IRENA
International Renewable Energy Agency

SHAPING SUSTAINABLE INTERNATIONAL HYDROGEN VALUE CHAINS

ISBN: 978-92-9260-616-9

Citation: IRENA (2024), *Shaping sustainable international hydrogen value chains*, International Renewable Energy Agency, Abu Dhabi.

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and clean economic growth and prosperity.

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Acknowledgements

This report was authored by Ann-Kathrin Lipponer, Emanuele Bianco and Arno van den Bos, under the guidance of Francisco Boshell, Ute Collier and Roland Roesch (Director, IRENA Innovation and Technology Centre).

Valuable input was also provided by IRENA colleagues: Arno van den Bos, Luis Janeiro, James Walker, Gondia Sokhna Seck, Michael Renner, Asami Miketa, Raul Miranda, Danial Saleem, Kenji Kato and Abdullah Fahad.

This report benefitted from the input and comments of experts, including Maximilian Kuhn (Hydrogen Europe), Magnolia Tovar (Clean Air Task Force), Frank Mischler (GIZ), Herib Blanco (McKinsey & Company), Dolf Gielen (World Bank), Oghosa Erhahon (RIFS), Greg Dolan (Methanol Institute), Smeeta Fokeer (UNIDO), Paulo Partidario (DGEG), Deger Saygin and Joseph Cordonnier (OECD), Markus Albuscheit, Ralf Ott, Dominik Bruckner, and Maryna Hritsyshyna (Hydrogenious), IRENA focal point for the Collaborative Framework on Green Hydrogen Colombia (Maria Carolina Nocua).

Publications and editorial support were provided by Francis Field and Stephanie Clarke, with design by PhoenixDesignAid. The report was edited by Jon Gorvett.

IRENA is grateful for the support received from the Government of Japan to produce this report.

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ABBREVIATIONS

BECC	bioenergy with carbon capture and storage
CBAM	Carbon Border Adjustment Mechanism (EU)
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CfD	contract for difference
DA	delegated act
DAC	direct air capture
DBT	dibenzyl-toluene
EHB	European Hydrogen Bank
EIB	European Investment Bank
EJ	exajoule
ESG	environmental, social and governance
EU	European Union
FCEV	fuel cell electric vehicle
FDI	foreign direct investment
g	gramme
GCC	Gulf Co-operation Council
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
GW	gigawatt
G7	Group of 7
H_2	hydrogen
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
ISO	International Organisation for Standardisation
kg	kilogramme
$kgCO_2eq$	kg of CO_2 equivalent
KPI	key performance indicator
kt	kilotonne
Ktpa	kilotonnes per annum
kW	kilowatt
kWh	kilowatt hour
LCA	life-cycle assessment
LCOH	levelised cost of hydrogen
LOHC	liquid organic hydrogen carrier
METI	Ministry of Economy, Trade and Industry (Japan)
MJ	megajoule
MOU	memorandum of understanding
Mt	million tonnes
Mtpa	million tonnes per annum
MW	megawatt
O&M	operation and maintenance
OEM	original equipment manufacturer
PDBT	perhydro-dibenzyl-toluene
PEM	proton exchange membrane
PJ	petajoule
PPA	power purchase agreement
PV	photovoltaic
QI	quality infrastructure
R&D	research and development
RED II	Renewable Energy Directive II
SDG	sustainable development goal
SMR	steam methane reforming
TFEC	total final energy consumption
TJ	terajoule
TWh	terrawatt hour
USD	United States dollar
VRE	variable renewable energy

EXECUTIVE SUMMARY

Low carbon hydrogen is key to achieving the goal to reach net-zero emissions by 2050. However, the techno-economic potential to produce low-cost, low-carbon hydrogen is not evenly distributed globally. The regions with the potential to produce it may not align with those that will have high future demand. This could lead to the creation of a new global market that not only trades low-carbon hydrogen but also its derivatives. This may reshape global energy trade and create opportunities for new players, including developing countries.

So far, the focus has been on emission intensity and cost, but this new global market may not only introduce new players - it could also bring about highly complex international value chains. These value chains, especially when involving developing countries, require a comprehensive sustainability approach that encompasses various dimensions. This report provides an analysis covering economic, governance and environmental aspects, as well as potential socio-economic benefits and possible risks for developing countries.

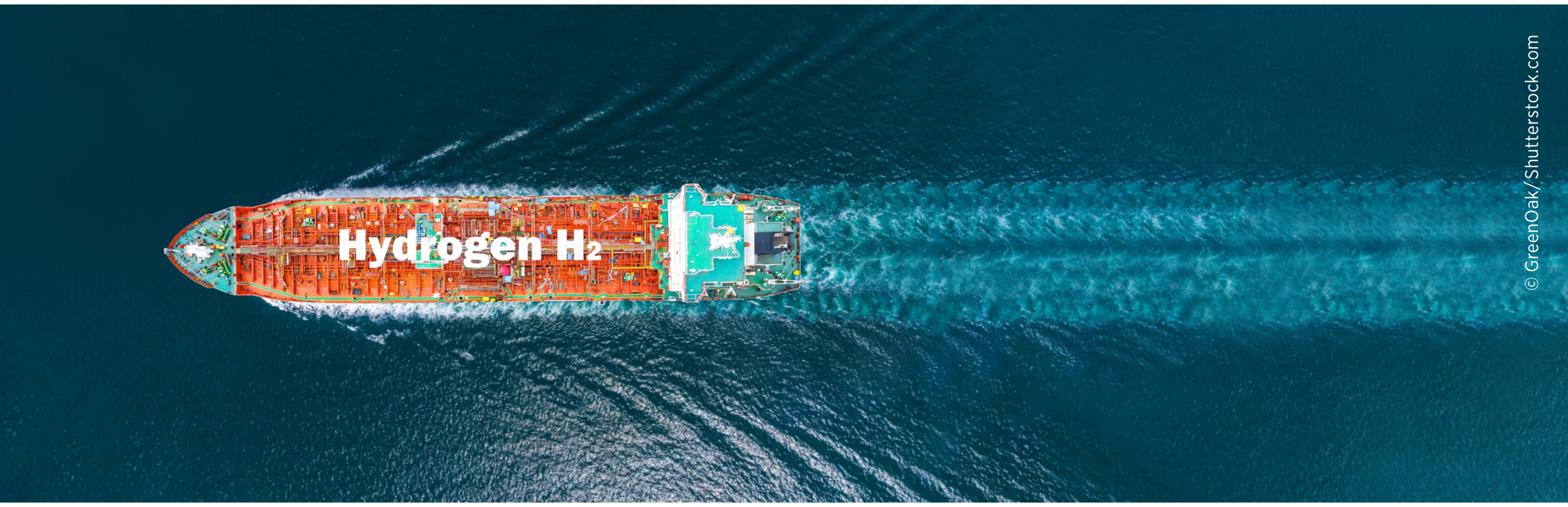
From an economic standpoint, cost-effective production of renewable hydrogen and its derivatives relies on access to cheap renewable energy, as well as access to water and land resources. Future market developments are expected to be significantly influenced by regulations and incentive schemes aimed at promoting global hydrogen production. These incentive schemes, such as the Inflation Reduction Act (IRA) in the United States and the auction system implemented by the European Hydrogen Bank (EHB), have the potential to greatly impact the location, technologies and characteristics of hydrogen production and consumption. They offer financial incentives that support the production of renewable hydrogen with lower emissions. Many of these new incentive schemes not only focus on domestic production but also extend to production in foreign markets.

Renewable-based hydrogen production through electricity is expected to face the least uncertainty in meeting future regulations in importing markets such as the European Union (EU), Japan and South Korea. It is also most likely to benefit from incentive schemes. For example, hydrogen regulations in the EU require all renewable hydrogen to demonstrate that the electricity used in its production is additional, even for volumes produced outside the EU. This means there is a need to focus on continuously adopting renewable energy sources in potential export markets, along with their hydrogen production development.

From a governance and strategy-setting perspective, there have also been significant developments. The Group of Seven (G7) members, as future major hydrogen demand hubs, have been very active in hydrogen policy-making. Additionally, more and more countries, including developing countries, are moving forward with strategy launches and policy developments. At the time of writing, at least 53 countries have launched a hydrogen strategy or roadmap. These vary in their commitment level and priority setting. Compared to G7 members, many developing countries have limited budgets, and project developers face high financing costs. Consequently, their strategies often focus on creating a business-friendly environment through enabling policies. These areas include fiscal incentives, infrastructure development, land permits and skill development.

Countries in the Global South have acknowledged the predicted import demand noted in the national hydrogen strategies of the Global North. In response, they have taken an export-oriented approach to address these markets. For this approach to be successful, however, the projected growth of the global hydrogen market will need to materialise as anticipated.

In terms of environmental impact, renewable hydrogen emits - on average or typically - less greenhouse gases (GHG) than blue hydrogen over its lifecycle. At the same time, when considering hydrogen production for



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export, it is crucial to address the potential for any environmental burdens being transferred to developing countries, if such an offloading of adverse impacts is to be prevented.

When it comes to long-distance transportation of renewable hydrogen and derived products, different carrier options exist, with varying infrastructure requirements and technical considerations. Most likely, there will be a multi-carrier future. The energy balance of these carriers is an essential factor in comparing their advantages and disadvantages. This report analyses four liquid hydrogen carriers from which hydrogen can be extracted at the destination. In many cases, however, it is more appropriate to use carriers directly as fuels or feedstock.

Energy consumption also varies depending on the type of hydrogen carrier. For liquid hydrogen, most energy is consumed in the producer country. For ammonia, liquid organic hydrogen carriers (LOHCs) and methanol, however, significant energy is required in the destination country during the dehydrogenation and cracking processes. This could pose a disadvantage, but it could be mitigated by using ammonia and methanol directly as fuel or chemical feedstocks, bypassing the reconversion step and its associated high energy consumption. In the case of LOHCs, the heat released during the hydrogenation step could also improve the energy and economic balance, if it can be used to help meet industrial, medium-temperature heat demand.

To ensure renewable hydrogen becomes a part of a just and equitable transition, it is important to make sure that developing countries that produce renewable hydrogen – and that may export a share of this – benefit from doing so, both economically and socially.

While the sector has the potential to create many jobs, it can be difficult to determine how many of these jobs will be long-term and of high quality – especially in developing countries. Furthermore, social acceptance and community involvement play crucial roles in the successful implementation of new energy technologies, particularly in the context of large-scale infrastructure development. This is especially relevant for building the supply structures needed to meet the growing demand for renewable hydrogen in the future. Community involvement, however, is often overlooked in this process. By promoting local industrial development, the co-benefits of renewable hydrogen production can be increased. Developing countries could create more sustainable jobs, add long-term value and improve their international competitiveness. They could also reduce the risks associated with the global hydrogen trade by participating in both the upstream and downstream activities of renewable hydrogen production. Therefore, it will be necessary to adopt a comprehensive industrial development policy to address the complexities of this changing landscape in a fair and equitable manner.

RECOMMENDATIONS

This report focuses on value chains that, on the one hand, involve developing countries as hydrogen suppliers, and on the other, future demand hubs, such as the G7. The recommendations address both ends of the value chain. They touch upon the opportunities presented by shaping international hydrogen linkages, but also address potential risks. Detailed descriptions can be found in Chapter 7.

RECOMMENDATION 1:
First movers should lead the way to comprehensive sustainability for green and renewable-based hydrogen value chains

Front runners have a unique opportunity to demonstrate how the renewable hydrogen sector can contribute to a global energy transition that is both fair and sustainable. This applies to local consumption, as well as to renewable hydrogen that is traded over long-distances.

The emissions intensity of the hydrogen value chain is one of the most critical factors in achieving climate goals. Emerging renewable hydrogen and hydrogen-derived commodity value chains should be truly sustainable and equitable. To achieve this, a comprehensive approach that considers more than just emissions intensity is necessary. Such an approach should consider the economic, environmental, social and governance aspects too.

ACTIONS SUGGESTED:

- Work towards a shared understanding of sustainability for renewable hydrogen projects on the strategic and project level. This should include environmental, economic and governance aspects and foster a just and sustainable renewable hydrogen sector.
- Share best practices and lessons learnt from first movers – especially those which have specifically assessed and addressed the impact of hydrogen on sustainable development.

RECOMMENDATION 2:
Mitigating environmental risks and maximising opportunities

Renewable hydrogen and its derivatives play a crucial role in achieving an energy system that aligns with the Paris Agreement's 1.5°C (degree centigrade) goal.

The value chains for such products will differ in shape, depending on the chosen technologies, efficiencies, and whether the final product is consumed locally or transported over long distances. To maximise the contribution of such chains to climate protection goals, it is important to minimise the emissions intensity along their entire length.

Scaling up renewable hydrogen production requires large-scale infrastructure projects, including extensive renewable energy deployment. This can have significant implications for local communities. Land requirements and water consumption are important factors to consider, especially in water-scarce regions.

When shipping over long distances, particularly with ammonia and methanol, it is also critical that they be handled carefully to avoid leaks. Developing quality infrastructure for the production and transportation of renewable hydrogen and its derivatives can help to ensure that they can be traded globally, while still being sustainable and safe. Future demand hubs can lead the way in highlighting the holistic environmental impact of renewable hydrogen production and in developing quality infrastructure for international trade.

ACTIONS SUGGESTED:

- Ensure that hydrogen economy development in exporting regions also drives the wider energy transition. Renewable energy deployments beyond those required to power production facilities – locally and in resource rich areas – should be supported.

- Co-operate at the national level with partner countries and internationally through intergovernmental fora on developing a robust quality infrastructure to ensure the safe use of hydrogen.

- Champion initiatives that emphasise environmental impact, resource efficiency and water management, avoiding the offloading of negative impacts in resource-rich areas.

RECOMMENDATION 3:
Consider the role of hydrogen derivatives in building markets

Hydrogen carriers allow the transport of hydrogen over long-distances from resource-rich countries to future demand centres. Ammonia and methanol are two examples of hydrogen carriers, each coming with different technical implications. Both of these have another role as hydrogen-derived commodities that are chemical feedstocks with potential functions themselves in the energy system.

Future demand hubs could therefore meaningfully support the development of derivative value chains in developing countries. This would be in addition to their historic and existing support for the development of renewable hydrogen projects.

The merit of such an approach is that it bridges two aspects of hydrogen value-chain development discussed in this report. First, that there is an opportunity for front runners such as G7 countries to support local market development of hydrogen and hydrogen-derivative value chains in developing countries; and second, from an efficiency perspective, energy losses can be minimised by building value chains around the direct use of the derived commodities themselves. It is also likely to be more convenient to transport the derivative commodities across long distances than transporting hydrogen itself – for example, from developing country producers to import markets in Europe, Japan and elsewhere.

Therefore, G7 countries should invest in market development, research, development and demonstration activities – as well as capacity building initiatives – which specifically target the derived commodities of ammonia and methanol.

The intent here could be two-fold. First, this support could help to develop efficient commodity export capacity. Second, it could also develop an opportunity to support deep decarbonisation and industrial development by growing production capacity and local use of the commodities in the local markets of developing countries. In their emerging hydrogen strategies, developing countries are increasingly recognising these opportunities. The G7 countries should support these initiatives, while also facilitating the development of future export capacity.

ACTIONS SUGGESTED:

- Invest in market development, research, development and demonstration activities, and capacity building initiatives that specifically target the hydrogen-derived commodities of ammonia and methanol.
- Support local decarbonisation and sustainable industrial development in developing countries, while in parallel facilitating the development of future export capacity.

RECOMMENDATION 4:
Collaborate on local value creation with a focus on developing countries

Many developing countries have the potential to produce significant amounts of renewable energy. This is an opportunity for economic growth and sustainable development. One way to leverage this potential is by producing and exporting renewable hydrogen and its derivatives. This can lead to various co-benefits, such as job creation, increased access to clean energy and the promotion of green industrial development. Achieving these outcomes requires careful planning, however. This includes strategies for the development of a skilled workforce in both the public and private sectors.

Global North countries can enable developing countries by supporting capacity-building that focus on renewable hydrogen technologies and sustainable energy practices. These steps can help equip the workforce of developing countries with the necessary skills to participate effectively in the global hydrogen sector.

By investing in capacity building, risks associated with the ramp-up of green hydrogen production can also be mitigated. This investment can ensure that developing countries can sustainably and equitably harness their renewable energy potential.

ACTIONS SUGGESTED:

- Exchange insights on potential benefits, including assumptions about job creation related to renewable hydrogen and derivates production.
- Invest in capacity building to develop a skilled local workforce in developing countries.

RECOMMENDATION 5:
Promote strategic partnerships at both the global and inter-regional levels

Encouraging the formation of strategic partnerships between potential suppliers of green hydrogen, global demand centres and technology providers is crucial in accelerating the adoption of advanced technologies across the hydrogen and commodity value chains. It is also vital in scaling up production capacities.

Front-runner countries can play a pivotal role in facilitating technology transfer, sharing best practices and leveraging financial and technical resources to support the hydrogen sector in developing countries. Social acceptance and local community involvement remain mostly overlooked, but can significantly contribute to preventing harm and maximising the benefits of renewable hydrogen production.

These strategic alliances are vital for overcoming technical and economic barriers, enabling more rapid deployment of renewable hydrogen projects, and ensuring that the benefits of the hydrogen transition are shared widely. Further formats for South-South co-operation can support exchanges between developing countries that face similar challenges and barriers when developing their hydrogen sectors

ACTIONS SUGGESTED:

- Facilitate knowledge transfer and the sharing of best practices, *e.g.* on social acceptance and community involvement. Such sharing and transfer should also take place in supporting the hydrogen sector in developing countries. Inter-regional co-operation between developing countries facing similar challenges should also be supported.

