Alliance for Industry Decarbonization

Green hydrogen

A cross-industry dialogue for sustainability

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About AFID

The goals of the Alliance for Industry Decarbonization (AFID) are: to foster the decarbonisation of industrial value chains; to promote the understanding of renewables-based solutions; and to promote the adoption of those solutions by industry, with a view to contributing to country-specific net-zero goals.

AFID is open to members and eco-system knowledge partners from any legal entity engaged in decarbonising industry, based on renewable energy solutions. This can include, but is not limited to, public or private sector industrial firms, industry associations, the financial community and intergovernmental organisations.

The International Renewable Energy Agency (IRENA) co-ordinates and facilitates the activities of AFID.

IRENA
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About this paper

This paper was developed jointly by members of the AFID Green Hydrogen Working Group (WG). It builds on exchanges and discussions among the WG members that took place during a series of meetings to realise joint initiatives. This paper is informed by the experience of AFID members and eco-system knowledge partners from different regions of the world.

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Abbreviations

AEM	anion exchange membrane
AFID	Alliance for Industry Decarbonization
CAPEX	capital expenditure
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CFGH	Collaborative Framework on Green Hydrogen
CO_2	carbon dioxide
DRI	direct reduced iron
EIGA	European Industrial Gases Association
EU	European Union
FID	final investment decision
g	gramme
GHG	greenhouse gas
GW	gigawatt
ICE	internal combustion engine
IEC	International Electrotechnical Commission
IECEx	IEC System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
kW	kilowatt
LCA	life cycle assessment
LCOH	levelised cost of hydrogen
Mt	million tonnes
MW	megawatt
OIML	Organisation Internationale de Métrologie Légale [International Organization of Legal Metrology]
OPEX	operating expenditure
PEM	proton exchange membrane
PTB	Physikalisch-Technische Bundesanstalt [German Metrology Institute]
PV	photovoltaic
SAF	sustainable aviation fuel
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
USD	US dollar

Executive summary

At the 2021 United Nations Climate Change Conference in Glasgow (COP26), an alliance of 32 nations and the European Union (EU) made a commitment to collaborate in propelling the rapid evolution and deployment of green hydrogen.

The shared aspiration of this alliance was to create a future in which accessible, cost-effective green hydrogen was widely available by 2030 (UNFCCC, 2021). Now, there is a growing cohort of nations that is charting a course to net-zero via a dedicated national hydrogen roadmap or strategy. Indeed, in recent years, green hydrogen has ascended the ranks of global priorities, emerging as a pivotal element in solutions to the intricate puzzle of clean energy.

In transportation, hydrogen fuel cells propel vehicles with zero emissions, exemplified by fuel cell electric cars such as the Toyota Mirai and the Hyundai Nexo. The railway sector is also ready, with Alstrom's recently-unveiled Coradia Stream a good example. In addition, green ammonia-powered railway engines are being explored by mining companies Fortescue and Vale.

At the same time, the aviation sector is looking at hydrogen as a sustainable aviation fuel (SAF) via projects like the ZeroAvia hydrogen-powered aircraft.

Green hydrogen can also be used to increase the liquid product yields from SAF production plants, as Alfanar is currently demonstrating. The Saudi Arabian company is exploring the use of green hydrogen to increase yields of SAF and a by-product, naphtha, from its Lighthouse green fuels SAF plant in Teesside, UK. Lighthouse green fuels will use the gasification + Fischer Tropsch production pathway to produce SAF from waste feedstocks.

In the chemical industry and refinery sector, green hydrogen is being used as a feedstock for cleaner production processes. Steel manufacturing is adopting hydrogen to reduce carbon emissions, as seen in projects by companies such as Thyssenkrupp. Moreover, the power generation sector is embracing hydrogen as an energy storage and grid balancing solution, via pilot projects such as the Orsted hydrogen power plant.

In addition, hydrogen forms the basis for e-fuels that can be used in existing automotive, aviation and marine engines, as well as other equipment in the construction, agricultural and off-road sectors. One example of this is the e-gasoline demonstration plant operated by HIF in southern Chile.

These examples underscore the diverse applications of green hydrogen in achieving cleaner and more sustainable industrial practices.

Yet, although green hydrogen is a vital piece of the energy transition and the decarbonisation journey, there are still many challenges preventing the industry from further ramping up.

These challenges exist in the regulatory, economic, social, technological and environmental fields. The aim of this report is to provide decision makers with actions that need to be taken into consideration, if these challenges are to be met.

In particular, in order to facilitate international trade and growth in the green hydrogen economy, there is an urgent need for a globally harmonised approach towards establishing a methodology and definition for identifying green hydrogen.

Decision makers should expedite such a global consensus on common methodology in order to establish clear definitions for categorising green hydrogen derived from electrical energy within the boundaries of a life cycle assessment (LCA) analysis.

Regulation and subsidies add further layers of complexity. In addition to the pursuit of a global consensus on green hydrogen regulatory definitions, national governments must also expedite the formulation of their own policies.

Indeed, in advocating for these global standards, it is crucial to recognise the nuanced regulatory landscapes in different countries. Methodologies should be developed that are sensitive to the unique characteristics of each country or region, ensuring they can be applied in a manner that accommodates and respects local particularities – especially concerning the behaviour of the local energy grid. This approach encourages the adoption of global best practices, while allowing flexibility for each country to tailor policies, recognising and valuing each jurisdiction's distinct advantages.

In addition to the use of existing, International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) standards in addressing safety and performance, IEC and ISO should also identify any additional standards that may be required to further support promotion of the green hydrogen economy.

AFID encourages reference to ISO/TC 197 (ISO, 2022) and IEC/TC 31 (IEC, 2019) as international standards within national and regional regulations. AFID also encourages the use of a harmonised approach to certification via the IEC System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres (IECEx). This is especially so for equipment, processes and equipment repair facilities at hydrogen hubs and ports, as well as for confirming the competence of persons working in these areas.

At the same time, a globally-harmonised approach to regulatory and subsidy regimes governing the whole green hydrogen value chain is a necessary basis for facilitating growth in the green hydrogen economy and its international trade.

Subsidies are vital for the development of a global renewable and low-carbon market and are used in all countries and regions. Supply-driven and market-oriented subsidies – such as tax reductions, grants or incentives – are fundamental tools for the development of the hydrogen market, and must be harmonised with demand-oriented approaches, where present.

Many regions prioritise national production and job growth via subsidies, creating competition that fosters a strong global market economy for green hydrogen. AFID calls on all regulators to collaborate in reaching a common approach to regulations, while making use of international standards to foster international trade and the development of a global green hydrogen economy and market. AFID further calls on all governments to remove import restrictions on subsidised green hydrogen and pursue a common understanding that subsidies around the world help to grow the green hydrogen market.

Technical and economic challenges are closely connected, influencing each other in enabling the development of a green hydrogen supply chain.

International co-operation and collaborative frameworks, such as the International Renewable Energy Agency (IRENA) – which enables the sharing of lessons learnt, cross-border expertise and other knowledge – are therefore essential in establishing a global framework for the development of the whole hydrogen value chain. Indeed, collaborative pathways are vital in unlocking the full potential of green hydrogen, with governments, industries and research institutions around the world recognising the need for joint efforts in driving renewables adoption.

Recommendations

1. This report notes the well-established international frameworks of the ISO, IEC and IECEx and the International Organization of Legal Metrology (OIML). It is recommended that use be made of these existing frameworks and services.

   It is also requested that work be expedited in order to achieve:
   a) A global consensus on a common methodology for defining boundaries that enable clear definitions to be established in categorising green hydrogen derived via electrical energy, and the boundaries of LCA analysis.
   b) A global consensus on the management system requirements necessary to facilitate a chain of custody.
   c) A common global ISO standard methodology for assessing the carbon footprint of different hydrogen production pathways. This is essential to allow the hydrogen with the lowest carbon footprint to reveal its climate benefits. Current work within ISO TC 197/SC1 (hydrogen at scale and horizontal energy systems) on the topic of a methodology for determining the greenhouse gas (GHG) emissions associated with the production, conditioning and transport of hydrogen to the consumption gate should be noted.

2. Concerning safety standards, it is recommended that countries and stakeholders refer to the ISO/TC 197 and IEC/TC 31 international standards within national and regional regulations.

3. Regarding the convergence of national and regional standards with international standards, the European Industrial Gases Association (EIGA) document 15/21As on gaseous hydrogen installations provides a good example.

4. Regarding conformity, it is recommended that a harmonised approach to certification be taken, via the IECEx. This is especially so for equipment, processes and equipment repair facilities at hydrogen hubs and ports, as well as for confirming the competence of persons working in these areas.

5. A call for collaboration should be made to all regulators in reaching a common approach to regulations that make use of international standards. These include ISO and IEC standards, supported by the international certification services of international organisations such as the IECEx and OIML.

