuously informing each other within their respective workstreams.

5. Define specific priorities depending on the national context

The development of quality infrastructure should be aligned with concrete national needs. These depend on the development status of the quality infrastructure itself, as well as on the current situation and plans for the development of green hydrogen. To assess the priorities, current and potential users of QI services in the sector should be consulted regularly. Also, consideration should be given to both the financial viability and the potential impact of services to be developed. Close co-ordination with neighbouring countries and at the regional level is advisable in this context, as not all QI services required by the green hydrogen sector are needed at a national level but may be provided abroad as a result of regional development strategies. Regional collaboration forums to share competences within unions replicating models of existing frameworks – such as the European Association of National Metrology Institutes (EURAMET) (on metrology); Inter American Accreditation Cooperation (on accreditation); and African Electrotechnical Standardization Commission (on standardisation) – can be a way to maximise efficiencies and avoid duplication of QI services for green hydrogen.

6. Base quality infrastructure on existing international standards

Given the global nature of the future green hydrogen market, international standards are the best basis to foster global compatibility, facilitate trade and use existing resources efficiently. Existing international standards for green hydrogen consider worldwide experience and result from a broad agreement among relevant stakeholders.

Taking this into account, international standardisation processes and reference to existing standards are crucial. Standardisation processes that, on the other hand, are limited to the national level increase the disparity of criteria and hamper the development of green hydrogen. It needs to be recognised that there are international standardisation gaps, in which case, national stakeholders, when needed, should evaluate and choose from different standardisation options, if available, based on cost-benefit analysis (*e.g.* availability of products and systems that comply with each option, including spares).

According to the priorities that countries have set to achieve their energy transition goals, it is strongly recommended that relevant stakeholders from the public and private sectors participate in the international standardisation committees of organisations such as ISO, IEC, ILAC, IAF and BIPM to ensure that they are aware of the ongoing QI discussions at the global level – which can be used to inform their national quality and institutional frameworks.

7. Participate in regional and international forums and organisations

Especially for emerging and developing economies planning to generate green hydrogen in the future, it is essential to engage actively in regional and international QI forums and organisations where related criteria, procedures and strategies are being defined. Examples in the area of standardisation include the Technical Working groups of the international organisations IEC and ISO mentioned above (IEC TC 105 "Fuel Cells Technologies", IEC TC 31 "Equipment for Explosive Atmospheres" and ISO/TC 197 "Hydrogen technologies"). Regional standardisation, metrology and accreditation organisations can provide a valuable forum to foster and co-ordinate the development of services required by the green hydrogen sector.[27]

The participation of emerging and developing economies in such organisations allows consideration of their specific requirements and conditions for the development of related services. Currently, the relevant processes tend to be dominated by industrialised countries. The recent push induced by the COVID-19 pandemic towards more digital and virtual processes in these organisations offer an opportunity for developing economies to increase their participation at both regional and international levels.

IRENA also has several multilateral initiatives that are looking into hydrogen development globally. An example is the Alliance for Industry Decarbonization which facilitates dialogue at the industry level and increases co-operation to help companies to develop solid decarbonisation strategies and implementation plans, aligned with their countries' and companies' net-zero and decarbonisation commitments. The Alliance serves as a global platform where participants exchange insights, experiences and best practices.

8. Foster capacity building

Given the wide application potential of hydrogen from industrial processes to energy storage and utilisation as fuel, for example, in transport, there is a strong impetus to ensure that this sector has qualified personnel. It is important that staff can assess and determine the conformity of their specific operations along the hydrogen value chain to the existing international, regional and national quality and safety requirements. These personnel will need to be made available across the entire green hydrogen value chain; equipment manufacturers; as well as operators of hydrogen plants and downstream industries or applications (DIN *et al*., 2024).

A particular facet of personnel training should focus on hazard management given hydrogen's large explosion potential differential. With regards to regulations and frameworks, there is a necessity to increase the specificity of qualification requirements for all hydrogen value chain stakeholders as well as ensure that qualifications for installation, conformance and inspection tasks are harmonised as much as possible. There must also be an emphasis on identifying which institutions are to take the lead in performing specific qualification development/ compliance tasks as well as ensuring these are reflected in technical rules and regulations pertinent to hydrogen (DIN *et al*., 2024).

To reimagine hydrogen capacity-building opportunities there should be a premium on developing specialised knowledge and skills for various segments of the value chain and ensuring those skills can be utilised in day-to-day working environments. International QI bodies should participate in defining areas of training within the ambit of quality and safety as well as how identified areas can be included in legal frameworks (DIN *et al*., 2024).

[27] *Examples for such regional organisations are the African Organisation for Standardisation (ARSO), the Inter-American Metrology System (SIM) and the Asia Pacific Accreditation Cooperation Incorporated (APAC).*

All implied actors and stakeholders (also including suppliers and service providers) have a responsibility to ensure they have trained personnel that are aware of the various legal frameworks underpinning the hydrogen economy as well as have competence on their application within their area of responsibility within the green hydrogen value chain. From the operation perspective, hydrogen project developers need to ensure that their employees can assess compliance in accordance with international best practices. Personnel also require specialised knowledge on risk assessments according to applicable regulations (DIN *et al*., 2024).

Some examples of quality personnel training and certification services include:

- **IECEx Certified Persons Scheme.** This provides the global explosive industries with a single system for the assessment and qualification of persons meeting the competency prerequisites needed to properly implement the safety requirements based on the suite of IEC international standards covering explosive atmospheres.
- **International Personnel Certification Association (IPC) management system auditors.** Endorsed by the IAF, the IPC provides a standardised framework for certifying management system auditors worldwide. The scheme aims to ensure the competence and proficiency of auditors in conducting management system audits based on international standards (IAF, 2024).
- **ISO digital learning platform.** This is an online platform hosted by ISO wherein users can access a wide range of digital learning solutions on standardisation and selected business skills, including standards related to hydrogen safety (ISO, 2024).
- **EURAMET training courses.** As a network of European metrological institutions, EURAMET organises several capacity-building workshops on different facets of metrology. There are also plenty of knowledge products in the field of metrology, including on aspects covered in the QI analysis (EURAMET, 2024).

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