1. INTRODUCTION

Recent energy crises, geopolitical challenges and climate disasters have once again shown the fragility of the world's energy infrastructure and flow.

Indeed, the transportation and trade of energy – particularly renewable energy – is increasingly becoming one of the greatest challenges on the path towards decarbonisation, affordability and supply security.

Creating robust and sustainable international value chains is therefore a key priority. The Group of 7 (G7) has acknowledged these challenges and has leveraged multilateral collaboration in an effort to effectively address them.

Reducing greenhouse gas (GHG) emissions is a key focus for the group, with renewable hydrogen playing a crucial role as an enabler in achieving that goal (G7, 2023).

Under Japan's G7 presidency, the group recommitted itself to accelerating the deployment of low-carbon hydrogen, both domestically and on a global scale. It also recommitted to doing this by developing rules-based, transparent global markets and supply chains. This builds upon the G7 Hydrogen Action Plan, launched in 2022, and highlights the significance of mutually beneficial collaboration between suppliers and consumers of renewable hydrogen and its derivatives.

1.1 DEVELOPING SUSTAINABLE INTERNATIONAL HYDROGEN VALUE CHAINS

Future renewable-based hydrogen and derivatives production will have the highest economic potential in areas with high renewable energy potential, good water and land availability, and low finance costs. Consideration of these physical properties, however, may not lead to a recommendation for production at scale in close proximity to anticipated demand centres. International trade can help match these potential supply and demand locations. This could lead to new value chains spanning the globe. These may include the manufacturing of equipment, semi-finished products and the production of hydrogen and its derivatives in resource-rich countries. Those commodities would then be transported via ships and pipelines before being used in hard-to-abate sectors elsewhere. These value chains will be complex and involve a large number of stakeholders.

Renewable-based hydrogen is therefore not only an option for the replacement of fossil-based hydrogen, the type that makes up the largest share of hydrogen production today. It is also an enabler for decarbonising hard-to-abate sectors in highly industrialised countries. At the same time, it opens up opportunities for Global South countries with low-cost hydrogen potential to develop new green industries which also have export potential.

Achieving all this will require substantial investment in infrastructure. To boost the development of renewable hydrogen production in regions better suited to cost-effective production, some future hydrogen-importing countries have already set up incentive schemes. Nevertheless, it is crucial that these developments are environmentally sustainable and socially just. They must consider the impact on the local environment, the energy and water supply, and on food security; they must also take into account social factors which may be impacted by new projects, such as job creation and community involvement.

This report assesses some of those aspects and shows that renewable-based hydrogen production and new value chains require a comprehensive approach to ensure long-term viability and success. This report focuses specifically on international value chains that involve future demand centres of renewable hydrogen and its derivates, such as East Asia and Europe, as well as future production areas with high renewable energy potential. The latter include African and Gulf Cooperation Council (GCC) countries.

It is essential to adopt a holistic and comprehensive approach to these value chains for the reasons listed below:

- **The complexity of long-distance value chains**
  International hydrogen value chains can be highly complex, especially when they span long distances. Managing and co-ordinating the various stages of the value chain across different geographical locations requires careful consideration and strategic planning.

- **Collaboration among diverse stakeholders**
  International hydrogen value chains require collaboration and co-ordination between a variety of stakeholders (such as governments, industries, research institutions and local communities) to operate sustainably in the long run.

- **Social acceptance**
  Social acceptance and community involvement are vital factors, especially in the context of large-scale infrastructure development. This also applies to building up supply structures to meet future green hydrogen demands. Learning from the best practices of others can help address these challenges. This does not only apply to international co-operation between suppliers and future demand centres. Co-operation and information exchange between developing countries on overlapping areas of interest can also help to address similar challenges.

- **Long-term sustainability and success**
  International renewable-based hydrogen value chains should aim to establish sustainable practices and pave the way towards long-term success. This objective requires a comprehensive examination of all aspects of the value chain. Every step must be scrutinised – from production and transportation to distribution and utilisation – in order to identify potential bottlenecks, optimise efficiency and maximise the environmental and economic benefits. Achieving long-term sustainability requires a pro-active and adaptive approach that responds to changing market dynamics and evolving technological advances.

Identifying the right framework and criteria for assessing international value chains can be challenging, however. This is due to the many aspects that need to be considered, some of which are not always easy to measure.

One approach is to adapt existing sustainability framework concepts to renewable hydrogen and select relevant dimensions (PtX Hub, 2021; UN, 2015). The country-specific context also matters. While one country may experience water scarcity, it might have enough land availability and renewable energy potential to realise large-scale renewable hydrogen projects. In contrast, another country may possess all the necessary geographical conditions, but struggle with political instability and access to finance.

1.2 SCOPE OF THE REPORT

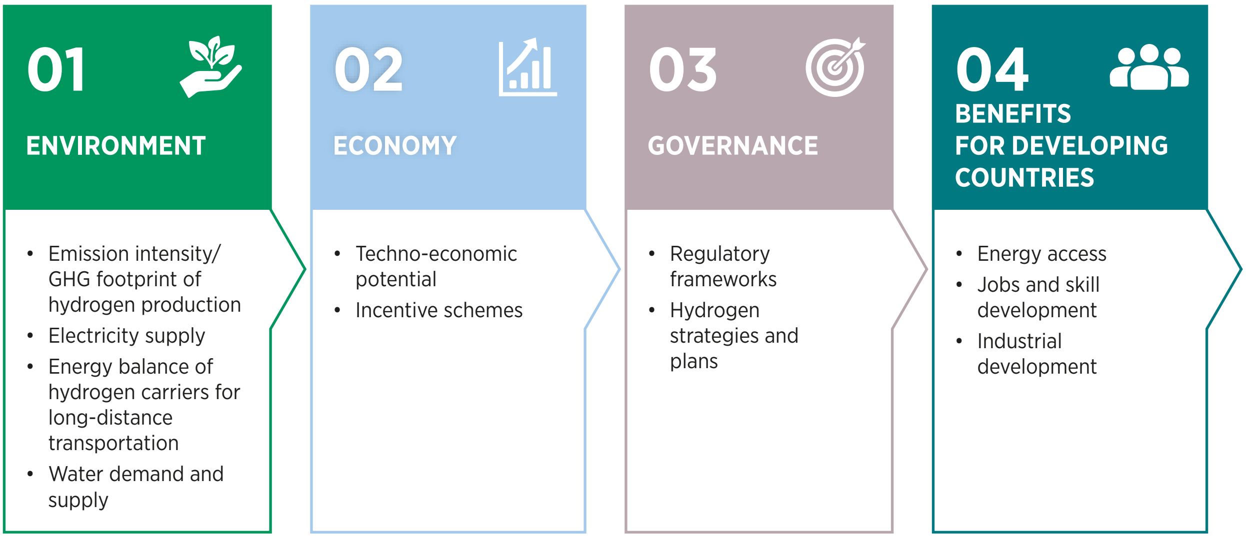
This report explores the renewable hydrogen value chains between remote and developing countries on the one hand, and future demand centres, on the other. The report takes a broad sustainability approach that goes beyond the emissions intensity of hydrogen production and includes aspects such as governance, economics and the potential socio-economic benefits for developing countries. The report then expands on the essential topics concerning international hydrogen value chains. It also adds analysis and connects these topics with recent developments in the fast-paced, renewable hydrogen world.

This report focuses on four inter-related dimensions that collectively contribute to comprehending international value chains. It should be noted, too, that modifications to one dimension can also impact the others. In addition, the report does not address all aspects that might be relevant for a comprehensive sustainability approach, but adds analysis to key topics that need to be considered. Figure 1 visually represents the dimensions and topics covered by this report.

International value chains may become more robust and equitable when they bring benefits to both the exporting and importing countries. It is evident that renewable hydrogen and its derivatives have the potential to play a significant role in decarbonising importing regions. It is crucial to ensure, however, that their production also creates substantial added-value for exporting countries. Yet, the extent to which an exporting country benefits economically from hydrogen production is yet to be fully defined. Local benefits will likely depend on related industries, and/or the distribution of the profits generated by hydrogen throughout the economy. This issue is further complicated by the fact that developing countries often need infrastructure, materials, skilled workers and technology from other countries. A balance is needed between promoting imports, respecting the autonomy of the local economy and avoiding dependencies that could have negative effects on the exporting countries' economies and societies (Ansari and Pepe, 2023).

This report begins by examining the key drivers of the renewable hydrogen trade. These include the role of renewable hydrogen in the global energy transition and the potential differences in low-cost renewable hydrogen production around the globe. The report then delves into the emissions intensities of different hydrogen production pathways, shedding light on the primary emissions factor for electrolysis-based hydrogen production: electricity supply.

Figure 1 Selected dimensions and aspects of sustainable international hydrogen value chains



The report also analyses how new regulations and incentive schemes may affect the production and consumption of specific hydrogen production pathways – not only within the countries that introduced those frameworks, but also globally. The report further explores one environmental aspect that is particularly relevant to hydrogen production in desert and water-scarce regions: the water demands of hydrogen production and the potential local impact on available water resources.

Next, the report examines one of the key enablers for international long-distance hydrogen transport: hydrogen carriers. In addition to their technical and infrastructure requirements, the report analyses the energy balance of different carriers and how this may affect value-chain creation.

The report then investigates the potential co-benefits of renewable hydrogen production for developing countries. Besides sharing insights into the energy access question, the potential for industrial development and job creation, the report also sheds light on the uncertainties surrounding potential co-benefits for developing countries.

Finally, the report expands IRENA's existing analysis on the hydrogen policy-making of G7 countries. It does this by examining the hydrogen strategies of selected Global South countries, each of which comes with different preconditions. The report offers insights into the strategic priority-setting of future renewable hydrogen suppliers. It does this in order to gain a more comprehensive overview of the emerging international structure and to see whether the plans of potential supplier countries and future demand centres are looking in the same direction.

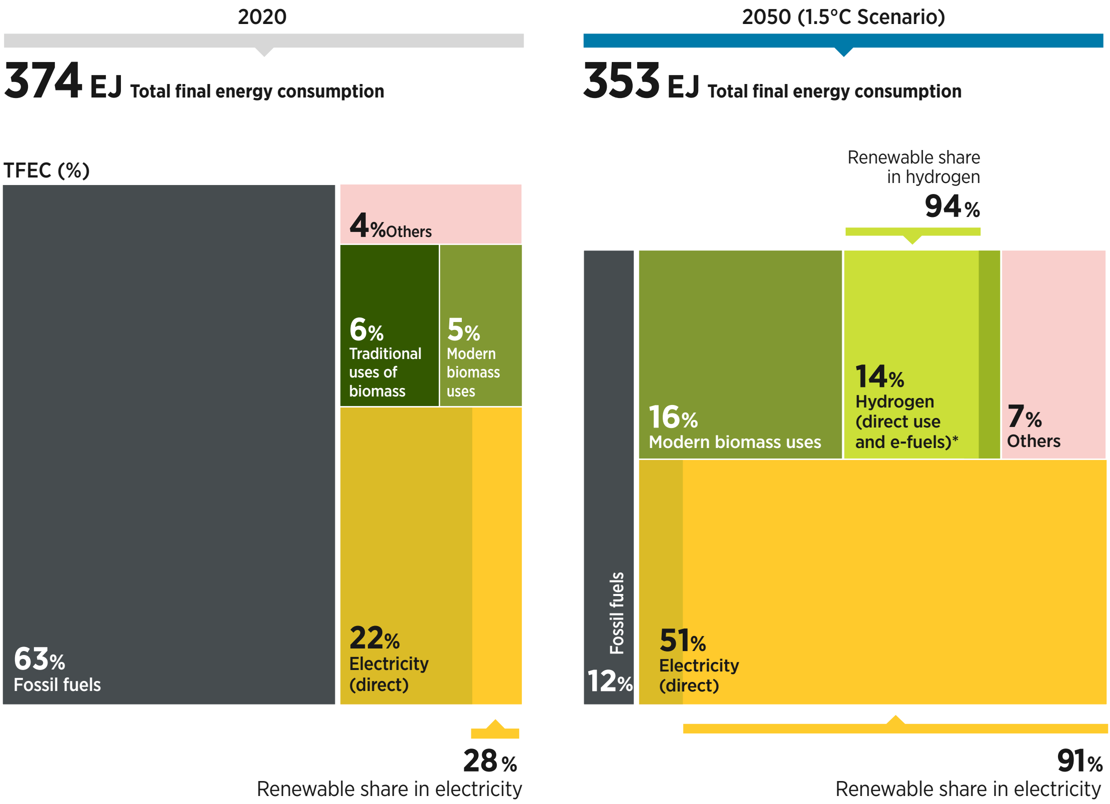
2. HYDROGEN PRODUCTION AND DEMAND: NOW AND IN THE FUTURE

2.1 CURRENT AND FUTURE GLOBAL HYDROGEN DEMAND AND ITS IMPLICATIONS FOR TRADE

G7 members have committed themselves to reaching net-zero GHG emissions by 2050 at the latest. This requires a comprehensive transformation of the power sector and of end-use sectors, including transport, industry and buildings. Their decarbonisation requires a bundle of various sector and process-specific measures and strategies.

The primary drivers of the energy system's decarbonisation are: enhanced energy efficiency, accelerated deployment of renewable energies, and direct electrification (IRENA, 2022a). In a net-zero scenario, electricity becomes the main energy carrier, accounting for more than half of global final energy consumption (IRENA, 2023a).

Figure 2 Breakdown of total final energy consumption (TFEC) by energy carrier: IRENA's 1.5°C Scenario



Source: IRENA (2023a).

There is a need, however, for a solution that can close the decarbonisation gap that occurs when the direct use of renewable electricity or fuel is not a technically viable or cost-effective solution.

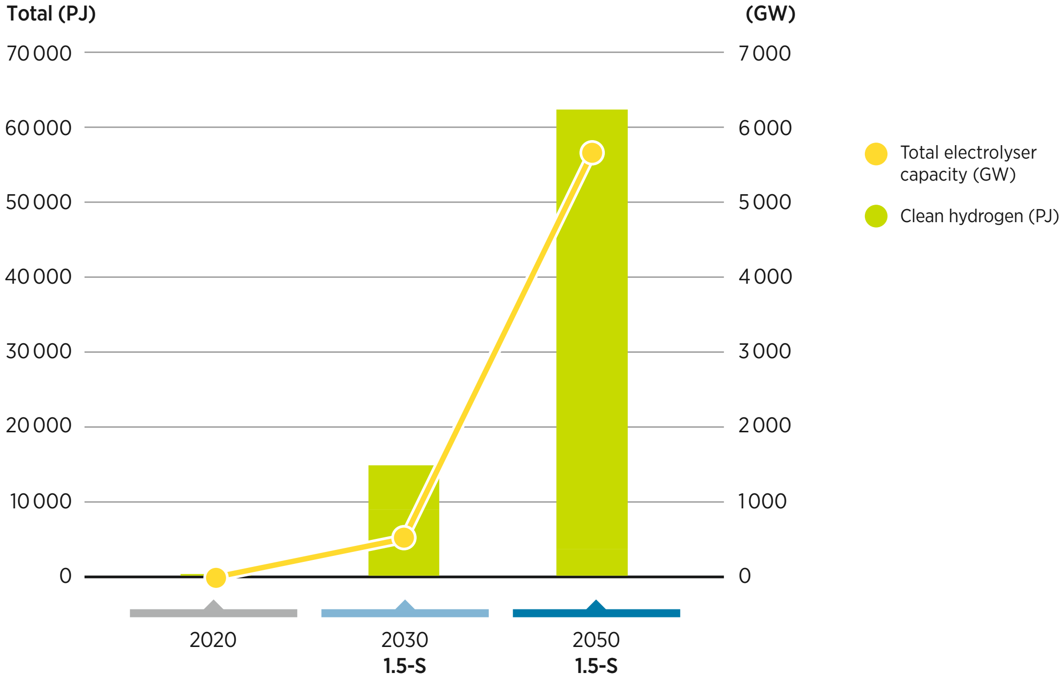
Hydrogen might become the link between renewable electricity generation and those hard-to-abate sectors (IRENA, 2022a). Renewable electricity can be converted to hydrogen via electrolysis, increasing renewable energy utilisation in end-uses. According to IRENA's 1.5°C Scenario, hydrogen and hydrogen derivatives will represent up to 14% of total final energy consumption by 2050 (IRENA, 2023a). Hydrogen and its derivatives will be essential in decarbonising important industrial goods, such as ammonia and steel. Additionally, it may be essential in the transportation sector for international shipping and aviation.

Today, the global production of hydrogen, which amounted to around 95 million tonnes (Mt) in 2022, is primarily derived from fossil fuels, with around a quarter of this coming from coal and the remainder from natural gas (IEA *et al.*, 2023). This fossil-based hydrogen is predominantly used in industries such as fertiliser production, oil refining, iron refining and other industrial processes. In a net-zero world, renewable hydrogen replaces grey hydrogen. In addition, hydrogen and its derivatives can be used in new applications, such as e-fuels.

As a result, in the 1.5°C scenario, total hydrogen production is projected to increase by over five times by 2050 in order to meet 14% of final energy demand. For this, the cumulative installed green hydrogen electrolyser capacity has to grow from a negligible amount today to some 428 gigawatts (GW) by 2030 and 5 722 GW by 2050, when a wide distribution of hydrogen production is envisaged across the world, as shown in Figure 3 (IRENA, 2023a).