6. A call should be made on all governments to remove import restrictions on subsidised green hydrogen. Governments should pursue a common understanding that subsidies help to grow the green hydrogen market, accelerate the use of green hydrogen and thereby contribute to the global reduction of greenhouse gas (GHG) emissions.

7. International co-operation in sharing lessons learnt, cross-border expertise and other exchanges of knowledge, are essential in establishing a global framework for the development of the whole hydrogen value chain. Collaborative pathways are essential in unlocking the full potential of green hydrogen. Governments, industries and research institutions around the world have recognised the need for joint efforts in driving the adoption of renewables.

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Introduction

The utilisation of hydrogen in industrial processes is not a novel concept – its application in diverse ways can be traced back throughout the history of industry. From early experiments to the modern era, the versatility of this gas as a clean and efficient energy carrier has led to its consistent presence in various industrial applications, proving its enduring value in driving innovation and sustainability across sectors.

Dating back to 1806, the first internal combustion engine was powered by a mixture of hydrogen and oxygen, not gasoline. Industrial synthesis of water into its two components was first undertaken as long ago as 1888, demonstrating that industrial hydrogen production and usage has existed for over a century. However, various enablers, such as an increase in energy demand, a drastic reduction in the cost of renewable energy, the agreement of Nationally Determined Contributions, and many other factors, have led to a more recent increase in the number of sectors using hydrogen as an energy source. This, in turn, has led to the need to develop more green hydrogen projects.

Green hydrogen has been hailed as a promising solution to the decarbonisation of industry and the achievement of climate goals. This concept involves producing green hydrogen by using renewable sources of electricity, such as wind and solar power. The result is a clean and versatile energy carrier that can be utilised by a variety of sectors, including transportation, industry and energy.

As the technology improves, green hydrogen also presents a possible future opportunity to store and transport renewable energy efficiently. Unlike direct electricity transmission, hydrogen can be stored for longer periods and transported over greater distances, making it suitable for regions with abundant renewable resources that may lack direct access to energy markets.

To unlock the full potential of green hydrogen, however, collaborative pathways are essential – a factor recognised by governments, industries and research institutions around the world.

One key collaborative approach is the development of hydrogen production hubs (also known as hydrogen clusters). These hubs concentrate production facilities and the industries that use hydrogen as feedstock, reducing infrastructure costs and promoting economies of scale. Countries such as Australia, Brazil, Germany and Japan are already investing in such hubs to accelerate the commercialisation of green hydrogen technologies (Santos *et al.*, 2013). Moreover, cross-sector partnerships are vital in integrating green hydrogen with existing industries.

Yet, even though green hydrogen is a promising solution in the energy transition and decarbonisation, it faces many challenges today.

From a regulatory perspective, government support is needed to strengthen the business case for green hydrogen projects, as well as for transport infrastructure for green hydrogen and its derivatives. Support for carbon pricing and an obligation for industries and businesses to buy green products would facilitate the ramp up of the green hydrogen industry.

In addition, selection of the appropriate technology and supplier is key for the hydrogen market. Right now, there are different technology suppliers for electrolysers, renewable energy, storage, conveyance, transportation and storage. The unavailability of round-the-clock renewable energy power supply – pump storage and avoiding hydrogen embrittlement[1] – are technological challenges faced by the industry. The need for capacity enhancement of electrolysers should also be considered.

1 Hydrogen embrittlement is a degradation process that reduces the mechanical properties of materials. This occurs due to the interaction between hydrogen atoms from the component's working environment (Broerman *et al.*, 2022)

A further challenge is the high requirement for demineralised water in the electrolysers used for hydrogen production, given that water availability for the hydrogen industry is poor in many parts of the world. In addition, ensuring green hydrogen availability at affordable prices and access to cheaper factor costs, such as renewable energy, are also challenges to be addressed. The absence for a requisite green premium also affects the price dynamics of green hydrogen, in comparison to conventional products. Pilot projects are key in terms of the scalability of commercial plants.

To accelerate the green hydrogen market, globally, governments should also align on international standards and certification, rather than focusing on country-based approaches. A common sustainability criterion for traded and supported hydrogen needs to be established.

To help overcome all these challenges, this report provides insights into green hydrogen definition and certification and how a global consensus can be achieved on these terms. The safety standards for generation, transport, storage and installation of green hydrogen should be considered in order to support a safe and sustainable ramp up of hydrogen production and consumption. The subsidy and regulatory disparities between the regions need to be aligned. To establish large-scale renewable green hydrogen hubs, techno-economic challenges and solutions are discussed in detail. Additionally, in order to facilitate the hydrogen market, the report thoroughly examines the roles of carbon and nitrogen as hydrogen energy carriers.

1 Green hydrogen: Definition and certification

Recent years have seen a growing focus on hydrogen – and especially green hydrogen – as a reliable and sustainable energy source. At the same time, however, misunderstandings and differences over what constitutes green hydrogen have also occurred. Attempts at the national and even regional level to define common criteria may therefore assist local communities. In these attempts, some countries and organisations have introduced a complex colour coding system to identify the origins of hydrogen and of the energy source required in its production.

In this report, hydrogen is classified as follows:

- Green hydrogen: hydrogen produced through electrolysis using renewable electricity.
- Grey hydrogen: hydrogen created from fossil fuels without capturing the GHGs produced in the process.
- Blue hydrogen: grey hydrogen with carbon capture applied to its production process.
- Turquoise hydrogen: hydrogen produced via methane pyrolysis, which splits methane into hydrogen gas and solid carbon.
- Pink hydrogen: hydrogen generated through electrolysis powered by nuclear energy.
- Yellow hydrogen: hydrogen produced using a mix of renewable and fossil energy.
- White hydrogen: hydrogen that is a natural geological feature in underground deposits and is extracted through fracking.
- Moss hydrogen: hydrogen reduced from biomass or biofuel via catalytic reforming or anaerobic digestion, and from gasification of plastic waste.

As can be seen, as an energy carrier, hydrogen can be produced via different pathways, each of which has a different and specific environmental impact. These different production methods and environmental impacts then affect the colour and classification of the hydrogen. Yet, while such classification may assist in quickly identifying the technology, equipment and process involved in a particular hydrogen project, not all countries follow this classification.

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1.1 A definition of green hydrogen

A definition of green hydrogen should take into account two criteria: whether or not it comes from renewable sources; and the level of sustainability (GHG reduction) of its product footprint.

In comparison to other methods of hydrogen production (blue or grey hydrogen), green hydrogen has the greatest potential to achieve GHG reductions, since it comes from renewable resources.

To facilitate growth at scale for green hydrogen, the starting point at the international level must be a clear, common and consistent definition and criteria of what green hydrogen is. This must be agreed by all countries, including national regulators and stakeholders.

For this to take effect we need both:

1. An international standard to outline a classification system that defines and specifies the origins of hydrogen, including the source of energy used in its production.

2. The international adoption of such an international standard without deviations.

Regarding the first point, the work of the ISO technical committee (TC) ISO TC 197 Hydrogen Technologies (ISO, 2022), should be expedited. Regarding the second point, a commitment by governments to both participate in the standards development process and adoption of completed standards is required.

At present, a uniform definition between countries of green hydrogen is missing. There is also often significant variation in definitions of green hydrogen between one geographical region and another. However, a universally accepted definition of green hydrogen would undoubtedly be helpful in promoting fair business and in GHG reduction calculations.

The reasons behind such variations are manifold. They include: the state of technological development; the cost and availability of renewable electricity; and challenges in the use of green hydrogen.

As generally understood, green hydrogen is that produced through electrolysis using renewable electricity, achieving a zero-carbon footprint. An example of this is the Brazilian National Interconnected System, which has around 145 000 kilometres (km) of extension and an electrical matrix of around 85% to 90% renewable energy. However, in regions where the electrical grid is still undergoing transition from conventional grey electricity to renewable, the production of hydrogen may not meet the criteria for green hydrogen classification before such transition is complete. This might dissuade or delay decisions to commence planning and development of large, at scale projects for green hydrogen generation.

Elsewhere, the generation of hydrogen using biomass or biofuels (moss hydrogen) could also achieve a zero-carbon footprint, potentially making it an attractive proposition in some countries. Currently, the technologies for producing hydrogen from biomass or biofuels are still in the developmental stages, yet this does still present a significant opportunity for certain countries to explore and invest in this emerging technology.

To encourage green hydrogen production across the globe, transition time must be allowed in locations where the availability of technology, regulations or renewable energy has still not been fully realised. Entities involved in hydrogen production in these regions must be given time to ensure zero carbon dioxide (CO_2) emissions in their processes. Needless to say, that the transition phase has to be as short as possible, with a target for a steady reduction in the carbon footprint for hydrogen production also met during this transition period.

This approach will promote the funding, use and development of technology for green hydrogen production while ensuring a consistent definition of green hydrogen to be established across the world.

An agreement should be reached on the international definition of green hydrogen that should not be subject to any region or country ramping up the hydrogen market. With a common agreement on the definition of green hydrogen by the ISO and IEC, we can link standards and regulations in different countries.

1.2 Certification

As defined in international ISO and IEC standards, certification provides independent, third party confirmation that specified requirements have been met.

During the IRENA workshop on Quality Infrastructure (QI) for Green Hydrogen, held on 21 June 2022, a panel discussion identified the important role that standards and certification play, particularly in instilling market confidence that the requirements of international standards are being met in areas concerning:

a) Safety and reliability
b) Confidence in stated claims
c) Commitment to a sustainable energy sector
d) Compliance with criteria set in the regulatory frameworks
e) Credit programmes and sustainability reports
f) Reduction of GHGs.

The minutes of that workshop include the following statements:

> *One way to overcome difficulties is to use the existing international standards of both the ISO and IEC and to identify areas where additional standards are required.*
>
> *Certification is equally needed in the whole value chain of electricity storage and production, including green hydrogen storage; some green hydrogen certification programmes already exist in which the customer gets a certificate of the safety and performance verification of the electrolysers. The collaborative work between IECEx and ISO TC 197* (ISO, 2022) *in providing international certification covering hydrogen, which includes green hydrogen, for both safety and performance as well as personal competence certification was also noted.*

These statements were also reiterated and re-emphasised during a quality infrastructure symposium that was organised in September 2023 together with the ISO, IEC and the German Metrology Institute (PTB) under the ambit of IRENA's Innovation Week 2023.

There are various approaches to certification that exist today whereby organisations – namely, certification bodies – offer certification schemes developed by the certification body themselves. This development is usually done in consultation with relevant stakeholders. Such certification schemes may be available at national or regional levels and may also be offered to organisations regardless of their country location.

While individual certification schemes may have an advantage of being adaptable to changing stakeholder needs, one significant disadvantage is the lack of a harmonised approach across the different certification bodies. This means that the actual evaluation, assessment and process of certification differs according to which certification scheme is being used. To tackle this issue, it is crucial to ensure that a methodology takes into account the unique characteristics of each country or region, particularly in the context of green hydrogen production.

A single global and harmonised approach to certification has the key advantage of ensuring that all certification processes, criteria and reporting are undertaken in a consistent, harmonised way. Various sectors have embraced this approach, including aerospace, food, railways, automotive, electrical and electronics, and the related renewable energy sectors of onshore wind, solar and marine.

A similar, single, globally harmonised approach is also recommended for the certification of green hydrogen. Organisations such as the IEC operate single international certification schemes where individual certification bodies (CB) – including but not limited to TÜV SÜD , Bureau Veritas, DNV, BSI, ITS, UL and many others – all come together to operate under a single set of international rules and standard operating procedures (Bureau Veritas, 2023; Clean Hydrogen Partnership, 2019; European Commission, 2023; TÜV SÜD, 2021).

Lastly, it is essential to note that while this report focuses on the green hydrogen route, certification schemes are equally crucial for other low-carbon pathways, such as biomass.

1.3 Next steps

This report makes the following recommendations for a globally harmonised approach towards a methodology and definition for identifying green hydrogen. This is, in turn, is the necessary basis for facilitating international trade and growth in the green hydrogen economy.

The report also notes the well-established international frameworks of ISO, IEC, IECEx and the OIML. It is recommended that these existing frameworks and services be used, while also requesting that work be expedited towards achieving:

1. A global consensus on a methodology for defining boundaries that establish clear definitions when categorising hydrogen derived from electrical energy, as well as the boundaries of an LCA analysis.

2. A global consensus of the management system requirements needed to facilitate chain of custody. A common global ISO standard methodology for assessing the carbon footprint of different hydrogen production pathways. This is essential to allow the hydrogen with the lowest carbon footprint to reveal its climate benefits. This recommendation also takes note of current work on a methodology for determining the GHG associated with the production, conditioning and transport of hydrogen to the consumption gate within ISO TC 197/SC1 (hydrogen at scale and horizontal energy systems).

2 Safety standards for the generation, transport, storage and installation of green hydrogen

Green hydrogen is an essential part of the transition towards an environmentally friendly alternative to traditional carbon-based fuels.

Support for green hydrogen from the global community continues to grow across all industries and sectors, as well as amongst stakeholders from governments to suppliers, to consumers.

While identified as a viable energy source, one of the characteristics of hydrogen is its flammability. The gas is extremely volatile and readily ignited, exerting enormous energy once this occurs. This characteristic is inherent to hydrogen regardless of the way it is produced and it is prone to explosions from unplanned ignition. There are many past examples of catastrophic damage and loss of life arising from explosions due to hydrogen.

The safety risks associated with generation, storage, transport and use of hydrogen are therefore well known. Many countries subject hydrogen to strict regulations, including compliance with strict safety standards and the need for certification/approval of equipment used in areas where hydrogen may be present. [2]

Regarding the transportation of hydrogen through existing pipelines, there is a serious danger of hydrogen damaging the pipes. This is particularly so for old gas pipelines which may suffer corrosion and other mechanical damage after long-term blended or 100% hydrogen service. A small volume of gaseous hydrogen in a mixture (just 1%) can lead to serious pipeline material deterioration and hydrogen embrittlement, particularly when combined with conditions of concentrated stress.

With greater use of hydrogen – even green hydrogen – a greater risk of fire and explosion therefore also occurs. Indeed, this is one of the greatest threats to the growth of the emerging green hydrogen economy, as this risk will certainly reduce the level of end-user acceptance.

2 Regulations governing green hydrogen should align with existing regulations that exist for hydrogen in general – for example, with the United Nations Economic Commission for Europe (UNECE) Common Regulatory Arrangement (see https://unece.org/sites/default/files/2024-01/RecL_CRA.pdf).

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2.1 International safety standards

Around the world and throughout history, the use of equipment in areas where flammable materials are present has seen explosion-related industrial accidents occur. These have sometimes cost many lives, as well as causing significant damage to equipment, infrastructure and the environment. Green hydrogen is still hydrogen and is therefore, by its very nature, a flammable gas. This, however, has been covered by international safety standards and international certification for many years.

During that time, it has been widely accepted practice to ensure minimum safety standards are applied in terms of the following four pillars:

1. Area classification: to determine the explosion hazard and its extent
2. Selection of equipment: to ensure the equipment's suitability for the explosion hazard and intended function and environment
3. Installation: to make sure equipment and systems are installed to ensure safety
4. Maintenance and repair: to ensure safety is on-going.

Examination of all four of the above must be conducted by persons that have demonstrated competence in these areas.

While national regulations exist in most countries, such regulations have a heavy reliance on an international approach to standards and conformity assessment schemes. Many national and regional regulations already use the technical requirements contained in the international standards drawn up by the IEC and ISO.

The basic principles of explosion protection have been applied in industry and mines for over 100 years. They have been codified in international standards, such as (IEC) 60079-0 (IEC, 2017) and the (ISO) 80079 series, and in conformity assessment best practice, such as ISO/IEC 17067 (ISO, 2013). They are also the basis of product certification systems, such as the IECEx (UNECE, 2022), (IECEX, 2024), within which around 100 certification bodies operate.

The principle of an internationally harmonised approach via the single international standards of the IEC and ISO is central to the recommendations contained in this paper.

The international standards of both the IEC and ISO provide the technical requirements, while international certification via a single system, such as IECEx, provides the full coverage and spectrum necessary to address:

- Equipment, components and systems
- Services used, including repair and overhaul, inspections and installations
- The competence of persons working in such areas.

Since 2011, a UNECE working party has been engaged with this topic and in 2022 it published the second edition of *A Common Regulatory Framework for Equipment Used in Environments with an Explosive Atmosphere* (UNECE, 2011).

On the topic of hydrogen distribution, there has been a push to promote the implementation of standards for design and construction of hydrogen pipelines, with one example being the American Society of Mechanical Engineers B31.12. This aims to guard against hydrogen embrittlement by increasing wall thickness. There has also been a strong call by pipeline experts to accelerate the development and standardisation of high-pressure gaseous hydrogen charging test methods, along with codes for investigating the susceptibility of steel pipelines to hydrogen embrittlement.

2.2 Recommendations

There are three recommendations from the IRENA Workshop on Quality Infrastructure for Green Hydrogen (21 June 2022), and the Quality Infrastructure Symposium (28 September 2023). These events discussed the use of existing ISO and IEC international standards to address safety and performance, while also highlighting to the IEC and ISO any additional standards that might be required to further support promotion of the green hydrogen economy.