Considering that 94% of hydrogen and its derivatives should be sourced from renewable sources, the electricity needed for green hydrogen in 2050 is comparable with current global electricity consumption (IRENA, 2022a; 2022b).

Figure 3 Global clean hydrogen supply in 2020, 2030 and 2050



Note: 1.5-S = 1.5°C Scenario; GW = gigawatt; PJ = petajoule
Source: (IRENA, 2023a).

Against the backdrop of these numbers, it is not only necessary to rapidly scale up the production of renewable hydrogen and its derivatives, but also crucial to carefully consider their application. In a net-zero world, energy consumption and capacity deployment will have to be carefully managed and balanced.

Although hydrogen can be utilised across the entire energy system, strategic decision-making is needed to determine the most efficient and cost-effective uses. Figure 4 shows the renewable hydrogen priority setting suggested by IRENA (IRENA, 2022c). A G7 communique recently acknowledged that “low-carbon and renewable hydrogen and its derivatives such as ammonia should be developed and used where they are impactful as effective emission reduction tools to advance decarbonisation across sectors and industries, notably in hard-to-abate sectors in industry and transportation” (G7, 2023).

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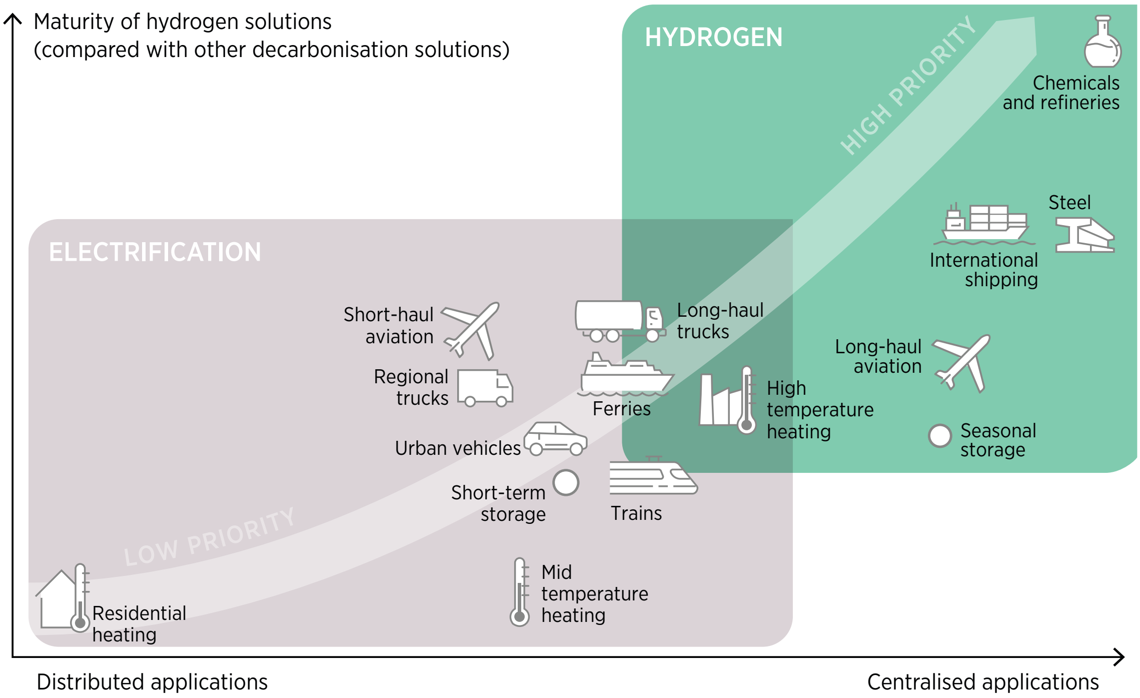
Figure 4 Renewable hydrogen priority setting



Note: On the x-axis, the end uses are placed according to the estimated average daily hydrogen demand for industry, refuelling stations and combustion devices, with a power relationship. On the y-axis the end uses are placed according to the differences between the technological readiness levels of hydrogen-based vs electricity-based solutions. This is not a static picture and priorities could change over time according to advances in technologies.

Source: (IRENA, 2022a).

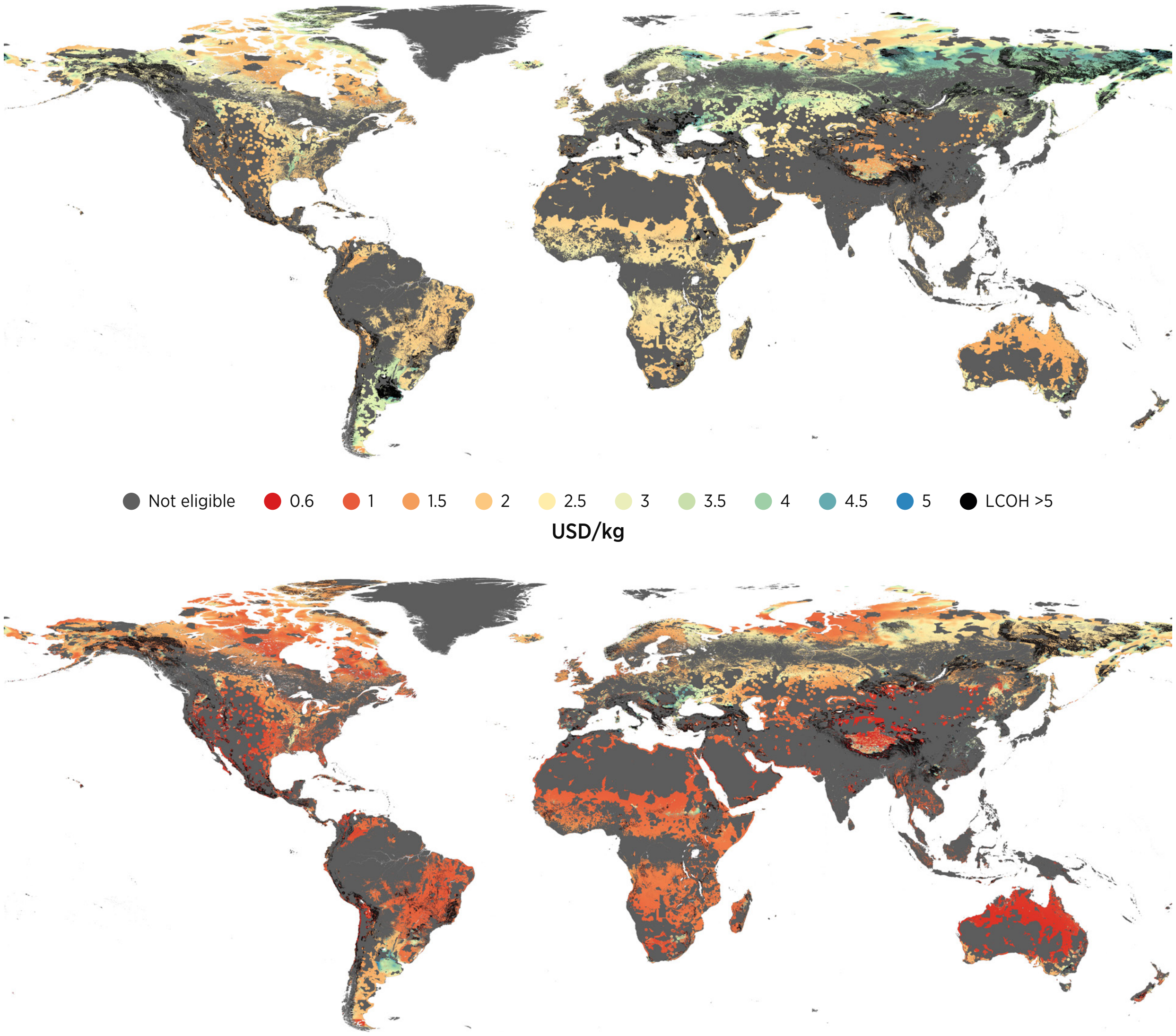
2.2 POTENTIAL FOR GLOBAL RENEWABLE HYDROGEN PRODUCTION

Access to abundant, affordable renewable energy is a crucial prerequisite for large-scale production of renewable hydrogen and its derivatives.

Hydrogen can be produced most cost-effectively in locations with the best renewable energy resources and low project development costs (IRENA, 2019). Therefore, parts of the production of renewable hydrogen and its derivatives will most likely take place in areas with a high potential for renewable energy, ensuring a reliable supply.

Additional factors influencing development include land availability, water access and the infrastructure options necessary for transporting and potentially exporting energy to meet the needs of significant demand centres. Renewable hydrogen and its derivatives offer the unique opportunity to produce, store and transport renewable energy from areas with substantial renewable energy potential to regions with significant hydrogen demand, but inadequate renewable energy supply (IRENA, 2022a). The technical global potential for renewable hydrogen is expected to be almost 20 times estimated global primary energy demand by 2050. The potential for green hydrogen, however, is not a fixed value. It depends on the balance between the cost and the available renewable capacity, which can change over time (IRENA, 2022d).

Figure 5 Global levelised cost of hydrogen (LCOH) in 2030 (top) and 2050 (bottom)



Notes: USD = United States dollars; kg = kilogramme. Assumptions for capital expenditure are as follows: for solar photovoltaic (PV), between USD 270 per kilowatt (kW) and USD 690/kW in 2030 and USD 225/kW and USD 455/kW in 2050; for onshore wind, between USD 790/kW and USD 1435/kW in 2030 and USD 700/kW and USD 1070/kW in 2050; for offshore wind, between USD 1730/kW and USD 2700/kW in 2030 and USD 1275/kW and USD 1745/kW in 2050; for electrolyser, between USD 380/kW in 2030 and USD 130/kW in 2050. The weighted-average cost of capital is set at 2020 values without technology risks across regions. Land availability considers several exclusion zones (protected areas, forests, permanent wetlands, croplands, urban areas, a slope of 5% for PV and 20% for onshore wind, population density, and water availability). Refer to IRENA (2022c) for more details.

Source: (IRENA, 2022a).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

According to IRENA's techno-economic optimisation model, in a 1.5°C scenario, approximately 25% of global hydrogen demand – equivalent to 18.4 exajoules (EJ)/year – will be traded internationally by 2050. Out of this, around 55% is expected to be transported as pure hydrogen through retrofitted natural gas pipelines, with a focus on two regional markets: Europe (accounting for 85% of this share) and Latin America. The remaining 45% of the internationally traded hydrogen is expected to be shipped, primarily in the form of ammonia, and used directly without being converted back into hydrogen.[1] Trade in commodities derived

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[1] *As these numbers are based on a cost-optimising model, they do not consider further deciding factors, such as political stability, energy security and economic development, among others.*

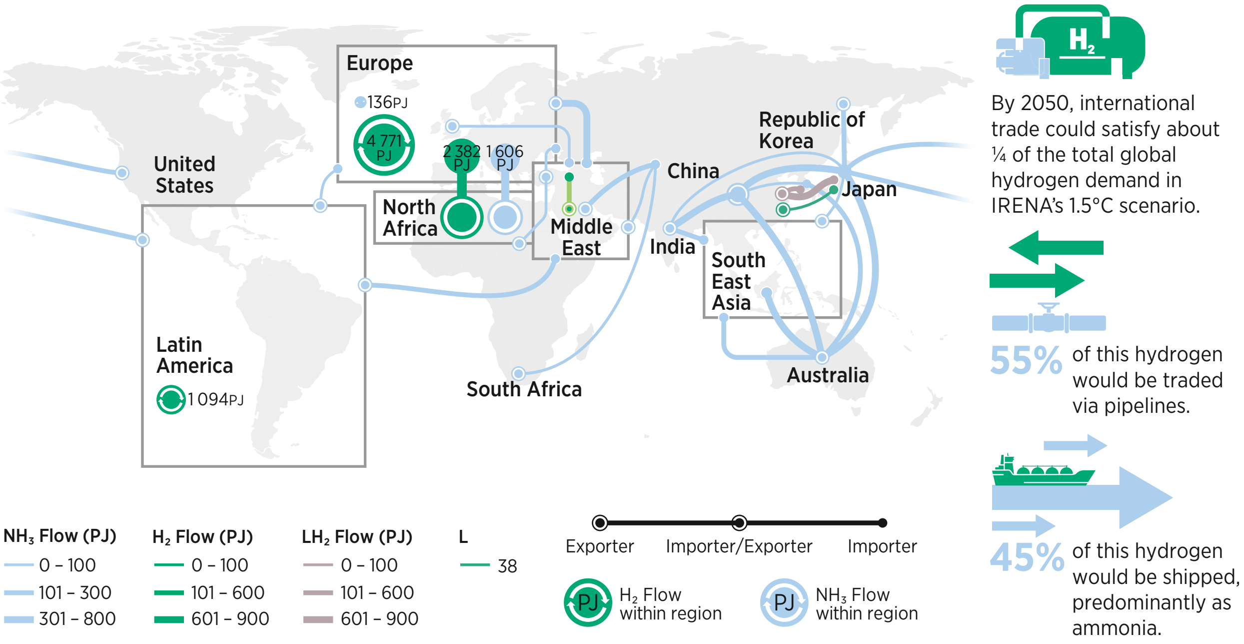
from renewable hydrogen will become more important than trade in pure hydrogen itself. In addition, there may not be a single primary derivative carrier, but rather several different modes. This will result in renewable hydrogen value chains of varying shapes, in terms of infrastructure and traded products. This may lead to a multi-derivative future (see Chapter 4).

With transportation costs being relatively low, even minor variations in hydrogen production costs can potentially drive relocations and trade. This could further result in increased competition among potential suppliers. This is because in contrast to today's oil markets, more countries have access to the primary feedstocks: renewable energy and water. Additionally, three markets – Europe, Japan and South Korea – are positioning themselves to become major hydrogen importers.

This uneven distribution of buyers and potential suppliers can result in an oligopsony, where a few large buyers establish the rules and regulations for many potential exporters. That is why it is essential to shape those new trade relations as justly as possible and ensure that the local added value created is not limited to a temporary boost for the construction industry (Altenburg *et al.*, 2023).

Based on current trade volumes, trade in hydrogen (including all production methods) is almost two orders of magnitude smaller than the trade in ammonia and methanol. Trade in hydrogen, methanol and ammonia, however, has increased significantly since 2020 (see Figure 7). Over the past two years, global imports of ammonia and methanol have shown strong growth, reaching USD 17.5 billion and USD 14.1 billion in 2022. As mentioned earlier, the expansion of green hydrogen production is expected to lead to an increase in hydrogen trade from the current low levels.

Figure 6 Green hydrogen and its derivatives: Trade projection by 2050 in the 1.5°C scenario



By 2050, international trade could satisfy about ¼ of the total global hydrogen demand in IRENA's 1.5°C scenario.

55% of this hydrogen would be traded via pipelines.

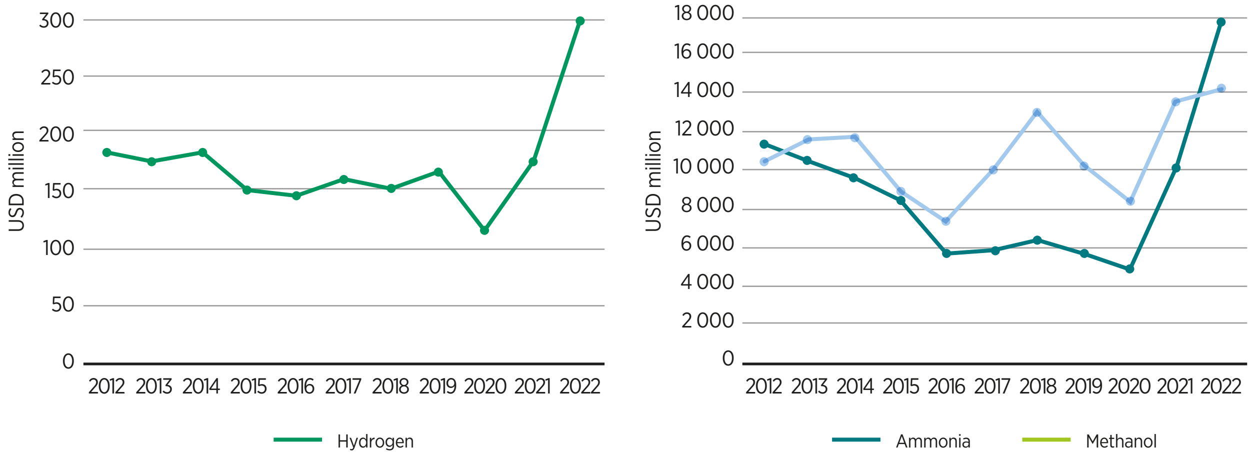
45% of this hydrogen would be shipped, predominantly as ammonia.

Notes: PJ = petajoules; NH_3 = ammonia; H_2 = hydrogen.

Source: (IRENA and WTO, 2023).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Figure 7 Global imports of hydrogen and its derivatives, ammonia and methanol



Note: Trade data do not allow for the differentiation of hydrogen based on the energy used in production.
Source: (IRENA and WTO, 2023).

3. ENVIRONMENTAL ASPECTS OF RENEWABLE HYDROGEN PRODUCTION

The primary motivator behind the push for hydrogen – and renewable hydrogen in particular – is its potential in helping achieve climate protection goals. It can do this by replacing fossil fuels, especially in hard-to-decarbonise sectors.