Recommendation 1

Safety standards: It is recommended that reference be made to ISO/TC 197 (ISO, 2022) and IEC/TC 31 (IEC, 2019) International Standards within National and Regional Regulations.

Recommendation 2

Convergence of national and regional standards with international standards: As an example, EIGA Gaseous Hydrogen Installations document 15/21 was used.

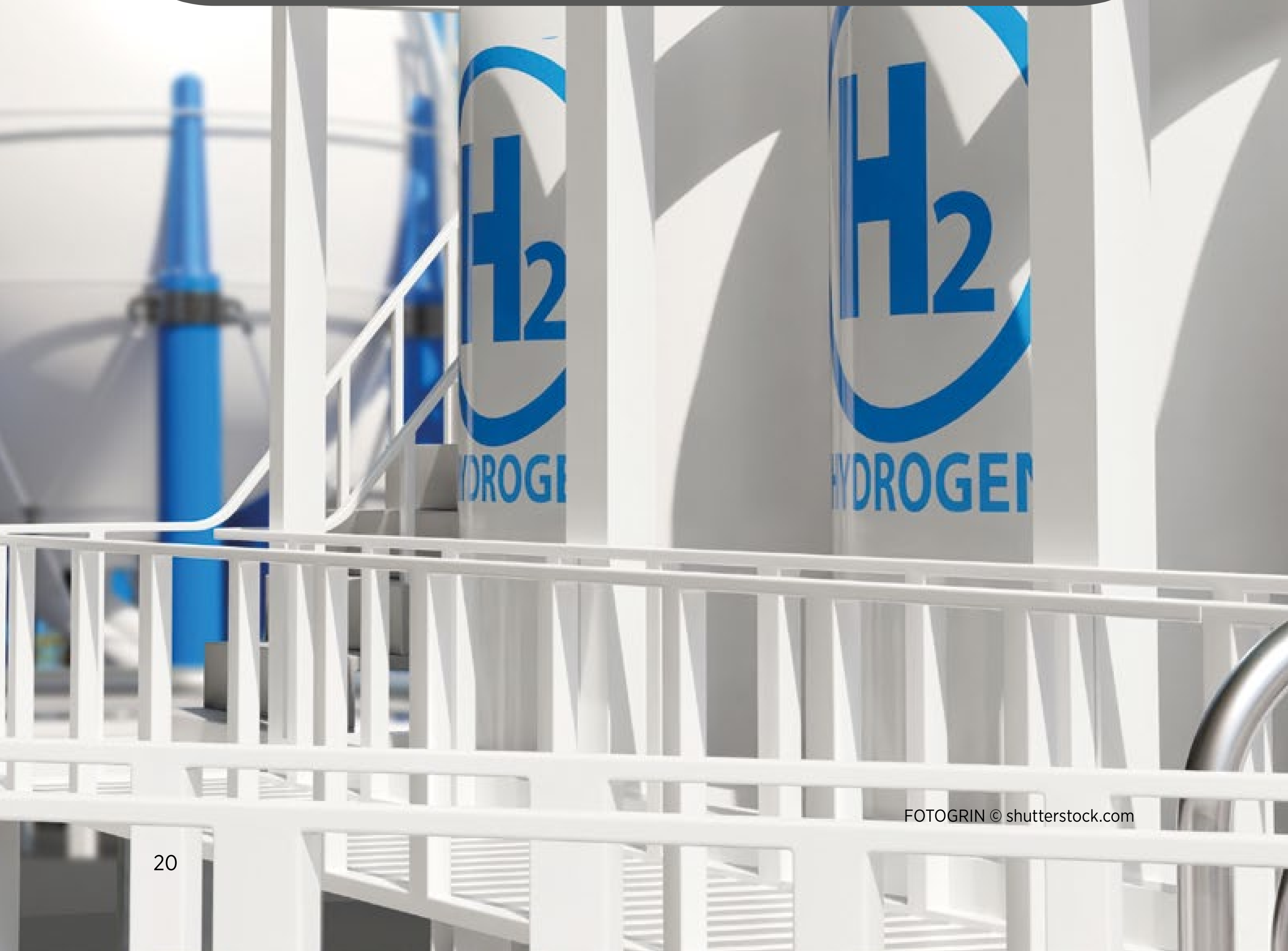
Recommendation 3

Conformity: Stakeholders are strongly encouraged to use a harmonised approach to certification via the IECEx, especially for equipment, processes, equipment repair facilities at hydrogen hubs and ports, and for confirming the competence of those working in these areas.

3 Subsidy and regulatory disparities between regions

In recent years, numerous countries have implemented subsidies and regulations to facilitate the commercialisation of green hydrogen. However, existing disparities among countries and regions pose challenges to the development of commercial-scale green hydrogen projects worldwide. It is therefore crucial to address the issue of varying approaches to subsidy and regulatory regimes across the green hydrogen value chain. This should cover production, transport, storage and consumption of the gas. It should also consider differences between countries, such as: the differing availability of renewable sources and energy production; different industrial structures that affect demand; and the existing and planned transport infrastructure. Examples of regulatory regimes that impede support for the global growth of the green hydrogen market include: divergent certification requirements and GHG methodologies; and divergences in safety, custody transfer and metrology regimes.

In the present market context, there is an urgent need for globally aligned green hydrogen regulations.



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3.1 Ongoing subsidies and regulations

It is the common goal of governments around the world to incentivise the commercialisation of green hydrogen to combat climate change and to make climate-neutral alternative energy sources such as this globally available. Over the past three years, numerous countries have implemented substantial subsidy schemes and regulations to incentivise industry investments in green hydrogen production and utilisation across various sectors, including transportation and industry. These schemes often align with industrial policy and energy security goals, with many nations viewing green hydrogen as a catalyst for fostering national industries and a skilled workforce.

Yet, there exists a significant variance in ideas and concepts regarding green hydrogen. Some regions exclude biomass as an electricity source for its production, whereas others incorporate nuclear energy. Furthermore, a globally harmonised methodology for calculating the GHG impact of green hydrogen is yet to be established, although an ISO standard is currently under development. Meanwhile, different countries and regions have published their own GHG calculation methodologies for green hydrogen's footprint.

Because of these divergent approaches to subsidies via regulations and standards that may create import barriers (sometimes intentional), international trade in green hydrogen remains challenging. Each target market that develops certifications that are not aligned with other markets creates obstacles for global customers such as the shipping industry. This key transport sector requires products adhering to the various jurisdictional regulations. An international approach would solve this disparity in green hydrogen regulations and prevent a mismatch between producers and consumers, resulting in more investments in the green hydrogen market.

In today's globalised world, the current patchwork of regulation around green hydrogen has limited value and has a negative impact on our climate and citizens. Maintaining this disparity will leave green hydrogen struggling to develop and grow to a commercial, at-scale level.

Differing approaches to regulatory regimes and subsidies for green hydrogen will result in rising prices and limited global availability for the following reasons:

- It creates market uncertainty as to where best to invest in green hydrogen production, as the market witnesses changing regulations.
- Few projects are able reach the investment stage, as uncertainty over certification and trade can make banks and potential customers wary. Many commercial scale projects could be abandoned at an early stage.
- Diverging approaches cause delays in the development of the green hydrogen industry as investors take a "wait and see" approach while regulators develop their own regulations.
- Addressing different regulatory regimes creates additional costs for the market and for consumers in covering supplier costs.

3.2 A harmonised approach to regulation

The issue of regulatory disparity is nothing new and in fact has existed for many years. Yet, when governments reach an alignment in regulatory requirements, the market and global community experience sustained benefits through falling prices, better quality and – above all – greater availability of the product.

As green hydrogen is by its nature a global commodity – with production and consumption centres often separated by borders or even oceans – a harmonised approach to regulation is paramount to its development. To allow full usability and trading of hydrogen as a commodity like oil and natural gas, standards and certification schemes have to cover all markets.

This regulatory framework should cover the following aspects:

1. **A definition of green hydrogen as a commodity**

2. **Safety rules**

3. **A GHG methodology for calculating the carbon footprint of green hydrogen**

   This ensures international consistency and comparability and enables accurate measurement of emissions throughout the hydrogen lifecycle. This consistency is critical for reliable reporting, effective policy making, and tracking progress towards global sustainability goals in the emerging green hydrogen sector.

4. **Custody transfer standards to support green hydrogen trading**

   Such protocols facilitate international trade in green hydrogen by establishing a common framework for the precise measurement of the quantity and quality of the gas being transferred from one entity to another. This ensures supply chain transparency, quality control and accountability. Consistent standards and calculations are needed to facilitate financial transactions with minimum financial risks between seller, buyer and government. To move forward, it could be a logical approach to adapt current standards for the oil and gas industry, such as OIML and the Measuring Instruments Directive (MID), to include hydrogen as energy carrier of feedstock. This would be done with the aim of medium- and long-term convergence towards a common regulatory framework.

Furthermore, to promote green hydrogen production, trade and consumption, the adoption of a book-and-claim custody model should be discussed globally. This model could enable the separation of hydrogen production from consumption, allowing producers to generate and sell green hydrogen certificates independently from physical hydrogen delivery. By localising consumption and optimising production where it is more convenient – such as in areas with high renewable energy sources – and integrating hydrogen into national grids, the model could reduce GHG emissions associated with long-distance transportation.

In addition, there is a need to advocate for digital systems covering the complete green hydrogen supply chain to be globally acknowledged and accepted by certification bodies. By promoting digital interoperability, this recognised digital framework can amplify market efficiency, streamline administrative procedures, enhance investor trust and minimise costs related to verifying the origin and characteristics of green hydrogen. A harmonised approach towards regulation will drive down transactional expenses, encourage cross-border trade and facilitate the achievement of globally ambitious renewable energy and sustainability goals.

3.3 A harmonised approach to subsidies

Government subsidies can play a crucial role in kickstarting market development and growing new technologies and industries. They can therefore provide substantial benefit to their communities, in the short, medium and long term.

Governments have rightfully implemented these incentives to bolster the production and utilisation of green hydrogen as an energy carrier, given its current lack of competitiveness against fossil fuel alternatives.

In the present market context, the approaches of different regions and countries towards subsidies for green hydrogen differ in their emphasis, scope and regulatory frameworks.

From an industry perspective, there is a clear preference for a supply- and market-driven approach to subsidies in the green hydrogen sector. This is on both the capital expenditure (CAPEX) and operational expenditure (OPEX) sides. Such an approach promotes minimal government intervention and provides targeted subsidies to produce green hydrogen, such as through tax incentives or grants.

On the other hand, some regions operate, if not directly favour, a demand-driven approach to bringing green hydrogen to the market. This approach involves the government setting increasing, obligatory quotas for green hydrogen use by companies or consumers. This can be realised, in part, through public auctions for green hydrogen.

In this respect, it is important that the demand-driven approach is adopted in a harmonised and easily implementable manner with policies that foster production investment, so as to maximise the growth opportunities for hydrogen markets.

Moreover, while subsidies are imperative for global green hydrogen production, certain regions hinder imports of subsidised green hydrogen in order to bolster their national industries. A divergent approach to subsidies inadvertently curtails investments, reduces overall availability and escalates green hydrogen prices.

While recognising the legitimate interest of individual states in guaranteeing the best conditions for the development of local green hydrogen markets, it is important to underline that the full development of these markets is linked to the emergence of an efficient international harmonisation of the different import and transport solutions. Future subsidy schemes for green hydrogen must be conceived with the common objectives of open competition and the avoidance of unnecessary trade barriers.

3.4 Recommendation

This report calls for a globally harmonised approach to regulatory and subsidy regimes. This approach should cover the whole green hydrogen value chain, with this a necessary basis for facilitating international trade and growth in the green hydrogen economy.

Subsidies are vital for global green hydrogen production and are used across all countries and regions. Supply driven and market-oriented subsidies, such as tax reductions or grants, are fundamental tools for the development of the hydrogen market. They must be harmonised with demand-oriented approaches, where present. Many regions prioritise national production and job growth via subsidies, creating competition that fosters a strong global market economy for green hydrogen.

Our joint objective of combating climate change and developing a green hydrogen economy should be at the forefront of all policies. From a climate perspective, each tonne of green hydrogen used will reduce global GHG emissions.

Further important objectives, such as energy security and decarbonisation, should be supported by industrial policies that are harmonised with the overarching goal of developing a global market for green hydrogen. This could be facilitated through comprehensive green hydrogen regulations.

We call on all regulators to collaborate in reaching a common approach to such regulations. We further call on them to make use of the relevant ISO and IEC international standards, supported by the international certification services of international organisations such as the IECEx and OIML. This will help foster international trade and the development of a global green hydrogen economy.

We call on all governments to remove import restrictions on subsidised green hydrogen. Such authorities should pursue a common understanding that subsidies around the world help to grow the green hydrogen market, accelerate the use of green hydrogen and thereby contribute to the global reduction of GHG emissions.

Additionally, carbon pricing could be another mechanism to enhance the viability of green hydrogen and its derivatives. By incorporating carbon pricing into the regulatory framework governing the green hydrogen economy, we can further encourage its adoption and contribute to the global effort to combat climate change. This approach aligns with our commitment to a comprehensive and globally harmonised strategy that encompasses regulatory, subsidy and pricing mechanisms. This ensures the sustainable development of a robust, global market for green hydrogen.

4. Techno-economic challenges and solutions for large-scale green hydrogen hubs

From the perspective of international market development, the establishment of large-scale green hydrogen hubs will be a crucial step in achieving the full maturity of the hydrogen market. Europe, for example, has a 2030 import target of 10 million tonnes (Mt) of hydrogen. This can only be met by the deployment of large-scale hydrogen hubs outside the continent. The purpose of this chapter is to analyse the techno-economic challenges that the realisation of these hubs poses – and to evaluate their related solutions from a developer's point of view.

The main hurdle in developing a large-scale hydrogen hub is to ensure the complete coverage of the entire value chain. This runs from renewable electricity production to hydrogen end-use, including transport and storage. One crucial aspect of this is the competitiveness of green hydrogen when compared to grey hydrogen and other decarbonisation solutions (*i.e.* green hydrogen, electrification, biofuels and carbon capture). Guaranteeing this competitiveness requires addressing several direct and indirect challenges.

Worldwide, there are several green hydrogen hubs being developed. For instance, both Brazil and Chile – which have high renewable energy potential – have announced ambitious green hydrogen projects to supply their internal demand, as well as the international market. In Brazil, Ceará is set to be the country's pioneer in green hydrogen production with the establishment of a hub at the Industrial and Port Complex of Pecém. The state government of Ceará has secured 36 Memorandums of Understanding (MoUs) and four preliminary contracts concerning green hydrogen production with various domestic and international companies, as it aims to position itself as a leading green energy hub (Oiticica, 2022; Renewablesnow, 2024).

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4.1 Market overview

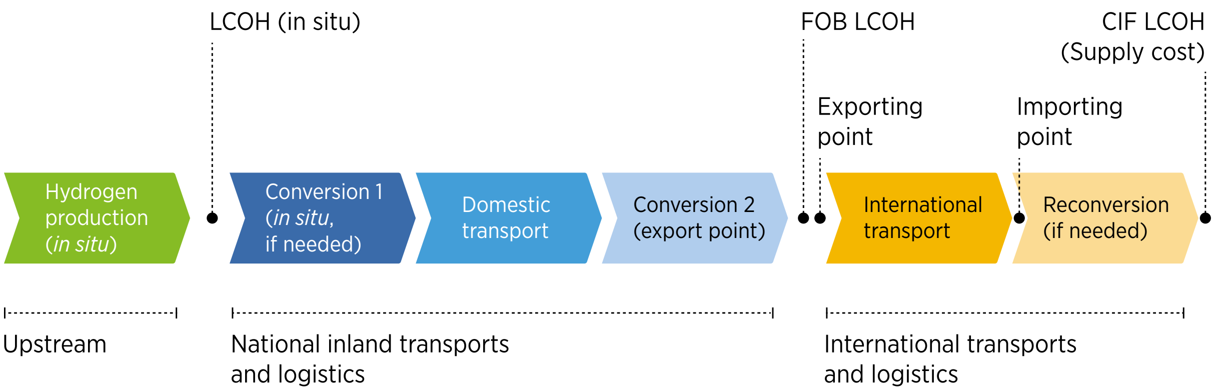
Globally, as of the end of January 2023, the hydrogen industry had announced more than 1 000 project proposals. This showed strong momentum in the sector, as the number of project proposals in May 2022 was less than 700.

Of the January 2023 total, around 800 projects aimed at being fully or partially commissioned by the end of 2030. These 800 had a total production target of 26 Mt/year of green hydrogen (230 gigawatts [GW] of electrolysis deployment) and 12 Mt/year of green hydrogen. In US dollar (USD) terms, these 800 projects represented a total investment of USD 320 billion, of which USD 29 billion had passed the final investment decision (FID).

Giga-scale project proposals (those larger than 1 GW) accounted for USD 150 billion of the USD 320 billion in total proposed investment (Hydrogen Council and McKinsey & Company, 2023).

Therefore, while the number of large-scale hydrogen hubs is increasing, their development faces some critical techno-economic challenges. These cover the entire hydrogen value chain, from renewable power and hydrogen production to transportation.

FIGURE 1: Large-scale hydrogen hub value chain



Source: (Boston Consulting Group, 2023).

Notes: LCOH = levelised cost of hydrogen; FOB =Free on board; CIF = cost, insurance and freight.