Countries and groupings like the European Union (EU) have defined what they consider to be “renewable hydrogen”. This has been a significant step for both domestic producers and importers into the EU, which has established the Carbon Border Adjustment Mechanism (CBAM) to prevent carbon leakage. This definition is additionally relevant for producers in helping them qualify for and benefit from mechanisms such as European Hydrogen Bank (EHB) auctions.

This is not the whole story, however, as the environmental impact of the large-scale infrastructure projects required to scale up hydrogen production will have a variety of effects. These must also be taken into account in assessing the local impact of such projects.

This chapter explores the environmental impacts of hydrogen production and highlights the key factors in these impacts. It focuses on the drivers of the emissions intensities of different hydrogen production methods, with an emphasis on green hydrogen production and the significance of electricity supply options in this regard. The chapter does not include hydrogen-derived products. Furthermore, the chapter explores the water demand of hydrogen production and its potential impact on local water supply and scarcity.

3.1 EMISSION INTENSITY FACTORS FOR HYDROGEN PRODUCTION

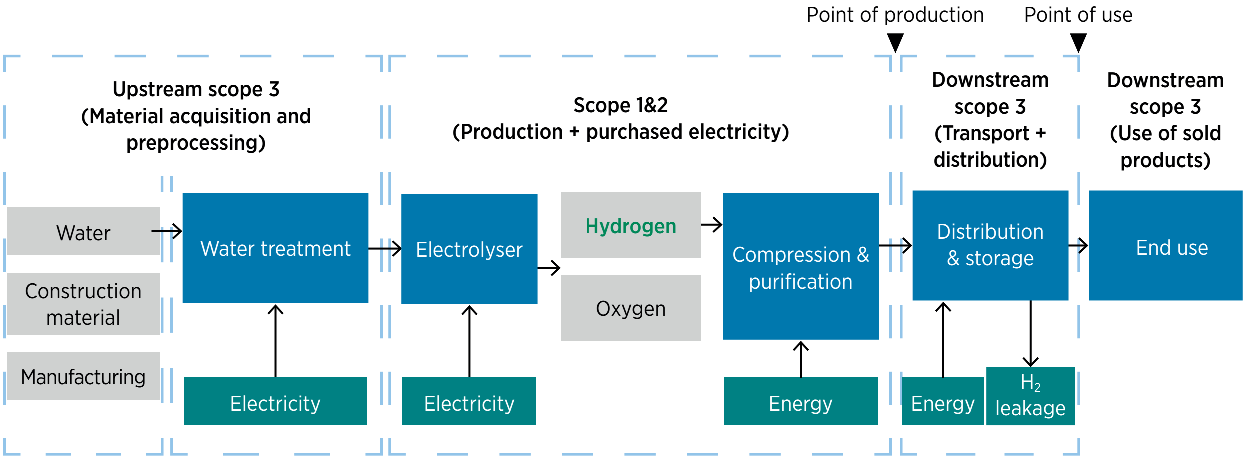
The sustainability of hydrogen and its value chain depends primarily on its emissions intensity. The lower the emissions intensity, the greater the contribution to achieving climate protection goals.

With the growing interest in hydrogen, a colour code (green, blue and grey hydrogen) has generally been adopted in order to differentiate hydrogen production pathways. The “clean” or “low-emissions” hydrogen monikers are often used to describe all production pathways that produce lower emissions compared to the traditional fossil fuel-based processes. However, these are not strictly defined terms (Mills, 2022). While the colour coding indicates the production pathway itself, it does not reflect the emissions ranges within each pathway. A thorough examination should therefore look at the factors that come into play when looking at emissions intensity, as well as asking which production pathway performs best, and how to calculate all this.

A widely used method to calculate emissions intensity is life cycle assessment (LCA, see Box 1). The International Organisation for Standardisation (ISO) harmonises LCA methodologies, as it is crucial that there is a single method to ensure transparency for business owners, policy makers and certification scheme holders. The ISO methodology for GHG emissions assessment for hydrogen on an LCA basis was unveiled at COP28 in Dubai (ISO, 2023) and marks an important step towards comparability, especially for certification purposes.

Figure 8 shows the renewable hydrogen supply chain and tags the carbon dioxide (CO_2) emission scopes along its length. This has been done based on the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) methodology (IPHE, 2022). This methodology was a key input in the standardisation work of the ISO.

Figure 8 Renewable-based hydrogen value chain and CO_2 emission scopes



Box 1 LCA as a tool for emissions accounting

LCA is a tool used for assessing and comparing the environmental impacts of different production pathways. LCAs investigate all the stages of a product's life cycle, from raw material extraction and material processing to manufacturing, distribution, use and end-of-life.

An LCA consists of four phases: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. While an LCA can provide a comprehensive evaluation of a product's environmental impact, its scope may, however, vary. Three varieties of LCA are therefore outlined below:

- A **cradle-to-gate** system boundary, which measures impacts from the point of raw material extraction to the point when the product is ready to leave the manufacturer's gates.
- A **cradle-to-grave** system boundary, which takes emissions from the point of raw material extraction to the point when the product has finished its useful life (EEA, n.d.).
- A **cradle-to-cradle** system boundary, which goes one step further and considers a circular economy. Impacts are measured from the point of raw material extraction to the point when the product is recycled or reused and starts a new life cycle (TÜV NORD, 2022).

There are multiple LCA-studies available for different hydrogen production pathways, each covering different scopes. The results of these assessments vary based on factors such as the specific product being evaluated, input variables, and the chosen system boundary. The differences in the methodological aspects of LCA studies result in discrepancies between studies, particularly when assessing rather complex value chains (Weidner *et al.*, 2023).

Box 2

Relevance for certification

Certification plays a pivotal role in the burgeoning trade in hydrogen and its derivatives, serving as a guarantee of compliance with diverse standards and regulations. These certificates are crucial for ensuring that products meet sustainability benchmarks. They are also key in ensuring emissions intensity and comprehensive environmental, social and governance (ESG) criteria are encompassed, thereby guiding consumer choices and underpinning the mechanics of global trade.

Despite the existence of multiple hydrogen certification systems, however, none are currently equipped for the complexities of international trade. Significant gaps remain in the accurate assessment of carbon footprints and adherence to ESG standards (IRENA, 2023b). The newly published ISO methodology helps to make products comparable and accurately assess whether they meet the criteria of different certification schemes.

Although a harmonisation of certification is desirable, mutual recognition can already enable trade flows. At COP28, more than 30 countries signed a declaration of intent to work towards mutual recognition of their hydrogen certification schemes – an important step towards facilitating the international hydrogen trade (COP28 UAE, 2023).

Besides direct emissions during hydrogen production, there are also indirect emissions linked to the production, conversion and transportation of essential input factors. Figure 9 displays the different hydrogen production pathways and the major factors for emission intensity associated with each of them.

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Figure 9 Overview of emissions intensity factors for different hydrogen production pathways

	GREY HYDROGEN	**BLUE HYDROGEN**	**GREEN HYDROGEN**
Process	Reforming or gasification	Reforming or gasification with carbon capture	Electrolysis
Energy source	Fossil fuels	Fossil fuels	Renewable electricity
Factors for emission intensity	**Natural gas reforming** • Emissions related to the manufacturing of gas turbines and other equipment. • More than 75% of upstream and midstream emissions are **methane emissions** from venting and leakages during gas production and transport. • Direct emissions from burning natural gas: chosen reforming method, with steam methane reforming (SMR) being the most widely used.[2] **Coal gasification** Direct emissions from production plant plus emissions from coal mining and processing. Less than 20% of emissions come from coal mining, processing and transport, while more than 80% are direct emissions from the production plant.	• Same as reforming or gasification. • Emissions related to the production of carbon capture and storage (CCS) plants. • Emissions related to natural gas consumption of CCS and related fugitive emissions. • Chosen carbon capture technology/ carbon capture rate/placement of capture in production process.	• Upstream and midstream emissions of electricity generation (*e.g.* emissions occurring in the manufacturing of panels, windmills etc. and sourcing electricity from the grid or from additional capacities). • Efficiency of chosen electrolyser technology (*e.g.* Alkaline/PEM/SOEC/ AEM).

Note: PEM = polymer electrolyte membrane; SOEC = solid oxide electrolyser cell; AEM = anion exchange membrane.
Sources: (de Kleijne *et al.*, 2022; Howarth and Jacobson, 2021; IEA, 2023a; IRENA, 2022e; Matia *et al.*, 2022).

Grey hydrogen has the highest emissions intensity among all hydrogen production pathways (CICE, 2023; de Kleijne *et al.*, 2022; Kolodziejczyk, 2023; Mills, 2022). Blue hydrogen can partially mitigate emissions through carbon capture, but it does come with the potential risks associated with methane leakages. Carbon capture rates vary and might increase over time, but will most likely not reach 100% very soon (Matia *et al.*, 2022). Furthermore, significant uncertainties remain regarding GHG emissions from the production of blue hydrogen. These emissions could be higher than is often assumed, particularly due to increased use of natural gas to power carbon capture and the related fugitive methane emissions. Howarth and Jacobson (Howarth and Jacobson, 2021) estimated that for their default assumptions,[3] GHG emissions for blue hydrogen are only 9%-12% lower than for grey hydrogen. Figure 10 displays further assessments of emission ranges for grey and blue hydrogen production. The sources include two different carbon capture rates – one at 56% and one more optimistically at 90%. A further study (Yan *et al.*, 2022) provides a well-to-gate estimation based on the GREET2021 model including fugitive emissions, while another (Longden *et al.*, 2021) also includes fugitive emissions. The emission variation results from the natural differences in the fossil fuel carbon content, estimated from Intergovernmental Panel on Climate Change (IPCC) default emission factors.

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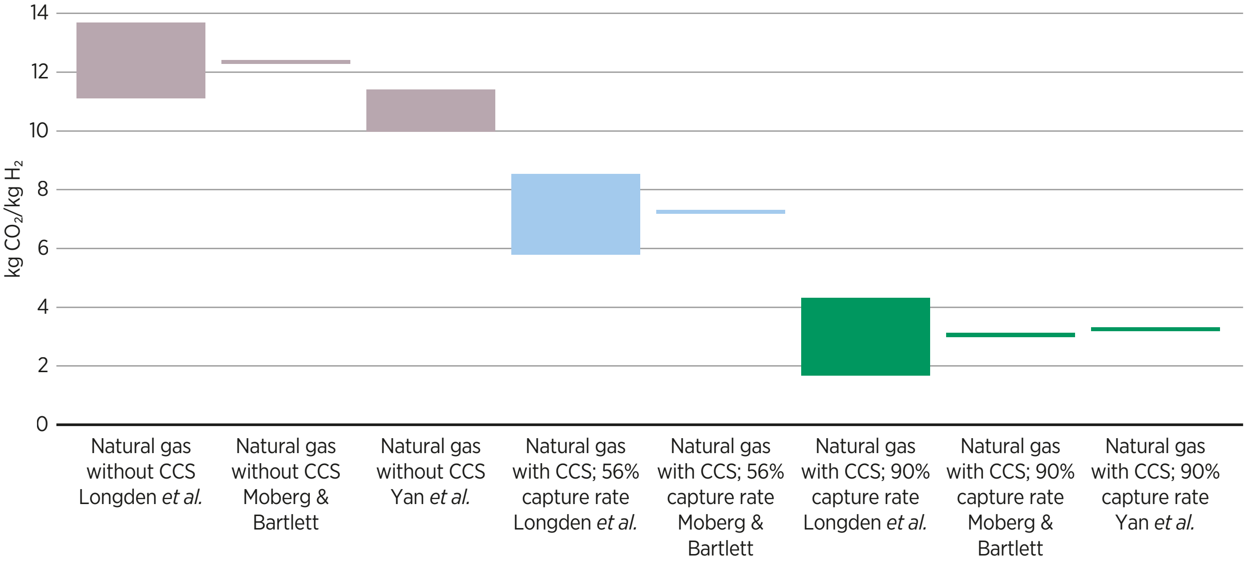
[2] *The SMR process is one in which methane is converted into CO_2 and hydrogen and the energy used to generate the heat and high pressure needed for the SMR process.*

[3] *Standard assumptions are a 3.5% emissions rate of methane from natural gas and a 20-year global warming potential. Captured CO_2 is assumed to be stored indefinitely, which is also an optimistic and yet-to-be-proven assumption.*

Figure 10 Emissions intensity for the production of hydrogen (kg CO_2 per kg H_2)



Note: CCS = Carbon, capture and storage.

Sources: (Longden *et al.*, 2021; Moberg and Bartlett, 2022; Yan *et al.*, 2022).

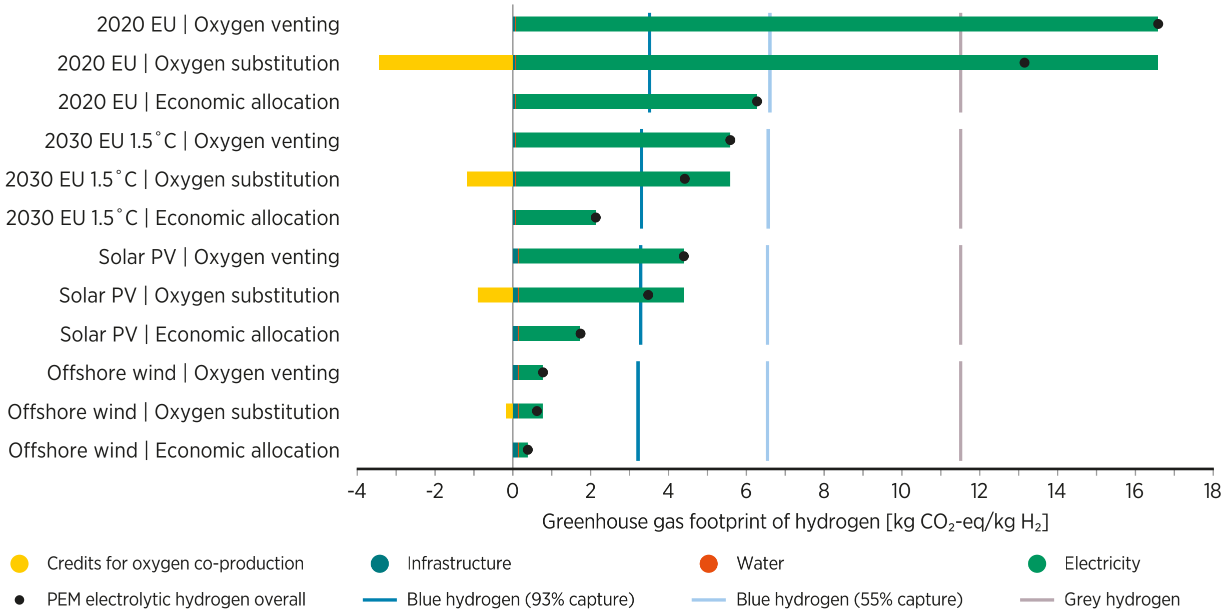
3.2 ELECTRICITY SUPPLY OPTIONS FOR ELECTROLYSIS-BASED HYDROGEN PRODUCTION

The process of hydrogen production through water electrolysis is entirely carbon-neutral, since its inputs (electricity and water) and outputs (hydrogen and oxygen) are free from carbon. As Figure 9 indicated, the most decisive input factor is the electricity supply. Using renewable electricity ensures that hydrogen electrolysis is carbon-free, with the only carbon emissions originating from the materials required for power generation and electrolysis (Mills, 2022).

Figure 11 illustrates the GHG footprint of hydrogen produced in the EU using various renewable sources (wind or solar) and both current and projected average grid electricity. The figure indicates the following:

- Hydrogen produced from renewable electricity exhibits a lower emissions intensity compared to blue hydrogen. This holds true in most scenarios, even when considering blue hydrogen production at the substantial carbon capture rate of 93%.
- The composition of the grid mix significantly influences the emissions intensity of electrolysis-based hydrogen production.
- Transitioning to a greener grid will result in the production of hydrogen with a reduced emissions footprint.

Figure 11 GHG footprint of hydrogen produced with different electricity sources; and current and future average grid electricity produced via PEM electrolysis



Note: The greenhouse gas GHG footprint of PEM electrolytic hydrogen for different electricity sources and multi-functionality approaches is in kg CO_2 equivalent (kgCO_2eq) per kg of hydrogen. The benchmarks for grey and blue hydrogen (the latter with a CO_2 capture rate of 55% or 93%) are based on (Bauer *et al.*, 2022) and were harmonised for each electricity source. Further details on assumptions and data input derived from (De Kleijne *et al.*, 2022).

Source: (de Kleijne *et al.*, 2022).

Using electricity from the grid comes with a set of challenges. The emissions intensity of hydrogen production can vary significantly based on the electricity supply mix of the grid. By assessing the electricity grid emission intensity, it becomes easier to determine the suitability and environmental benefits of utilising grid electricity for hydrogen production in a specific environment. Even though electricity grids today are not net zero, the global share of renewable energy in electricity capacity has consistently increased over the past decade, from 27.2% to 40.2% (IRENA, 2023c). Further greening of electricity grids could be expected, leading to lower emission intensity for hydrogen production from the grid over time.

Measures must be in place, however, to prevent increased fossil fuel-based power generation due to increased electricity demand for hydrogen production. "Additionality" safeguards help to avoid a situation where renewable electricity used for hydrogen production is diverted away from other uses. Figure 12 displays an overview of set-ups for hydrogen production via electrolysis and indicates the implications for respective carbon intensities.