Factors such as costs, land availability, renewable energy resources, access to capital, permitting time, demand creation and funding may influence the direction of the hydrogen market.

Those markets may have the following characteristics:

- **Local hydrogen market, or hydrogen valley:** Potentially, any country can produce hydrogen, leveraging its own renewable resources and land availability. In this case, the levelised cost of hydrogen (LCOH) ***in situ*** represents a good parameter for the final hydrogen price to end-users. This is because of the lower transportation cost, which is mainly related to final distribution.

- **Centralised domestic production:** Large-scale projects can be located strategically in areas with greater renewable resources, land availability and a higher-level transport infrastructure. In Europe, southern Italy and Spain are ideally positioned to take advantage of abundant solar resources, while northerly regions like Denmark, Sweden, and parts of the UK and Germany are optimal for wind-based hydrogen projects due to their significant wind resources. Large-scale projects allow for a lower LCOH than in local hydrogen valleys, as they can benefit from a more optimised design and economies of scale.

- **International market:** Some of the largest demand centres, such as the European Union (EU), Japan, and the Republic of Korea, may not be in a position to produce low-cost hydrogen in sufficient quantities to fully meet their demand. In contrast, regions with high renewable energy and ample land availability, such as parts of Australia, Africa, Asia, Latin America and North America, could produce cost-competitive green hydrogen in quantities that exceed domestic needs. In this case, the final hydrogen price – or the LCOH adjusted for cost, insurance and freight – will be a sum of the hydrogen production cost, the cost of conversion into derivatives such as ammonia, the cost of transport and re-conversion into hydrogen. According to many providers, around 20% of global hydrogen production will be used for trade by 2050 (Boston Consulting Group, 2023; Deloitte, 2023).

In all cases, from 2025 to 2050, hydrogen production will cover 80% of the cumulative investment over the entire hydrogen value chain (Boston Consulting Group, 2023; Deloitte, 2023). Consequently, production cost challenges will play a dominant role, directly or indirectly.

4.2 Challenges

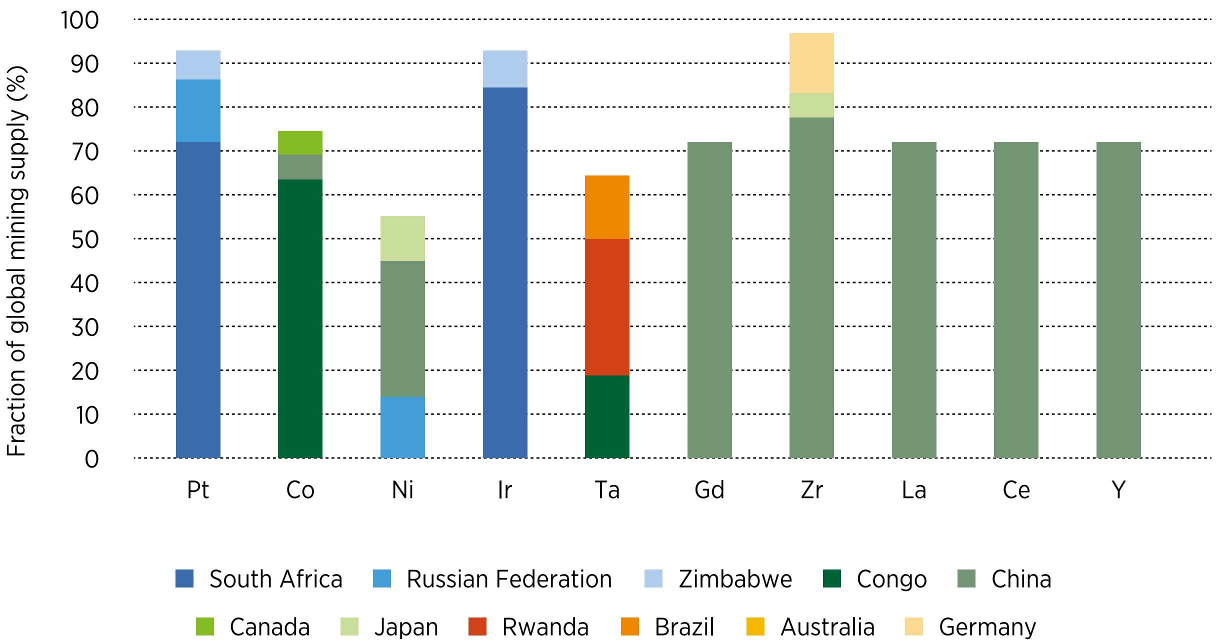
Regarding manufacturing capacity, to date, hydrogen output has been much lower than manufacturing capacity. In 2022, for example, there was 1 GW of output, as opposed to 14 GW of capacity. Therefore, in the short term, there will not be any potential criticality in the development of the new hydrogen projects pipeline. By 2030, if all the announcements from manufacturers are realised on time and at scale, the potential output of the electrolyser manufacturing facilities worldwide will be sufficient to support the deployment of all the announced production projects (IEA, 2023).

Regarding the main critical raw materials for the sector, the proton exchange membrane (PEM) electrolyser needs iridium, titanium and platinum. Iridium use is currently between around 1 gramme per kilowatt (g/kW) and 2.5 g/kW. Global iridium production currently stands at approximately 7 to 7.5 t/year with the majority concentrated in South Africa. This precious metal finds widespread application in various industries, serving as a fundamental component in corrosion resistance alloys, catalysts and in the fabrication of electronic devices. To meet a demand of between 3 GW per year (GW/year) and 7.5 GW/year of PEM electrolysers, a substantial increase in iridium production is therefore imperative. Specifically, this would necessitate a rapid doubling of existing iridium production capacity, or a significant reduction in the iridium content required (IEA, 2022; IRENA, 2023; IRENA, 2020).

Another challenge is the use of per- and poly-fluoroalkylated substances. Some of these are vital ingredients in PEMs and anion exchange membranes (AEMs), yet could be banned in the EU and elsewhere due to concerns over their impact on human health and the environment. This would limit the adoption of these technologies in some regions and consequently slow the rise of green hydrogen projects.

Generally, the supply of critical materials for electrolysers is mostly dominated by a few countries. South Africa, for example, mines over 70% of the world's platinum and over 85% of its iridium. This severely constrains the spread of PEM electrolysers, with limited short-term alternatives in sight for the replacement of these materials.

FIGURE 2: Top producers of raw critical materials used in electrolysers



Source: IRENA, 2020.

Notes: Pt = platinum, Co = cobalt, Ni = nickel, Ir = iridium, Ta = tantalum, Gd = gadolinium, Zr = zirconium, La = lanthanum, Ce = cerium, Y = yttrium.

To overcome these material and regulatory challenges, carrying out a plan for giga-factory development might help to increase manufacturing capacity. At the same time, however, manufacturers need sufficient real commitments by future hydrogen producers to invest. Indeed, while manufacturers have announced plans for further expansion, aiming to reach 155 GW/year of manufacturing capacity by 2030, only 8% of this capacity has reached the FID stage or beyond (IEA, 2023).

Moreover, new developments in technology could reduce and diversify the demand for critical raw materials. Examples of this include AEMs, solid oxide electrolyser cells, platinum-free technologies and others. Another promising concept under examination involves a hybrid approach, where a combination of electrolyser types is employed. For instance, deploying a 200 megawatt (MW) PEM electrolyser alongside gigawatt-scale alkaline counterparts could yield the advantages of both technologies.

These developments will also have a direct deflating impact on hydrogen production costs. Indeed, overall CAPEX typically accounts for at least 80% of LCOH. This includes, in addition to the electrolyser and relative balance-of-plant costs, the CAPEX for renewable energy in a direct, physical or virtual connection (Deloitte, 2023). Along with the different variables, electrolyser CAPEX has an important impact on LCOH and driving costs down is the key to making hydrogen economical. Solar photovoltaic (PV) CAPEX is already low, while another important CAPEX factor could be represented by the maturity level of energy storage technologies necessary to run the system reliably and continuously.

In addition to the reduction of manufacturing costs (in terms of CAPEX), there are other potential levers for reducing LCOH:

- Engineering and construction processes can be streamlined, implementing a "design one, build many" approach. Modularising systems and considering manufacturing options in economically advantageous countries can also be undertaken.
- In the short term, financial support (both for CAPEX and OPEX) can be given to ramp up the market.
- An increase in efficiency may reduce the size of electrolysers and the amount of renewable energy consumed in order to produce a given quantity of hydrogen.
- Investments can be made in transmission and in boosting the share of renewable energy in national grids. Long operating hours can be guaranteed using on-grid systems. As an example, in Brazil, renewable energy has a share of more than 80% of the energy mix with an interconnection transmission system.
- An increase in full load equivalent operating hours – using a mix of renewable sources, energy storage and oversizing of renewable energy plants – would spread initial and ongoing investment costs over a larger output, reducing the financial requirement per unit produced.