System designs can be optimised to minimise cost and increase flexibility as necessary, depending on a number of factors. These include: the variability of electricity supply (*i.e.* constant consumption of grid electricity, or direct feed from variable solar or wind farms); the technology used for the stack and the flexibility of hydrogen demand (*e.g.* constant demand for chemical processes, or general annual demand for export without hourly or daily constraints). Power storage can help to decouple variable supply from hydrogen demand (IRENA, 2020).

The EU has released delegated acts, which contain the specifications for renewable electricity that must be met to qualify for "renewable hydrogen" production. They also contain the methodology for calculating GHG emissions. Similarly, the United States has proposed regulations outlining the requirements for the clean hydrogen tax credit under section 45V. Both the EU and the US have set criteria for additionality, temporal and geographical correlation, although they differ in their specific requirements.

Figure 12 Set-ups for hydrogen production via electrolysis

	STAND-ALONE CONNECTED ELECTROLYSERS		CO-LOCATED ELECTROLYSERS	
	INFLEXIBLE[4] ELECTROLYSERS (GRID TO HYDROGEN)	FLEXIBLE ELECTROLYSERS (GRID TO HYDROGEN)	CO-LOCATED	CO-LOCATED INCLUDING GRID CONNECTION (GRID)
ENERGY SOURCE	Grid electricity mix	Grid electricity mix based on carbon intensity or price signals	Depends on the source it is connected to	Electrolyser connected to grid and energy source connected to grid
STABLE HYDROGEN OUTPUT	Yes	No	Depends on source	Yes, if topped up by grid
EMISSION INTENSITY	Depending on the emission intensity of the respective grid	Uncertain, but could only run when high level of renewable in grid	Depends on source	Depends on source

Sources: (AURORA Energy Research, 2022; Erbach and Svensson, 2023).

Within the EU regulations, the additionality requirement refers to the idea that any new renewable hydrogen production should be accompanied by new renewable electricity generation capacities. As a result, the rules dictate that hydrogen producers must establish power purchase agreements (PPAs) with new and unsupported renewable electricity generation capacities.

The criteria on temporal and geographic correlation are in place to ensure that hydrogen production takes place when and where renewable electricity is available. These criteria, see Table 1, aim to prevent the demand for renewable electricity used for hydrogen production from incentivising more fossil electricity generation (EC, 2023a).

Table 1 Methods to prove the energy used is renewable based on EU criteria

METHOD OF RENEWABLE ENERGY PROVISION	ADDITIONALITY	TEMPORAL CORRELATION
Direct use of renewable power without grid connection or at same grid node with smart metering system	Unsubsidised renewable plant not older than 3 years	/
Grid-connected in a bidding zone with 90% renewable power in the previous year	/	/
PPA with renewable power installation in same or adjacent bidding zone with an average emission intensity over 64.8 grammes (g) CO_2 equivalent (eq)/kilowatt hour (kWh)	From 1.1.2028: PPAs with unsubsidised renewable plant not older than 3 year	Until 31.12.2029: same month From 1.1.2030: same hour
PPA with renewable power installation in same or adjacent bidding zone with an average emission intensity under 64.8 gCO_2eq/kWh	/	Until 31.12.2029: same month From 1.1.2030: same hour

Note: /= not applicable.
Sources: (EC, 2023b; Quitzow *et al.*, 2023).

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[4] *The term flexibility refers here to the mode of operation (whether hydrogen is being produced regardless of time of day, price, hourly carbon intensity of power, or they follow those parameters to meet certain economic/environmental objectives).*

Table 2 Proposed US rules for the production of clean hydrogen[5]

	INCREMENTAL (ADDITIONALITY)	TEMPORAL CORRELATION	DELIVERABILITY (GEOGRAPHICAL CORRELATION)
CONDITIONS	Power plant generating electricity should have a commercial operation date no more than 36 months before the hydrogen production facility.	There should be a temporal correlation between the electricity (backed by "energy attribute certificates" – EACs) and the fuel production unit.	The electric generating facility is in the same transmission region as the hydrogen production facility.
TIMELINE		Before 1 January 2028, production should match the generation within the same calendar year. On or after 1 January 2028, it must match generation within the same hour.	
EXEMPTIONS	Generation from zero-or near-zero emissions that: • Might retire if they sell electricity for hydrogen production. • Reduce curtailment. • Regions in which electricity is 100% generated by low-emissions sources.		

Source: (IRS, 2023).

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[5] *The U.S. Department of the Treasury is required to use the 45VH$_2$-GREET model to calculate lifecycle greenhouse gas (GHG) emissions of hydrogen production (DoE, 2023).*


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The rules in the United States are only proposed at the time of writing, with more details still needing to be decided. While the EU rules only focus on renewable energy, the proposed US rules also include carbon capture and nuclear.

The proposed regulations for hydrogen production in the United States differ from the EU hydrogen rules in terms of the "additionality" criterion, see table 2. While the EU rules limit the subsidies that electricity generation facilities can receive, the proposed US rules do not impose any such restrictions. Both the EU rules and the US rules require hydrogen production to meet an hourly matching requirement, but the EU allows market participants until 2030 to prepare for this rule, while requiring monthly matching until then. Conversely, the proposed US rules allow for annual matching up to 2027. The deliverability requirement in the proposed US rules is similar to the "geographical correlation" under the EU hydrogen rules, which stipulate that hydrogen and electricity must be provided in the same or interconnected "bidding zones". The EU hydrogen rules also apply to hydrogen and derivatives imports, but the European Commission acknowledges that these rules must be adapted to the region of production (Cockerham *et al.*, 2024).

3.3 IMPACT OF INCENTIVE SCHEMES AND REGULATIONS ON HYDROGEN MARKET DEVELOPMENTS

Recently, several new incentive schemes, regulatory frameworks and mechanisms have been introduced which could have a significant impact on the global hydrogen market.

One such scheme is the Carbon Border Adjustment Mechanism (CBAM) of the EU, which aims to put a price on the emissions included in imported hydrogen and hydrogen-derived products. The Inflation Reduction Act (IRA) in the United States financially benefits hydrogen that is produced with less carbon intensity. Japan is in the early stages of designing its incentive scheme for domestically-produced and imported hydrogen, which follows a contracts for difference (CfD) approach. These developments could have a major impact on hydrogen markets and the type of hydrogen that they will consume. These schemes could also have a significant impact on countries that aim to export hydrogen and hydrogen-derived products. This, in turn, may affect project outlines and the type of hydrogen that will be produced.

This section provides a summary of these major developments and explores indications for the further development of the hydrogen market.

The European Union (EU)

The EU CBAM has now entered its transitional phase. CBAM is a measure designed to address carbon leakage, which occurs when carbon-intensive industries move production to regions with less stringent climate regulations.

The CBAM will impose a carbon cost on specific imported goods entering the EU market, corresponding to the emissions generated during their production. This initiative aims to establish fair pricing parity between domestically produced and imported products, thereby deterring carbon leakage and advocating for cleaner practices within the global industry.

Hydrogen is included in the first transitional phase, with the first reporting period for importers starting 31 January 2024. During the transition period, importers of goods that fall under the scope of the new rules will only be required to report the GHG emissions (both direct and indirect) that are embedded in their imports. They will not be expected to make any financial payments or adjustments during this period (EC, 2023c).

CBAM will serve as a mechanism for internalising carbon emissions from imported hydrogen and derived products, in the long run translating ecological benefits into economic benefits.

According to its delegated acts, the European Commission has defined renewable hydrogen as that which achieves a 70% reduction in emissions in comparison to the fossil fuel benchmark of 94 gCO_2eq/megajoule (MJ). This reduction marks a threshold of 3.38 $kgCO_2eq$/kg of hydrogen on a well-to-wheel basis (in reality, the emissions threshold for hydrogen production that is not onsite is lower). Both domestic and international producers exporting renewable hydrogen to the EU will be subject to the regulations specified in the delegated acts (EC, 2023a). Looking at developing countries aiming to export, this means that the additionality requirement seeks to ensure that existing capacity is not cannibalised. This does not address the issue of diverting generation capacity investments for export-oriented activities, instead of providing access to everyone.

Box 3

The European Hydrogen Bank (EHB)

The EU has identified hydrogen as a strategic priority and has been very active in terms of policy making, as well establishing incentive schemes to support the off-take of renewable hydrogen.

In 2020, the EU established an ambitious hydrogen strategy which requires both substantial hydrogen deployment and imports from regional and international markets. The REPowerEU package, published in 2022, sets a further target of 10 Mt of renewable hydrogen produced within its borders by 2030 and another 10 Mt imported from international producers (EU, 2023).

Renewable hydrogen production is not yet competitive. Therefore, the European Commission has designed the EHB to promote the use of clean energy sources and reduce carbon emissions by providing financial incentives to businesses and consumers who adopt green hydrogen technologies. The EHB aims to facilitate investments in green hydrogen production, aligning with the REPowerEU targets. The EHB is built on four core pillars: creating an EU domestic market; facilitating international imports to the EU; promoting transparency and co-ordination; and streamlining existing financing instruments. The EHB's primary objective is to bridge the cost differential between renewable hydrogen and fossil fuels, especially for early projects.

To achieve this, an auction system, modelled on the German H_2Global scheme, was implemented for renewable hydrogen production. This system will provide producers with a fixed price payment per kilogramme of hydrogen produced for a maximum operational period of ten years (EC, 2023d). In August 2023, the European Commission released the terms and conditions for the upcoming EU EHB pilot auction. Projects participating in this auction must become operational within five years, bringing most of them close to 2030. The highest allowable bid for the fixed premium, known as the ceiling price, is set in euros (EUR) at EUR 4.50/kg of hydrogen produced. This rate may be subject to review in subsequent auction rounds. In this initial pilot auction, support is available for projects located within the European Economic Area and the auction will award up to EUR 800 million to renewable hydrogen producers. Proposals will be ranked and awarded from lowest to highest bid price until the EUR 800 million is exhausted (EC, 2023e).

The United States

The US IRA puts emissions intensity in the centre of its incentive scheme. Tax credits are only applicable to hydrogen production in the United States (though the "sale or use" may take place outside of the United States). The Clean Hydrogen Production Credit introduces four, technology-neutral credit tiers based on the emissions intensity of the hydrogen, as shown in table 3. The scheme provides financial benefits for hydrogen with a lower emission intensity, compared to hydrogen with a higher intensity. Tax incentives can be granted to producers who produce "low-carbon hydrogen" ranging from USD 0.60/kg H_2 up to USD 3/kg H_2 on a well-to-gate basis (IRS, 2023). The tax credit increases as the carbon intensity decreases, as shown in the table 3.

Table 3 IRA tax credit tiers

CREDIT TIER	EMISSIONS INTENSITY ($kgCO_2eq/kg\ H_2$)	MAXIMUM TAX CREDIT (USD/kg H_2)
1	0-0.45	USD 3.00
2	0.45-1.5	USD 1.00
3	1.5-2.5	USD 0.75
4	2.5-4	USD 0.60

Source: (IRS, 2023).

The values in Figure 10 indicate that blue hydrogen, in the best case scenario of a 90% carbon capture rate, could benefit from credit tier 4. Blue hydrogen requires high levels of capture and storage to fully leverage the financial incentives provided by the IRA. However, the IRA has also provided relevant updates regarding the tax credit, 45Q, which incentivises the use of carbon capture and storage across several industries, including hydrogen. The IRA extends the construction deadline date for carbon capture or direct air capture (DAC) facilities under Section 45Q until 1 January 2033. It also modifies the capacity requirements and base credit amounts for the credit. The 45Q incentives increase from USD 50/tonne (t) to USD 85/t for storage in saline geologic formations from carbon capture on industrial and power generation facilities. They also range from USD 50/t to USD 180/t for storage in saline geological formations from DAC (CATF, 2023). This update is expected to drive carbon capture technologies forward in the United States and means that companies now have an alternate route for benefitting from subsidies for blue hydrogen. They cannot benefit from 45V and 45Q at the same time (IRS, 2023).

Japan

In its Basic Hydrogen Strategy, published in June 2023, Japan announced its targets for hydrogen usage and water electrolyser capacity. The strategy also outlined the country's plans to enhance the hydrogen industry's competitiveness. These plans include developing support schemes to build a large-scale and resilient supply system focusing on low carbon intensity hydrogen. The strategy update aims to not only to develop the domestic market, but also to expand into overseas markets (ANRE, 2023).

The Japanese Ministry of Economy, Trade and Industry (METI) has issued an interim report on promoting the supply and utilisation of low-carbon hydrogen and its derivatives. This outlines METI's plan for a subsidy programme which aims to close the cost gap between clean low-carbon hydrogen and its derivatives and their fossil counterparts. It also aims to institute a support programme to develop the domestic facilities necessary to expand hydrogen usage. The programme on the cost gap intends to cover both domestically produced and imported hydrogen. It will be designed as a CfD model between the benchmark price and reference price.

According to the interim report, Japan intends to set the emissions intensity threshold of 3.4 $kgCO_2eq/kg\ H_2$ as the upper limit to be eligible for the subsidy (METI, 2023b).

The subsidy's reference price is determined based on one of three options. First, it can be calculated using the cost of raw materials and fuels displaced by clean low-carbon hydrogen upon arrival in Japan, such as liquefied natural gas or coal. The cost can be determined by adding an assessment of the "environmental value" to the aforementioned cost. Second, the actual sales price of hydrogen or its derivatives upon arrival in Japan or at domestic production sites can be used as a reference. Third, the reference price can be calculated based on past transaction records with traded prices, when these have been used in the existing hydrogen and ammonia market.

It is important to note that these reference prices may increase due to the implementation of carbon pricing and other regulatory measures. As a result, the amount of subsidy is expected to gradually decrease over time (METI, 2023b).

Box 4

Quality infrastructure for robust and sustainable hydrogen value chains

A modern quality infrastructure (QI) is crucial for ensuring the quality and safety of renewable hydrogen value chains, particularly those that cover long distances. It is essential to monitor, measure, and validate the technology and infrastructure used for producing and transporting renewable hydrogen to ensure that these perform as required. Additionally, it is important to be able to trade renewable hydrogen on a global scale while maintaining the sustainability and safety of production and its derivatives. Developing a QI for renewable hydrogen can facilitate this process.

QI refers to the national system of organisations, policies, legal frameworks and practices that are necessary to assure quality, safety, and sustainability of products and services. The pillars of QI are metrology, standardisation, accreditation and conformity assessment (including testing, certification, and inspection). A well-functioning QI can attain quality assurance and generate confidence in the market regarding the conformity of renewable hydrogen products, processes, and services.

QI creates the technical basis for the development of the renewable hydrogen sector. It reduces safety, financial and reputational risks in the sector, while at the same time supporting the achievement of the intended positive sustainability impacts of investments. The integration of renewable hydrogen in a low-carbon economy will require additional and improved QI services.

IRENA, along with the German Metrology Institute (PTB) and funding from the German Federal Ministry of Economic Co-operation and Development (BMZ), is implementing a project with the goal of developing a roadmap outlining how to establish a quality infrastructure ecosystem for clean hydrogen production. The desk research study revealed that there are numerous international and national certification and standards available for green hydrogen, but they need to be globally harmonised. Additionally, services for accreditation, metrology, and testing – especially in emerging economies – are either lacking or need to be developed at a fundamental level before they can be applied to hydrogen. It is expected that the roadmap will be available towards the latter half of 2024.

3.4 WATER SUPPLY

Water and energy are two vital resources that are inextricably linked. Significant amounts of water are used in every part of the energy sector, from fuel production to electricity generation. In some countries, the energy sector accounts for a significant share of water withdrawals and consumption, in particular for thermoelectric power plants. This demand can put a strain on freshwater resources, especially as climate change worsens. That also holds true for renewable hydrogen production, as water is the second most significant input factor after electricity.

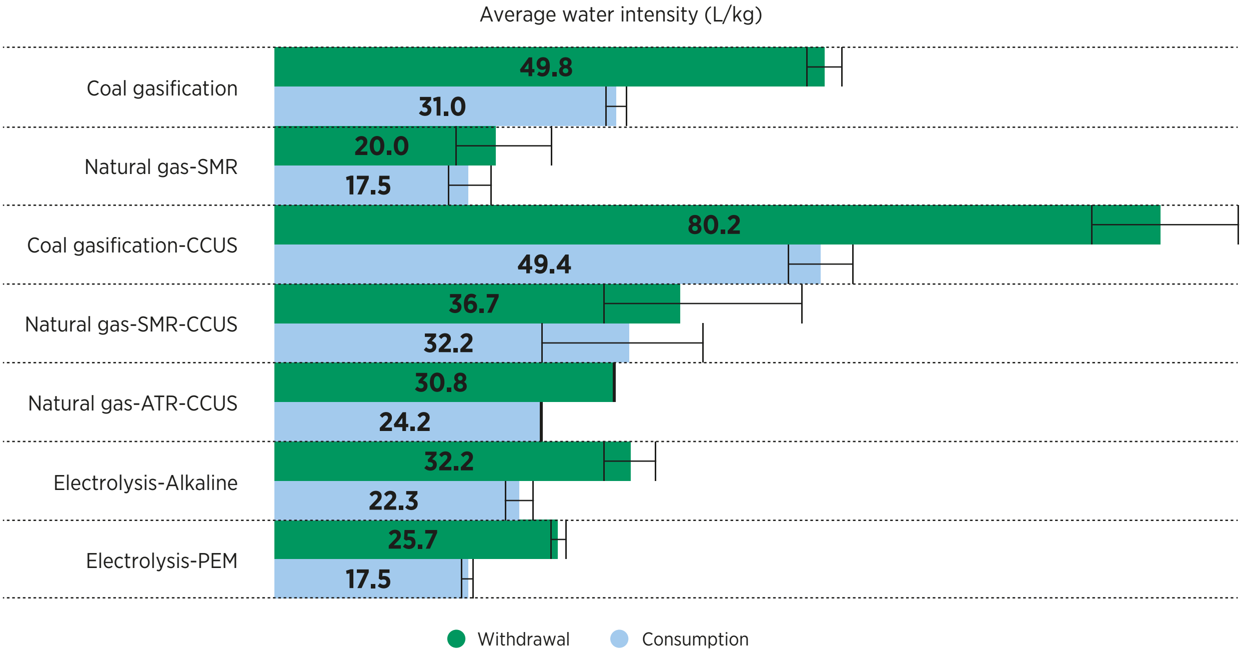
To address the potential competition and risks to the energy security resulting from water scarcity, water perspectives must be integrated into energy sector planning.