Indeed, the availability of reliable, stable and widely available renewable energy production, leveraging solar, wind, hydro and geothermal resources, is the main requirement when designing a large-scale hydrogen hub. Often, regions with large renewable energy resources and ample land availability are unable to exploit their renewable potential due to electricity grid connection constraints. In this case, hydrogen production can help to facilitate renewable energy, addressing challenges by adopting off-grid, demand side management and/or energy storage configurations for flexibility. The best solution depends the site characteristics resulting in an optimum balance between the costs of electrical connection, electrolyser and storage.

Moreover, once the hourly correlation between the renewable energy supply and the consumption of the electrolysis plant is known, the problem becomes more evident. In Europe, for example, anticipated developments in EU regulations – specifically the EU Delegated Act expected by 2030 – could significantly enhance the alignment between renewable energy supply and the energy demands of electrolysis plants. Understanding this hourly correlation will be crucial for accurately sizing renewable installations in relation to the plants. A renewable plant oversizing would allow an increase in the load factor of the electrolysis plant. Yet it also poses the issue of valorising the excess renewable production, which can be done only if a grid connection is available.

On the other hand, if a renewable energy plant's capacity is equal to the capacity of the electrolysis plant, this usually does not allow for sufficient electrolysis plant usage. This results in a high CAPEX component in the LCOH, while also resulting in hydrogen supply continuity issues. The availability of a grid that is capable of absorbing the excess renewable production therefore plays a key role in business model optimisation. Conversely, grid availability allow the electrolysis plant to be fed by a portfolio of different renewable energy sources, hence maximising usage. In this regard, feeding the electrolysis plant with solar PV plants only, without battery energy storage systems, would not allow an increase in the electrolysis plant's usage above 35%-40%, even if there were significant renewables oversizing (this figure varies depending on the geographical location of the plant). Generally, the electricity grid plays a key role in reducing the overall project risk, but its availability and resilience to natural disasters and equipment failure is a further challenge to be improved for hydrogen production. Rules for temporal correlation must be made flexible in countries where the electricity mix is highly renewable and interconnected, such as Norway and Brazil.

Another potential challenge could be the fresh water supply. While currently, this is not likely to be a strong barrier to a large-scale green hydrogen hub in many regions, a more significant problem may be future water stress caused by climate change. Producers should therefore address this challenge. Some viable solutions with a low impact on the LCOH include desalination, or water reuse.

Once the hydrogen is produced, efficient and low-cost transportation and storage is also necessary to enable international trade in hydrogen and its derivatives. In particular, the competitiveness of derivatives must take into account their technological availability and conversion and reconversion efficiencies.

Leveraging the availability of existing/planned infrastructure, such as ports, terminals, pipelines, hydrogen backbones and depleted gas fields, could enable the realisation of a repurposed large-scale hydrogen hub. However, in some cases, repurposing existing assets creates further techno-economic challenges. These include safety and issues arising from low energy density. In addition, different transport solutions – such as pipelines, or via conversion into derivatives such as methanol and ammonia – must be assessed according to the distances needed to be travelled, as well as technical aspects such as safety, efficiency and technological readiness.

Indeed, the development of low-carbon, non-intermittent hydrogen from sources such as steam methane reforming with carbon capture and storage (CCS), or from nuclear power, could provide flexibility in production. This would be useful in optimising infrastructure sizing and facilitating the creation of the first large-scale hubs – as is currently happening in the United States.[3]

Hydrogen developers must also ensure bankability. Financial institutions will closely scrutinise the chosen electrolyser technology as a crucial component of their technical and commercial due diligence process. Key aspects under scrutiny include process guarantees and the presence of well-defined risk mitigation measures.

Furthermore, some of the best locations for hydrogen projects may suffer from high country-related political risk. In such cases, private investors and lenders would expect higher rates of return to compensate for greater political risk. International and green finance can, however, help lower the cost of capital for green hydrogen projects in such instances.

For developers to take an FID, the securing of an off-take agreement and potential government funding is key. Most projects that are either at the FID stage or have gone beyond it have either captive off-take – the company has its own, internal demand for hydrogen – or long-term off-take contracts.

As the involvement of an anchor hydrogen off-taker is one of the main challenges, the primary consideration when embarking on a hydrogen project is the strategic location of the production facilities – or at least their accessibility via cost-effective transport solutions. One key aspect involves proximity to existing hydrogen consumers, such as refineries, petrochemical plants, fertiliser plants, mining operations and off-grid users. Secondly, assessing the potential for displacing natural gas with hydrogen in established thermal applications – particularly within industries like metals and iron production – becomes pivotal.

3 Clean hydrogen is being produced at the Nine Mile Point Nuclear Station in Oswego, New York. This facility is pioneering the generation of clean hydrogen via nuclear power in the United States (Office of Nuclear Energy, 2023).

Existing public support mechanisms are, however, currently more focused on the production side. This is despite recent efforts to support the financing of operations. These efforts include the European Hydrogen Bank, H2Global and national support schemes, along with the obligations on green hydrogen demand set by the European authorities under RED III. Indeed, public support mechanisms to test and make competitive the end-use of hydrogen and its derivatives in hard-to-abate sectors, such as steel, flexible power and transport, are still insufficient.

Enabling hydrogen end-uses must also overcome further challenges. In the transport sector, for example, these include the implementation of an adequate hydrogen refuelling station plan.

Finally, effective policy intent in the implementation of the clean energy transition via green hydrogen is an additional challenge that must be faced. In particular, definitions within the regulatory framework must be considered in order to promote international trade. Standardisation between different countries and jurisdictions in the certification of hydrogen and its derivatives can facilitate hydrogen exports as well as help define the necessary regulations for hydrogen transportation.

4.3 Recommendation

There is a global commitment to develop green hydrogen projects in order to foster the decarbonisation of the energy system. However, there are challenges that need to be addressed if the development of a green hydrogen supply chain is to be achieved. The technical and economic challenges are closely connected, influencing each other. Therefore, to ensure rapid and efficient market development, all of these factors must be addressed in parallel and in a co-ordinated manner at the national and global levels. It is crucial not to neglect any challenge, as stopping one can slow down the whole process.

At the same time, none of these challenges is insurmountable. International co-operation, sharing lessons learnt and cross-border expertise gained, is therefore essential in establishing a global framework for the development of the whole hydrogen value chain. Collaborative pathways are also essential in unlocking the full potential of green hydrogen. Governments, industries and research institutions around the world have recognised the need for joint efforts to drive its adoption.

4.4 Key take-aways from IRENA's Collaborative Framework on Green Hydrogen

As part of the global renewable energy transformation, the Collaborative Framework on Green Hydrogen (CFGH) plays a pivotal role in fostering productive dialogue, co-operation and co-ordinated action to expedite the development and deployment of green hydrogen and its derivatives. The framework leverages IRENA's expertise in green hydrogen, as well as the knowledge and experience of its membership.

In 2023, the CFGH focused on taking stock of global green hydrogen deployment after years of strategy development and project announcements. The CFGH looked into developments on the demand side, as well as on the supply side. It also examined how green hydrogen value chains could be established in a truly sustainable way that benefitted all.

Some of the key takeaways included:

Strategies and regulatory frameworks

- Taking stock of where the world stands in terms of demand for green hydrogen and its derivatives is crucial in understanding the progress made in recent years. Many strategies and project plans have been launched, with most countries focusing on hard-to-abate sectors.
- The last two years have also seen an evolving policy and regulatory landscape, which is essential for the successful creation of demand. It is important to continue monitoring progress and adapting strategies. There are a variety of policy measures needed to ramp up green hydrogen production and use, including: common standards for trade; achieving the targets set by the Paris Agreement; and promoting local production of green hydrogen in regions such as Africa.
- Promising policy and regulatory developments are taking place. These include the European Hydrogen Bank, the planned Japanese tax credit, and the Inflation Reduction Act in the United States (FCHEA, 2022; Reuters, 2023).

Creating demand

- The demand for hydrogen and its derivatives in, for example, the steel and shipping industries is expected to rise substantially due to the increasing number of both small and large-scale projects being implemented.
- Efforts are being made in the direction of demand creation and building skills and the capacity to close technical knowledge gaps related to the production and use of hydrogen and hydrogen derivatives.