One approach is to reduce the water intensity of energy production by transitioning to renewable energy technologies such as solar PV and wind. These consume only limited amounts of water during the production stage. Scaling up renewable power, particularly solar PV and wind, combined with improved cooling technologies, could therefore significantly reduce the water withdrawal intensity of electricity generation. By 2030, this reduction could be 42% in China and 84% in India (IRENA and China Water Risk, 2016; IRENA and WRI, 2018).

Hydrogen production does not only require water as a feedstock (pure water), but also for cooling purposes. Comparable to the findings on emissions intensity, the choice of production path matters: green hydrogen has a smaller water footprint than blue or grey hydrogen production.

Average water withdrawal and consumption intensities are visualised in Figure 13. More details on these values can be found in (IRENA and Bluerisk, 2023).

Figure 13 Comparison of average water withdrawal and consumption intensities by hydrogen production technology



Notes: ATR = auto-thermal reforming; CCUS = carbon capture, utilisation and storage; kg = kilogramme of hydrogen; L = litre; PEM = proton exchange membrane; SMR = steam methane reforming. Tap water (or sources with similar water quality) is used, or assumed to be, the water source behind these data points. For blue hydrogen, the cooling requirements for CCUS systems are included. For PEM and ATR, available data points are limited, since these technologies are relatively new – thus the much smaller ranges of values.

Source: IRENA and Bluerisk (2023).

As shown in Figure 13, when it comes to water usage, PEM technology stands out with one of the lowest water consumption, averaging around 17.5 litres (L) of water per kilogramme of hydrogen (L/kg H_2) produced. SMR also has the advantage of requiring the least water withdrawal, which is approximately 20 L/kg H_2 it generates. In contrast, coal-based hydrogen production methods prove to be the most water-intensive, both in terms of withdrawal and consumption. For instance, coal gasification without CCUS necessitates the withdrawal of about 50 L of water and consumes 31 L of water to produce one kilogramme of hydrogen. This exceeds the water requirements of non-coal-based technologies. The incorporation of CCUS into fossil fuel-based methods also leads to increased water intensity. This is because CCUS systems demand significant amounts of cooling, reducing production efficiency and requiring water for their sorbent. With CCUS integrated, coal gasification, for instance, can require as much as 80 L of water to produce one kilogramme of hydrogen, which is 61% higher than coal gasification without CCUS.

It is evident that the green hydrogen pathway has a lower water impact. Globally, however, the projected 491 Mt of green hydrogen needed by 2050 in IRENA's 1.5°C pathway would require around 11.5 billion cubic metres (m^3) of water a year. While this number may look daunting, it also represents less than 0.003% of current freshwater consumption.

Yet, while the global impact on water consumption might not be significant, its local effects on water stress can be substantial. Neglecting these local impacts can result in the cancellation of projects, as demonstrated in the case of Kallis Energy Investments. In 2021, they unveiled plans for the ambitious 6 gigawatt (GW) Moolawatana plant, intended to harness solar and wind resources in the northern desert region of South Australia for hydrogen production and export. These plans were ultimately abandoned after a feasibility study revealed unacceptable environmental and permitting challenges associated with water supply and desalination.

National hydrogen strategies should explicitly consider the water aspect. Many green hydrogen investors are targeting locations with abundant solar PV and wind resources to reduce the LCOH and maximise capacity factors. However, these sunny regions often suffer from water scarcity. Many planned electrolyser capacities are slated for water-stressed areas like Australia, Chile, Oman and Saudi Arabia.

In cases where freshwater resources are insufficient, green hydrogen projects may need to resort to desalination. This approach would increase water withdrawal by a certain percentage, raise energy consumption by between 1% and 2% and add USD 0.02-0.05 to the cost of one kilogram of hydrogen (Caldera and Breyer, 2017). Some green hydrogen projects are presented as opportunities to enhance water security, but while desalination can be costly for sectors like agriculture or small industries, its use in green hydrogen production only slightly raises costs and energy consumption.

Nonetheless, most desalination projects are concentrated in a few regions – notably the Middle East. As hydrogen production becomes more widespread worldwide, combining desalination projects with hydrogen production could increase water supply by promoting the development of multipurpose desalination facilities in water-stressed regions. It could also disseminate desalination expertise beyond the main markets to regions such as North Africa and Latin America.

4. ENABLERS IN THE TRANSPORTATION AND TRADE OF RENEWABLE HYDROGEN: A HYDROGEN CARRIER TECHNOLOGY UPDATE

Hydrogen can be transported in various forms. For long distances it can be transported as a gas through pipelines, or as a cooled liquid in ships. Hydrogen can also be chemically converted into other hydrogen-carrying commodities, such as ammonia, methanol or liquid organic hydrogen carriers, and transported in liquid form.

The transportation of hydrogen or its derived commodities from areas with high renewable energy potential to demand centres elsewhere is a vital link to creating international value chains. While IRENA's calculations suggest that 55% of the internationally traded hydrogen will travel via pipeline, 45% will be transported via ship (IRENA, 2022f).

A range of technological options can serve as hydrogen carriers, each with their own advantages and disadvantages. This chapter provides an overview of these hydrogen carriers, including their infrastructure requirements and safety considerations. Due to their varying requirements and technologies, carriers may compete for different trade routes, requiring a case-by-case assessment.

This chapter focuses on the long-distance shipping of liquid hydrogen carriers, from which hydrogen can be extracted at the destination – though in many cases it makes sense to use the carriers as fuels or feedstock directly. Other commodities such as green steel (steel that is reduced using green hydrogen) or green chemicals (those that can be made partially using green hydrogen) are covered in separate publications, as they come with additional complexities and are not used to extract energy in the destination countries.

The following sections look at LOHCs, liquid hydrogen, ammonia and methanol, noting that ammonia and methanol can serve as hydrogen carriers as well as direct fuels and chemical feedstocks for various applications. This example shows the additional complexity added to an international value chain when a technology option requires sustainably-sourced carbon.

4.1 AMMONIA

Production pathway

Ammonia can be used as a chemical feedstock or as an energy carrier. Potentially, vessels can also be retrofitted to use ammonia as a maritime fuel.[6]

Renewable ammonia is produced from renewable hydrogen, which in turn is produced via water electrolysis using renewable electricity. This hydrogen is converted into ammonia using nitrogen that is separated from air, via the so called Haber Bosch process (IRENA and AEA, 2022). The process is conducted under conditions of high temperature and pressure, ranging from 350°C to 800°C and 100 to 400 bar, respectively. Once liquefied, ammonia can be transported by a chemical tanker via suitable terminals and with appropriate port storage facilities.

While ammonia production is an energy intensive process, the Haber-Bosch process is highly efficient. When hydrogen is recovered from ammonia, purification is required so that no residues are present (IRENA and AEA, 2022). Renewable hydrogen production represents about 90% of the energy needed to make renewable ammonia, with electrolysis involving about 36 gigajoules (GJ) per tonne of ammonia. This is equivalent to around 50% energy efficiency (IRENA and AEA, 2022). Improvements in electrolyser efficiency will be reflected on the efficiency of renewable ammonia.

On the other hand, the energy required to make renewable ammonia remains small with respect to renewable hydrogen (IRENA and AEA, 2022). By 2050 – and in the context of a 1.5°C scenario – the market for ammonia as a fuel for maritime transport and stationary power is projected to increase. Indeed, global demand for the commodity could increase from 183 Mt in 2020 to as much as 688 Mt by 2050 (IRENA and AEA, 2022).

Infrastructure

Currently, between around 18 Mt per annum (Mtpa) and 20 Mtpa of ammonia is shipped internationally (IRENA and AEA, 2022). While green ammonia production scales up and matures, as a first phase this international trade of grey ammonia could be substituted by low carbon green ammonia for current uses (fertiliser, chemicals). This could make use of the existing shipping and port infrastructure. In the long term, as ammonia starts to be used for new applications, such as maritime transport fuel or power generation, major investments will be required. Existing capacities will have to expand by 10 to 15 times, requiring annual, multi-billion dollar investments in both transport and storage. As an example, 235 ships with a capacity of 85 000 m^3 are needed by 2050 to accommodate for the additional 354 Mt of ammonia projected to be shipped (IRENA and AEA, 2022). If ammonia is used as an intermediate energy carrier and is later used to recover hydrogen, ammonia cracking technology would also be needed, with this still a relatively immature technology.

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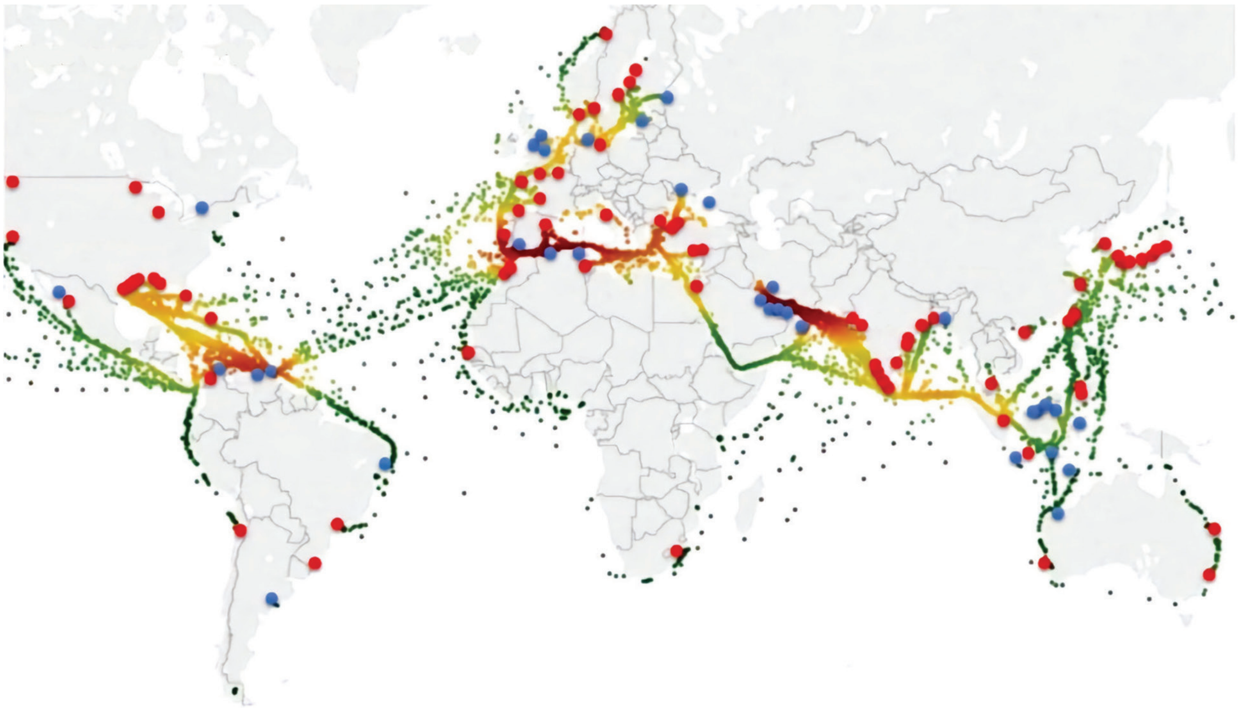
[6] *Note that there are currently no commercial vessels with this capability, although pilot studies suggest this is technically feasible. Retrofitting, however, would currently cost over 50% of the market value of the vessel (Atchison, 2023).*

Figure 14 Ammonia shipping infrastructure, including a heat map of liquid ammonia carriers and ammonia port facilities in 2017



Note: Green and yellow dots show intensity of maritime liquid ammonia trade routes.
Source: (The Royal Society, 2020).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Safety

Ammonia is a hazardous chemical, as it is a toxic gas in ambient conditions. For this reason, it is often stored as a liquid under refrigeration at a temperature of -33°C, rather than under pressure at 7.5 bar. Ammonia is corrosive, toxic and potentially life-threatening upon inhalation (IRENA and AEA, 2022). Ammonia leakages can cause environmental and health damage. Therefore, handling ammonia with care throughout the entire transport chain is crucial in order to minimise the risk of leaks. The industry has accumulated decades of experience handling ammonia, with it important to follow established best practices and standards.

Cost

At present, renewable ammonia costs around USD 720/t in regions boasting optimal solar and wind resources. Projections suggest this cost will drop to USD 480/t by 2030 and further decline to USD 310/t by 2050. A carbon price of around USD 150/tCO_2 is estimated to be sufficient for renewable ammonia to compete with non-renewable ammonia (IRENA and AEA, 2022).

Box 5

Producing green ammonia in Namibia

In Namibia, the Hyphen project has a clear goal: to generate green hydrogen and, eventually, green ammonia. The plan involves constructing wind farms and solar PV plants in the country with a combined capacity of seven gigawatts (7 GW). This ambitious plan will require investments of approximately USD 10 billion, equivalent to Namibia's entire gross domestic product (GDP). The European Investment Bank (EIB) is expected to provide crucial financial support, and German companies are actively participating in the initiative.

Once fully operational – a status expected to be achieved before the end of the decade – the project would produce 2 Mtpa of green ammonia for both regional and global markets. Namibia is planning to tap into its abundant land resources and renewable energy potential to make this project a reality. It is estimated that during the construction phase, the project would generate around 15 000 jobs and provide long-term employment opportunities for approximately 3 000 individuals. European companies, such as RWE, have already shown interest in potentially importing products from this project.

Hyphen's uniqueness lies in Namibia's combination of strengths and weaknesses. While the country is sparsely populated, it has vast land availability and renewable energy potential. On the other hand, it faces challenges such as water scarcity and geographical distance from its intended export markets, making it harder to reach cost competitiveness in exports (HYPHEN, 2023; Reuters, 2023; RWE, 2022; Stratmann, 2023).

4.2 LIQUID HYDROGEN

Production pathway

Liquid hydrogen is produced by cooling hydrogen from its gaseous form into liquid. This liquefaction process involves the use of compressors, heat exchangers and expansion engines, as well as throttle valves to reach the level of cooling desired. This is a highly energy intensive process,[7] as it requires very pure hydrogen and several compression cycles (Allevi and Collodi, 2017). One of the simplest ways to liquify hydrogen is through the Linde cycle or the Joule-Thomson expansion cycle, with the liquid hydrogen produced then stored at a temperature of -253°C (Allevi and Collodi, 2017).

Infrastructure

Infrastructure is a major constraint when it comes to liquid hydrogen. Currently, investment in import terminals is very low (IRENA, 2022a), while the cost of ships that could carry liquid hydrogen is very high, due to the cryogenic requirements and the low volumetric energy density of hydrogen. These factors place this carrier at a disadvantage in comparison to other methods of transport. As of today, only one ship[8] exists in the world that is capable of transporting liquid hydrogen.

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[7] *Requiring between around 38 MJ/kg of hydrogen and 43 MJ/kg of hydrogen. See also Figure 15 in section 4.5.*

[8] *This ship is Kawasaki Heavy Industries' Suiso Frontier, which has shipped coal-derived hydrogen from Australia to Japan. It can hold 1250 m^3 H_2.*

SUISO FRONTIER
©Hunini, CC BY-SA 4.0, via Wikimedia Commons

Currently, facilities at a scale adequate to meet the global need for liquid hydrogen do not exist. Facilities such as liquefaction plants, storage tanks, ships and regasification units, would therefore have to be greenfield (IRENA, 2022a).

Safety

Liquid hydrogen has been adopted as a fuel in space technology for several decades now. In comparison with compressed gas, it has a relatively higher density and fewer risks associated with storage (Allevi and Collodi, 2017). Nevertheless, liquefaction of hydrogen occurs at temperature equal to −252.9°C, requiring sophisticated insulation techniques.

Cost

Cryogenic temperatures lead to high capital costs across the whole value chain. Liquid hydrogen would therefore require up to twice the investments required for other carriers such as LOHC and ammonia (IRENA, 2022a). The increased cost lies in the shipping and the liquefaction plants. This cost is reduced by around 75%, however, when the scale increases to 100 kilotonnes per annum (ktpa) of hydrogen (IRENA, 2022a). Nonetheless, an increase of such scale would still not be enough to achieve commercialisation of the value chain.

4.3 LOHCS

Production pathway

LOHCs are organic chemicals that react reversibly with hydrogen to form easily transportable chemicals (Wang *et al.*, 2021). Common LOHCs include toluene, dibenzyl toluene and benzyl toluene (Weichenhain, 2021).