Establishing supply structures

- LCAs are complex but effective tools for assessing the carbon footprint of any product and should be used to closely align incentives with emissions. It is essential to create value chains that are sustainable in a broader sense.
- It is important to avoid developing countries being left behind. Developing countries should have a beneficial role in the development of future hydrogen value chains, given the existing renewable resources of many developing countries.
- Green hydrogen has the potential to not only reduce carbon emissions but also drive a new pathway for industrial development in the Global South. The local production of green hydrogen and its derivates in the African continent, for example, could trigger local production of fertilisers and provide added value to green hydrogen's national demand. Therefore, it is important to consider the potential benefits of green hydrogen beyond its impact on carbon emissions, while also exploring ways to leverage adoption of green hydrogen for broader industrial and socio-economic development.
- Hydrogen transport via pipeline is the most cost-effect way, even though it comes with its own challenges. Many countries aim to repurpose existing natural gas pipelines and blend hydrogen in with them. More insights are needed, however, into challenges such as hydrogen embrittlement and pipeline compressor requirements.

5 Utilisation of hydrogen by different industries

Green hydrogen is a clean fuel with a high level of energy per kilogram. It is also a very potent reduction agent in chemical reactions. Given its remarkable versatility and environmentally friendly characteristics, green hydrogen has therefore emerged as a pivotal player in the global effort to make industry and transportation sustainable and clean.

In the steel industry, green hydrogen is rapidly gaining prominence as a substitute for conventional coal-based processes. The gas facilitates direct reduction methods, resulting in the production of "green" or low-carbon steel, effectively curbing GHG emissions. Indeed, the deployment of hydrogen in direct reduced iron (DRI) processes ingeniously reduces iron ore (iron oxide) with a minimum of CO_2 emissions, with water vapor the only major by-product. This transition from the traditional, blast furnace - basic oxygen furnace route to the green hydrogen-powered DRI route could potentially cut emissions by between 80% and 90% – a significant leap towards net-zero targets. Hydrogen-based DRI technology has already been tested in a variety of pilot projects, while several commercial installations are also currently underway.

In the fertiliser sector, hydrogen plays a vital role in decarbonising ammonia production, an integral part of the fertiliser manufacturing process. The adoption of green hydrogen in this process contributes substantially to reduced carbon emissions, helping address the environmental concerns of the agricultural industry. Additionally, hydrogen serves as a critical feedstock in the chemical sector, facilitating processes such as methanol production and hydrogenation reactions and substantially reducing the carbon footprint of the sector.

Carbon capture from waste gases with a high-concentration of CO_2 in industries such as steel, petroleum and chemicals – as well as in bioethanol, pulp and paper production and biomass combustion and gasification – is also gaining prominence. Waste gases from industries such as steel, energy and petrochemicals can provide a cheaper source of CO_2 for carbon capture projects. Indeed, the careful selection of sources of waste gas rich in CO_2 – such as blast furnace gas – could effectively reduce costs. Captured CO_2 can be repurposed by using green hydrogen to produce value-added chemicals and fuels. These include ethanol, methanol, polycarbonate, sustainable aviation fuel (SAF), e-gasoline, e-liquefied natural gas, dimethyl carbonate, dimethyl ether and others. Carbon capture and utilisation (CCU) using green hydrogen has the potential to develop green products at a lower cost and promote sustainability in the chemical and fuel industries. It will also encourage the development of new technology and intellectual property.

Hydrogen's application also extends to electricity generation in gas turbines and fuel cells, offering a dependable and clean energy source. This is especially so when it is paired with renewable energy for enhanced power grid stability.

In summation, hydrogen's adaptability and its potential to curtail GHG emissions make it a promising solution for a multitude of industries. These range from steel and transportation to fertiliser production and beyond. As technologies and infrastructure continue to evolve, hydrogen is being progressively assimilated by various sectors, playing a pivotal role in the pursuit of a more sustainable and carbon-neutral future.

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6 Methanol and ammonia made from green hydrogen

As the world grapples with the urgent need to transition to renewable energy sources, green hydrogen is becoming an important driver in this transformation. Yet, world-class production sites for green hydrogen – those with the world's best wind and solar resources – are often situated an ocean away from the world's major consumption hubs. Deployment of green hydrogen and the subsequent use of those remote renewable resources therefore requires an efficient and reliable method of transport. Green hydrogen cannot be easily transported over long distances, however. One solution to this challenge could be to combine hydrogen with CO_2 and nitrogen. This could be a gamechanger and allow green hydrogen to be bottled and safely transported by ship to the world's consumption centres. The integration of hydrogen with either CO_2 or nitrogen would also enable the use of the world's best renewable energy sources in geographically remote and isolated regions that would otherwise remain untapped.

6.1 Renewable hydrocarbons as energy carriers

As well underpinning global energy systems, hydrocarbons are a key support for both society and industry. This is mainly due to their high energy density, stability and easy-to-handle infrastructure. Green hydrogen combined with carbon provides renewable hydrocarbons. These act as a substitute for their fossil counterparts and offer a wide range of applications.

A promising renewable hydrocarbon made from green hydrogen is e-methanol (CH_3OH), which can be described as a platform fuel. In the maritime industry or in chemical applications, it can be used directly as a fuel. Additionally, e-methanol can be downstream-processed into other climate-neutral fuels. These include e-gasoline, SAF or e-diesel for construction equipment and agricultural machinery, as well as chemicals such as those used in the production of plastics. This makes e-methanol an even more valuable and adaptable resource. With its diverse value chain and potential to reduce carbon emissions across multiple sectors, e-methanol made from green hydrogen represents a promising path towards a more sustainable future.

In addition, renewable hydrocarbons have a significantly higher energy density compared to pure hydrogen gas. This characteristic is vital for long-distance transportation and storage, where maximising energy per unit of volume is essential. The extensive network of pipelines, storage facilities and transportation systems used by conventional hydrocarbons can be repurposed for the transport of renewable hydrocarbons. This repurposing reduces the need for entirely new infrastructure, accelerating the deployment of renewable energy and thereby the reduction of GHG emissions.

However, in the combustion of renewable hydrocarbons, CO_2 is inevitably emitted into the atmosphere. Thus, the pivotal role of CO_2 utilised in the synthesis process becomes apparent, as it significantly influences the overall reduction effect of GHG emissions associated with renewable hydrocarbons. Ultimately, to establish a complete, climate-neutral cycle, renewable hydrocarbons must rely on CO_2 captured directly from the atmosphere, or from sustainable biogenic sources. In the interim stage, however, the efficient capture and use of carbon emissions from industry can accelerate global GHG reductions by recycling industrial emissions and displacing the burning of fossil CO_2.

Indeed, the adoption of renewable hydrocarbons produced from sources such as biomass can provide a substantial incentive for the advancement of CCU and CCS technologies, notably direct air capture. Compelling renewable hydrocarbons to increasingly adopt CO_2 from atmospheric capture, a sustainable climate-neutral loop can be established. This strategic approach allows renewable hydrocarbons to promote negative emission technologies such as direct air capture.

6.2 Renewable ammonia as energy carriers

Nitrogen-based molecules, particularly ammonia (NH_3), can also play an important role as potential carriers for green hydrogen. This is due to their distinct characteristics and versatility.

Ammonia has a high hydrogen density and allows for efficient hydrogen storage and transport in liquid form. Liquid ammonia can be stored at moderate pressures and ambient temperatures, simplifying logistics compared to pressurised or cryogenic hydrogen storage. Due to these features, green ammonia is a very attractive fuel for long-distance transport – especially for shipping, in which ammonia engines are currently under development. Furthermore, ammonia is already one of the most widely produced and traded chemicals globally, with an established infrastructure for storage, transport and distribution. This network can be leveraged for green ammonia transport, enabling its integration into existing supply chains.

However, despite the advantages as an energy carrier, ammonia also presents certain disadvantages. One significant concern is its high toxicity, posing a risk to human health and the environment if not handled with care. Additionally, ammonia is flammable in specific concentrations, further emphasising the importance of proper storage and transportation protocols. Its potential to contribute to air pollution and aquatic ecosystem disruption, particularly when released into the environment, also underscores the need for stringent safety measures during its production, use and disposal.

6.3 Common approach

Renewable hydrocarbons and green ammonia offer unique advantages for renewable energy transport, exploiting otherwise untapped renewable resources in remote locations and making them available worldwide. Furthermore, renewable hydrocarbons such as e-methanol and e-ammonia can be directly used for reaching climate neutrality in transport, global trade, construction, agriculture and the chemical sector.

This report therefore strongly advocates that governments have a common approach to international production, transport and trade in renewable hydrocarbons and e-ammonia and to rapidly upscale the global production of green hydrogen at the world's best renewable energy production sites.

7 Conclusion

Green hydrogen has emerged as a frontrunner in the pursuit of sustainable energy solutions. Its ability to store and transport renewable energy, coupled with its potential to decarbonise industries, positions it as a vital component of the clean energy transition. Collaborative pathways involving governments, industries and research institutions are crucial in overcoming challenges and realising the full potential of green hydrogen. As global co-operation and technological advances continue to shape the energy landscape, green hydrogen is poised to play a pivotal role in a cleaner and more sustainable future.

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