LOHCs can be used to transport hydrogen in two steps: hydrogenation and dehydrogenation. During hydrogenation, hydrogen is loaded into the liquid carrier at atmospheric pressure and is stored and distributed without boil-off losses. When hydrogen is needed, a dehydrogenation reaction in a dedicated plant is necessary. The products of dehydrogenation are hydrogen and the unloaded carrier, which can be loaded with hydrogen again for the next cycle. The release of hydrogen is an endothermic process (Weichenhain, 2021), which could lead to GHG emissions, depending on the energy source used.

Infrastructure

The hydrogen is "loaded" into the carrier (hydrogenation) at the exporting site and "unloaded" at the importing terminal (dehydrogenation). LOHC compounds are mostly oil derivatives and can make use of existing facilities with no boil off losses under ambient conditions.

Conversion (hydrogenation) and reconversion (dehydrogenation) are currently being undertaken in pilot projects, with the first commercial scale plant under construction, with commissioning planned for 2025 (Hydrogenious, 2023). Shipping could be undertaken in the same way that crude oil is transported today, with limited adaptations (IRENA, 2022f). Indeed, the similarity with hydrocarbons such as diesel allows for a repurposing of the existing infrastructure – notably tanks, trucks and vessels. This is a major advantage for LOHC's, as oil tankers that would otherwise become stranded assets, as the world progressively phases out the use of fossil fuels, can be reused.

Table 4 shows the existing number of ships that transport crude oil today and how they could be used to transport hydrogen in the form of LOHCs. Only two very large crude carriers (VLCCs) could carry enough LOHCs to import 1 Mtpa of hydrogen from Morocco to Rotterdam (a distance of 1 438 nautical miles, which can be covered in 3.8 days).[9] A scenario transporting LOHCs over longer distances, such as Gladstone (Australia) to Yukohama (Japan), which takes 9.5 days to cover 3 367 nautical miles, 1 Mtpa of hydrogen could be carried by 4 VLCCs.

Table 4 Number of ships required to transport 1 Mt of hydrogen using LOHC

TYPE OF SHIP	VLCC	AFRAMAX	SUEZMAX	SMALL TANKER	PANAMAX
Number of ships currently in operation	810	668	571	83	78
Deadweight tonnage (1 000s of tonnes)	280	100	150	62.5	70
Hydrogen content (kg H_2/kg LOHC)	6%	6%	6%	6%	6%
Hydrogen delivered per ship (ktH_2 equivalent)	17	6.07	9.11	3.79	4.25
Energy delivered per trip (terajoules [TJ])	2 040	729	1 093	455	510
Number of roundtrips for 1 Mtpa hydrogen import	59	165	110	264	235
Number of days per roundtrip	8.6	8.6	8.6	8.6	8.6
Minimum number of ships required for 1 Mtpa hydrogen import	2	4	3	7	6

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[9] *Assuming 1 day is needed for loading/offloading per roundtrip.*

Safety

LOHCs are generally safe and easily stored, transported over long distances and adequately handled (Weichenhain,2021). Furthermore, LOHCs are non-toxic and non-explosive, but hazardous to aquatic environments (Weichenhain, 2021)

Cost

Most organic carriers are specialised chemicals that are currently produced in limited quantities. Production would therefore require scaling up multiple times to satisfy this new market. These carriers also have a high cost, which leads to a high initial investment, due to the need to build inventory. Furthermore, there are losses (0.1% per cycle) that would also require compensating.

For the period from 2030 to 2050, Godinho *et al.* estimate logistics costs for transportation between Portugal and the Netherlands varying between EUR 0.30/kg H_2 and EUR 0.37/kg H_2 for dibenzyl toluene (DBT)-perhydro dibenzyl toluene (PDBT). For toluene (TOL)-methylcyclohexane (MCH), the costs vary between EUR 0.28/kg H_2 and EUR 0.34/kg H_2 (Godinho *et al.*, 2023).

4.4 METHANOL

Currently produced mainly from hydrocarbons, methanol is a key product in the chemical industry and an emerging fuel. It is a building block in the production of other chemicals such as formaldehyde, acetic acid and plastics. A transition to renewable methanol could potentially expand methanol's use as a chemical feedstock and fuel, while also moving the industrial and transport sectors towards net carbon neutral goals (IRENA and Methanol Institute, 2021).

Production pathway

Renewable methanol is usually classified into two types, according to the feedstock used. First, there is bioethanol, which is produced from biomass. This can consist of forestry and agricultural (solid) residues and by-products, biogas from sewage, municipal solid waste (MSW), or black liquor from the pulp and paper industry. Second, there is e-methanol, also called power-to-liquid (PtL), which is obtained from biogenic or air-captured CO_2 and green hydrogen.

Technology pathways for bioethanol can be divided into: (1) gasification or pyrolysis of biomass (solid or liquid); and (2) reforming of biogas in order to produce the synthesis gas (syngas) that is then synthesised into methanol in the same way grey methanol is produced.

Renewable e-methanol, on the other hand, is generated through methanol synthesis using CO_2 captured from renewable sources. These could be bioenergy with carbon capture or DAC, along with renewable hydrogen (IRENA and Methanol Institute, 2021). The sourcing of the renewable CO_2 is key for the sustainability of the methanol, but also impacts the cost structure and overall production efficiency. The efficiency of renewable e-methanol production is further determined by the electrolysis method, technology maturity and the methanol synthesis process (IRENA and Methanol Institute, 2021)

Though bioethanol is not necessarily a hydrogen carrier (it does not require the production of hydrogen), we include it here, since hydrogen can be recovered from methanol regardless of how it was made. Green hydrogen can also be used to increase the methanol yield from biomass by over 50% (Ajdari, Sima, 2021).


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Infrastructure

Methanol is currently available in more than 100 major ports. Since methanol is a liquid at ambient temperature and pressure, modifying oil infrastructure to accommodate methanol storage and distribution is relatively inexpensive compared to other alternatives (IRENA and Methanol Institute, 2021).

Safety

While methanol is flammable and toxic, it is a relatively safe carrier and is handled much like gasoline. It is also readily biodegradable, which makes it non-hazardous to the aquatic environment. When undergoing reforming to extract hydrogen from methanol, a few traces of carbon monoxide (CO) can be present (Li and Kawanami, 2023). Methanol is a stable molecule with a light colour, making it easily stored under standard environmental conditions (Li and Kawanami, 2023).

Cost

Methanol spot prices have ranged between around USD 250/t and USD 500/t in Europe and China and USD 400/t and USD 700/t in the United States over the last three years.[10] Current production costs of e-methanol are estimated to be in the range of USD 800-1 600/t, assuming the CO_2 is sourced from bioenergy with carbon capture and storage (BECCS) at a cost of between USD 10/tCO_2 and USD 50/tCO_2. If CO_2 is obtained by DAC, which has costs currently ranging between USD 300/tCO_2 and USD 600/tCO_2, then e-methanol production costs would be in the range of USD 1 200/t and USD 2 400/t (IRENA and Methanol Institute, 2021).

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[10] *See www.methanol.org/methanol-price-supply-demand/*

4.5 COMPARING HYDROGEN CARRIERS

Table 5 provides an overview of the different carriers and the most important considerations when comparing them.

Table 5 Overview of hydrogen carriers

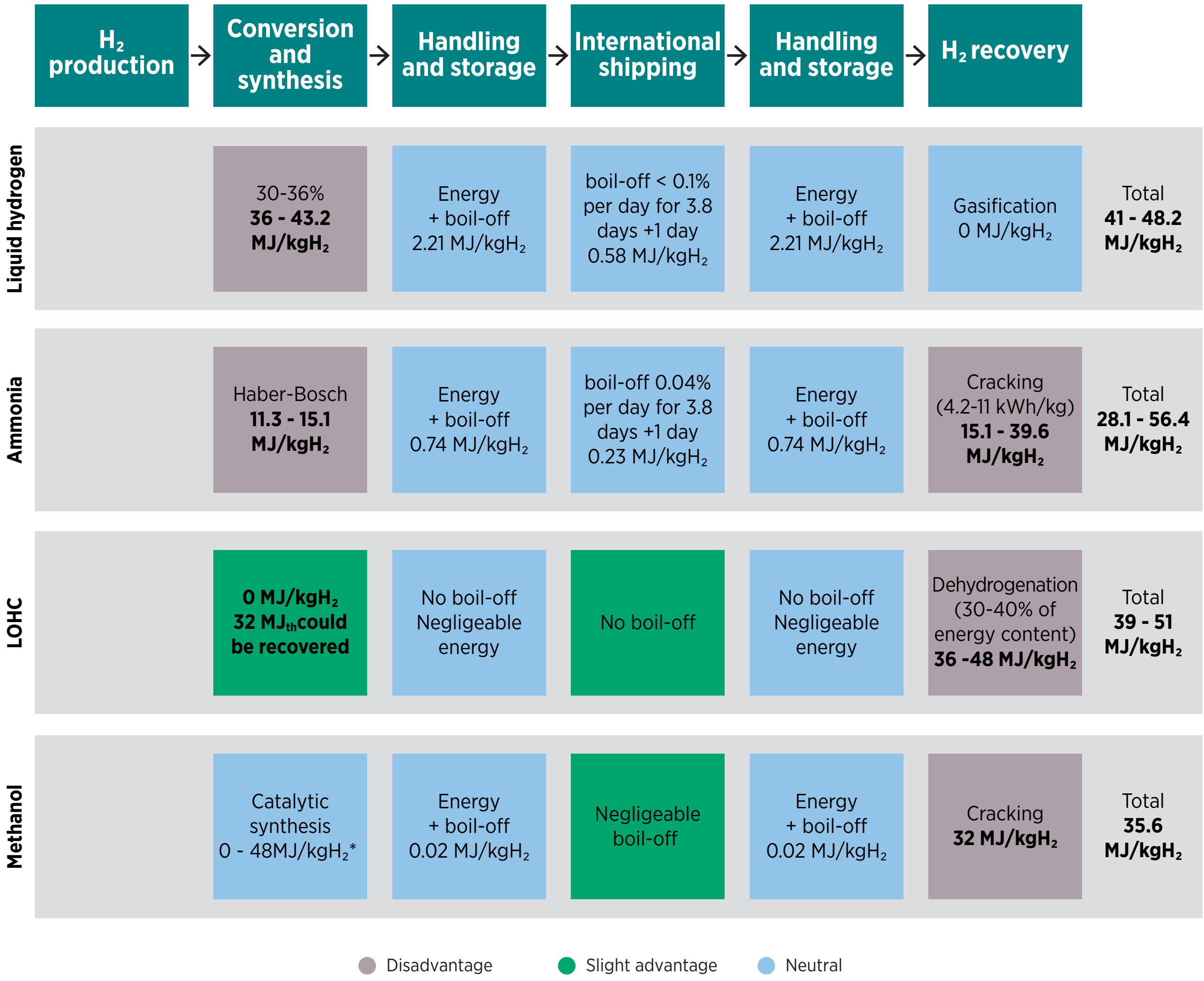
	AMMONIA	LIQUID HYDROGEN	LOHC	METHANOL
INFRASTRUCTURE FOR EXPORT	• Already produced at large-scale and traded globally. Liquefied, it can then be transported by a chemical tanker. • Direct use as a feedstock (for chemical industry) possible without major infrastructure modification. • Used as a hydrogen carrier, it needs to be reconverted to hydrogen via cracking. • Large-scale cracking still to be proven.	• Can be transported by ship using specially modified isolation tanks. • Distribution from the landing port may follow by trailer. This allows direct delivery to customers. • Alternatively, the liquid hydrogen can be reconverted to gas and fed into grid infrastructure.	• Can be transported as oil currently is using existing infrastructure, making it suitable for multi-modal transport. • Can make use of existing fleet of tankers. • An example of LOHC is toluene (TOL), which is converted to methylcyclohexane (MCH) when reacted with hydrogen. • For transport, the TOL is "hydrogenated" – placed in chemical tanks – and transported to the destination. Once received, it can be "dehydrogenated" to release the hydrogen, while the TOL can be sent back for reuse.	• Liquid methanol is first stored in storage tanks at the port and then loaded onto chemical tankers. • At the port of destination, the methanol can be transported via existing distribution routes for chemical raw materials (including trailer and rail transport). • The infrastructure for importing chemicals and thus methanol is available and could be used straight away.
TECHNICAL CONSIDERATIONS	• High energy density and hydrogen content. • Carbon-free carrier. • Can be used directly in some applications (*e.g.* fertilisers, power generation, maritime fuel). • Ammonia combustion generates emissions of nitrogen oxides which may require scrubbers.	• High energy losses for liquefaction (30%-36% today), which calls for larger energy supply. • Boil-off losses (0.05%-0.25% per day) during shipping and storage.	• High (25%-35%) energy consumption for dehydrogenation (importing region) • May require further purification of the hydrogen produced, depending on the use, *i.e.* for fuel cells • Hydrogen is produced at a pressure of 1 bar, requiring compression. • Only 4%-7% of the weight of the carrier is hydrogen. • No clear chemical compound that is the most attractive. • Carrier losses every cycle (0.1% per cycle).	• Methanol is a commonly used basic chemical raw material. • It can potentially be used as an energy carrier to recover hydrogen at the destination. However, the dehydrogenation step is a complex, energy-intensive process. • Methanol can be used directly as a fuel, avoiding dehydrogenation. • The CO_2 source (*e.g.* from an industrial point source or captured from ambient air) is a critical factor in energy and cost efficiency.

Energy balance of hydrogen carriers compared

In addition to the considerations outlined above for each hydrogen carrier, another way to compare the advantages and disadvantages of each mode is by looking at the energy balance between the hydrogen production in the source country and the delivered hydrogen in the destination country. In this, although there are still important differences between literature sources, specific projects, and technologies, some contrasting characteristics can still be determined, with strategic lessons derived from them.

Figure 15 and figure 16 show the various forms of energy consumption in the main steps of the long-distance supply chain of various hydrogen carriers. These figures do not include the energy required to produce the hydrogen (which would be the same for all carriers), from the gate of the hydrogen production to the gate of hydrogen recovery.

Figure 15 Energy consumption along the supply chain for selected carrier pathways



	H_2 production	→ Conversion and synthesis	→ Handling and storage	→ International shipping	→ Handling and storage	→ H_2 recovery	
Liquid hydrogen		30-36% **36 - 43.2 MJ/kgH$_2$**	Energy + boil-off 2.21 MJ/kgH$_2$	boil-off < 0.1% per day for 3.8 days +1 day 0.58 MJ/kgH$_2$	Energy + boil-off 2.21 MJ/kgH$_2$	Gasification 0 MJ/kgH$_2$	Total **41 - 48.2 MJ/kgH$_2$**
Ammonia		Haber-Bosch **11.3 - 15.1 MJ/kgH$_2$**	Energy + boil-off 0.74 MJ/kgH$_2$	boil-off 0.04% per day for 3.8 days +1 day 0.23 MJ/kgH$_2$	Energy + boil-off 0.74 MJ/kgH$_2$	Cracking (4.2-11 kWh/kg) **15.1 - 39.6 MJ/kgH$_2$**	Total **28.1 - 56.4 MJ/kgH$_2$**
LOHC		**0 MJ/kgH$_2$** **32 MJ$_{th}$ could be recovered**	No boil-off Negligeable energy	No boil-off	No boil-off Negligeable energy	Dehydrogenation (30-40% of energy content) **36 -48 MJ/kgH$_2$**	Total **39 - 51 MJ/kgH$_2$**
Methanol		Catalytic synthesis 0 - 48MJ/kgH$_2$*	Energy + boil-off 0.02 MJ/kgH$_2$	Negligeable boil-off	Energy + boil-off 0.02 MJ/kgH$_2$	Cracking **32 MJ/kgH$_2$**	Total **35.6 MJ/kgH$_2$**

● Disadvantage ● Slight advantage ● Neutral

Notes: *Assuming e-methanol production through catalytic synthesis from H_2 and CO_2. When free waste heat and CO_2 are available, no additional energy would be required (low end), while at the high end, CO_2 is obtained through direct air capture (DAC) using 'Liquid DAC' energy use of 6.6 GJ/tCO_2 (IEA, 2023b).

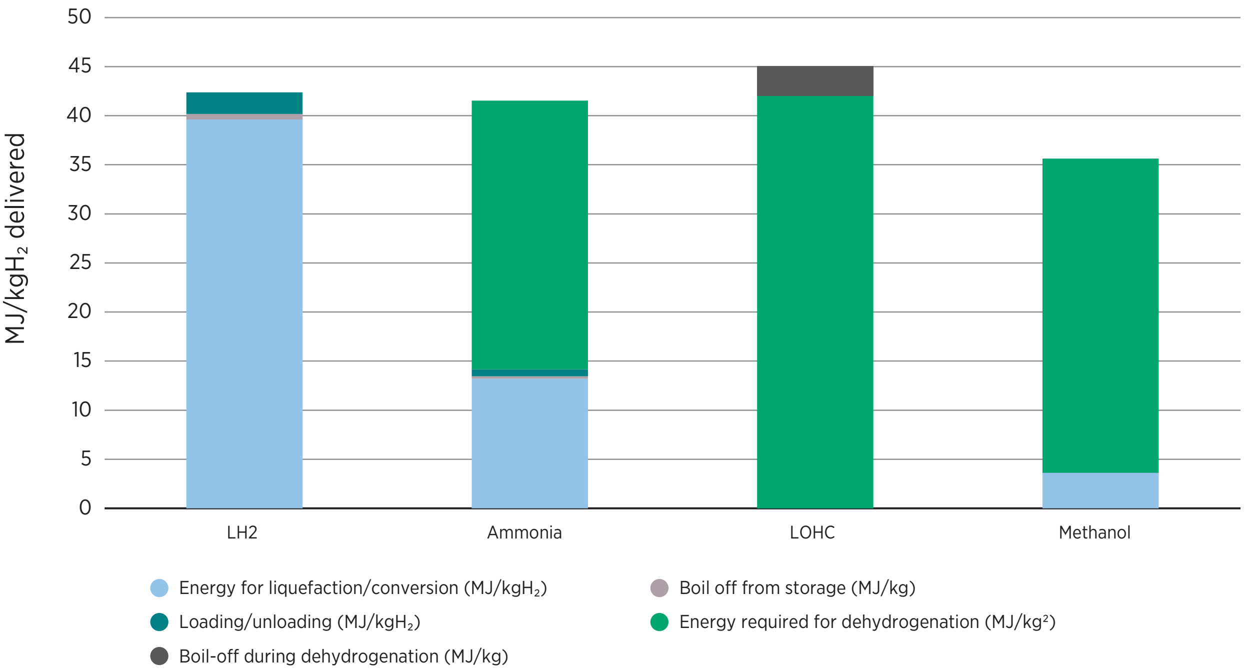
MJ/kgH_2 = megajoules per kilogram of hydrogen

Sources: (IRENA, 2022f; IRENA and AEA, 2022; IRENA and Methanol Institute, 2021; OIES, 2022).

In the case of liquid hydrogen, most of the energy is consumed in the producer country. In the case of ammonia, LOHCs and methanol, however, the dehydrogenation and cracking steps require significant amounts of energy in the destination country, which could be a disadvantage. However, this can be mitigated in the case of ammonia and methanol, if these commodities are used directly as fuel or chemical feedstocks, thereby avoiding the last reconversion step and its related, high-energy consumption.

In the case of LOHCs, thermal energy released during the hydrogenation step could improve the energy and economic balance, if this heat can be used by a local industrial source of medium-temperature heat demand (around 250°C).

Figure 16 Energy cost of shipping hydrogen over different carriers



Sources: (IRENA, 2022f; IRENA and AEA, 2022; IRENA and Methanol Institute, 2021; OIES, 2022).

5. CO-BENEFITS OF RENEWABLE HYDROGEN PRODUCTION FOR DEVELOPING COUNTRIES

In many developing countries, the potential for renewable energy is high, sparking hopes that the production and export of green hydrogen and its derivatives will not only drive economic growth, but also contribute to achieving sustainable development goals.

Green hydrogen production has the potential to yield multiple benefits, such as creating jobs, expanding access to clean energy and fostering green industrial development. Various agreements and new partnerships between developing and future importing countries characterise this as a win-win solution: industrialised nations get green hydrogen and commodities, while developing countries gain investments, jobs and technology transfers in return.

This positive outcome will not be automatic, however, and mutual benefits are not guaranteed. Depending on the respective local situation, there may be associated risks with the ramp-up of green hydrogen production. It is crucial to consider potential adverse environmental, socio-economic or political effects. There could be competition for resources, such as water and renewable electricity, between local demand and export requirements. It is important to acknowledge that the socio-economic benefits of the renewable hydrogen sector remain uncertain. This uncertainty stems from the fact that renewable hydrogen production has yet to reach a scale that allows for reliable assumptions about its socio-economic impact. The extent of local economic benefits hinges on the location of related industries and the equitable distribution of hydrogen-generated profits throughout the economy.

When exploring partnerships between Global North and Global South countries for exporting hydrogen and derived commodities, it is essential to pay close attention to and give careful consideration of potential challenges and implications. To ensure success, the right frameworks need to be in place, addressing all relevant aspects when building green hydrogen infrastructures.

This chapter looks into some of the areas that will be directly or indirectly affected by the hydrogen sector. These include: energy access, opportunity for islands and job creation. The chapter will not only spotlight the opportunities associated with green hydrogen production in developing countries, but also shed light on some of the risks that need careful consideration.

5.1 ENERGY ACCESS

Building large-scale renewable hydrogen production facilities carries significant implications for local communities and national energy systems, particularly when connecting electrolysers to the grid. To ensure sustainability and equity, it is crucial to consider these implications in the context of holistic energy sector planning.

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Some countries striving to produce renewable hydrogen and to export it face the challenge of limited energy access for their populations, let alone access to clean energy. The risk arises when countries prioritise becoming exporters without first meeting local energy needs, potentially leading to competition for scarce renewable energy supply. One of the major motivations for some of the developing countries striving to become hydrogen exporters is their high renewable energy potential, often times not fully leveraged.

The key question is how to transform this risk into an enhanced clean energy access opportunity. One possible solution involves directing a portion of investments towards accelerating the decarbonisation of the power grid and increasing energy access.

One feasible strategy is to allocate a portion of these investments towards enhancing the decarbonisation of the power grid and expanding energy access. This could involve enacting policies that require power plants to be deliberately oversized, with a segment of their output dedicated to the local grid and thus directly contributing to broader energy access.

An added benefit of commissioning renewable power plants for hydrogen production is the accumulation of knowledge and expertise within the country. This local capacity building is invaluable, as it not only supports the immediate projects but also equips the nation with the skills and experience needed to replicate success in future renewable energy power plants, reducing the perceived risk of such investments. In essence, the push towards green hydrogen production can act as a catalyst for broader renewable energy adoption, driving in tandem both technological advancement and sustainable development.

The pursuit of renewable hydrogen and derivative export should not come at the expense of decarbonisation and energy access goals, either. Countries must strike a balance between these priorities and use hydrogen and its derivatives as a tool to achieve sustainable development. By investing in renewable energy infrastructure, regulating variable renewable energy (VRE) plants effectively, and leveraging expertise gained from previous installations, countries can achieve their decarbonisation goals while also promoting economic growth and job creation.

5.2 OPPORTUNITIES FOR INDUSTRIAL DEVELOPMENT

Producing and exporting renewable hydrogen holds the potential for economic growth in developing countries, yet it comes with uncertainties and risks.

Currently, only three major hydrogen-importing markets are emerging: South Korea, Japan and the EU. These future import markets – all of them highly industrialised – are striving to maintain their local industrial clusters while reaching their climate goals by importing renewable hydrogen. While many Global South countries may be able to produce cost-competitive renewable hydrogen, this situation may lead to unequal power dynamics and an oligopsony, where a few large buyers set the rules for numerous potential exporters.

To ensure mutual benefits in emerging value chains, it is crucial to explore ways to maximise socio-economic advantages in developing countries. One approach is to expand value chains locally, which would increase local value creation. This approach follows a pattern that has been observed throughout industrial history: industry tends to follow energy sources. Access to energy has traditionally been one of the major factors that determines the location of industrial activity. For centuries, steel industries have emerged in locations with access to coal and iron ore (Lovins, 2021), as it has been found to be more efficient to produce iron briquettes or steel at sites with coal deposits, rather than transporting coal. As a result, coal-rich areas have often attracted wider industries.

The question is how expanding local value creation related to renewable hydrogen can be undertaken. Opportunities for this exist both upstream and downstream in the renewable hydrogen industry, as outlined below.

- **Upstream:** One way to enhance value creation upstream is by developing local manufacturing of components such as electrolysers, compressors, valves and metering equipment. While this may not be feasible for smaller markets, in some cases it can contribute to the local economy.

- **Downstream:** Another approach to creating higher local value is by processing green hydrogen into products with increased added value, such as renewable ammonia, methanol, and green iron. This transformation could contribute to the development of local industries like fertiliser or green steel production, generating both local use and higher revenues through exports. Expanding local value chains can also create more long-term job opportunities within the community.

The global energy transition will change the sources of energy capture, conversion and distribution globally. In a net-zero future, therefore, access to cost competitive energy will be determined largely by renewable sources of electricity. As renewable hydrogen production is inherently coupled to cost-competitive renewable energy generation, this may have an impact on industrial development.

Three elements can drive this phenomenon, namely: the willingness of industrial agglomerates to relocate or open new facilities; the cost of transporting energy; and the difference in cost of renewable energy (Mcwilliams and Zachmann, 2021).

Setting up new production facilities in renewables-rich countries can imply the closure of plants elsewhere, but does not do so necessarily. The energy transition offers scope for growth in many industries, with ammonia and steel two examples relevant to renewable hydrogen, as detailed below.

- **Ammonia:** According to IRENA's estimates, by 2050, transitioning to a scenario that aligns with the Paris Agreement's goal of limiting the global temperature rise to within 1.5°C would result in a market for ammonia of 688 Mt. This is nearly four times larger than the current market, which produces 183 Mt annually.

This ammonia would be decarbonised, with 566 Mt coming from new renewable ammonia production (derived from renewable hydrogen and renewable power). Additionally, there would be complementing fossil-based ammonia production in combination with carbon, capture and storage (CCS) (IRENA and AEA, 2022).

- **Steel:** The demand for steel is expected to continue increasing in the future, with global demand projected to rise from about 2 000 Mtpa today to 2 500 Mtpa by 2050. It is crucial to consider the availability of high-quality, cheap and abundant renewable and iron-ore resources for future green steel production (IRENA, 2023d).

Transporting green goods across continents will likely be cheaper than transporting green hydrogen in any form. Energy-intensive industries have the opportunity to establish new facilities in countries with low-cost renewable surpluses, exporting semi-finished products (*e.g.* reduced iron) or finished goods (*e.g.* cars). As a result, the cost of energy may be the key factor in the relocation decision, although other factors such as the availability of a skilled workforce or proximity to customers may also play a significant role.

Box 6

South-South co-operation on renewable hydrogen development

An increasing number of developing countries have created hydrogen strategies to move towards sustainable and clean energy systems. These countries primarily adopt an export-oriented approach, where they identify partner countries interested in importing hydrogen and work together to establish infrastructure and trade relationships. They usually sign Memorandums of Understanding (MOUs) to start trade development (see also Chapter 6).

However, there is limited collaboration between developing countries, which is a missed opportunity. These countries often face similar challenges and barriers when developing their hydrogen sectors. These include limited funding, a lack of technology and a lack of the expertise required for efficient hydrogen production and storage. They also include deficiencies in the associated infrastructure.

Sharing experiences, best practices and lessons learnt can accelerate the development of effective measures and policies to address these barriers. Facilitating information exchange and collaboration between developing countries can assist in identifying potential solutions. This can include: partnering on research projects to solve common challenges; working together on policy development to create a favourable regulatory environment for hydrogen production and trade; and exploring opportunities to jointly export hydrogen to international markets, thus enhancing their collective bargaining power. Alternatively, identifying potential local off-takers of green hydrogen can improve the industrial activity of the regions.

5.3 JOBS IN THE RENEWABLE HYDROGEN SECTOR AND DEVELOPING A HIGHLY-SKILLED WORKFORCE

Based on IRENA's calculations, investing in electrolysers and other renewable hydrogen infrastructure could create approximately 3.8 million jobs globally by 2030 and 6.5 million jobs by 2050. These calculations are based on the macro-econometric model used to compute the 1.5°C Scenario[11] for IRENA's *World Energy Transitions Outlook*. This equates to an electrolyser capacity of 428 GW by 2030 and 5 722 GW by 2050 (see Chapter 2).

However, it is uncertain exactly how many jobs will be created and how they will be distributed across different countries. While some governments are addressing job creation and skills development for the renewable hydrogen sector in their hydrogen strategies, approaches differ in assessing the expected job creation potential. Additionally, different methodologies are used to estimate the number of direct and indirect jobs that can be created in the development and operation of renewable hydrogen value chains. One methodology involves estimating job creation based on the industry's annual turnover, as explained in Box 7 (Bachaus *et al.*, n.d.).

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[11] *This scenario describes an energy transition pathway in which the increase in global average temperature by the end of the present century is limited to 1.5°C, relative to pre industrial levels. It prioritises readily-available technology solutions, including all sources of renewable energy, electrification measures and energy efficiency, which can be scaled up at the necessary pace for the 1.5°C goal.*
IRENA assesses the socio-economic footprint of the energy transition by adopting a macro-econometric approach. The 1.5°C Scenario, together with its associated investment costs and various policy assumptions, is used as inputs into a fully-fledged global macro-econometric model, that takes into account the links between the energy system and the world's economies within a single and consistent quantitative framework.
The model used for the analysis is the Energy Environment-Economy Global Macro-Economic (E3ME) model, developed by Cambridge Econometrics. A full description of the energy sector of each country or region has been fed into the model, with cost and investment data in power generation, energy efficiency, transmission and distribution grids and energy flexibility, as well as carbon taxes and fossil fuel subsidy phase-out. The energy sector parameters (e.g., installed capacities, energy mixes) are exogenously provided. The model has a proven track record of policy and policy-relevant projects. Those projects include the official assessments of the EU 2030 climate and energy targets and the long-term Energy Roadmap, and contributions to the IPCC on the economic impact of climate change mitigation.

Box 7

Estimating job creation based on industry turnover across the value chain

The steps in this methodology include the following:

1. For a defined country (or region) and year, starting from target clean hydrogen demand and production and price targets, the yearly turnover is calculated as:

   volume (kg/year) x price (USD/kg) = turnover (USD/year).

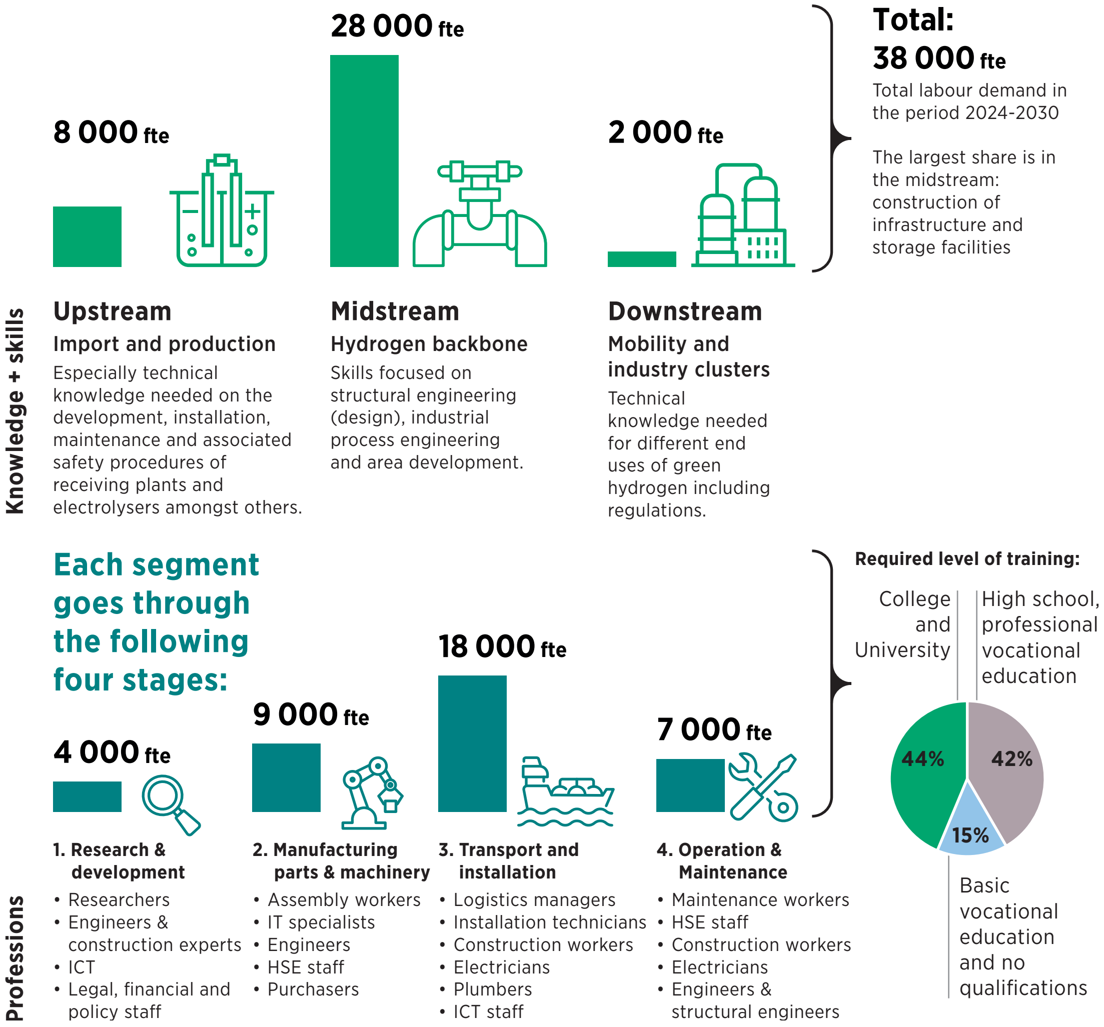
2. This turnover is then allocated to different economic sectors that participate in the value chain (for example, research and development (R&D), original equipment manufacturers (OEMs), industrial gas production, renewables, infrastructure (pipelines) and demand sectors such as chemicals, transport and other relevant parties.
3. For each of these sectors, typical multiplier factors are used (direct and indirect jobs/ USD million turnover) which can be translated into total job creation. As technology scales, and as the sector becomes more efficient, the number of jobs created per USD 1 million in turnover normally declines over time.

Jobs created in the OEM, R&D and infrastructure installation sectors are mainly temporary in nature, while jobs created in operation and maintenance (O&M) are there for the long term.

Box 7 **Continued**

A further distinction can be made regarding how the turnover is allocated to upstream (hydrogen production), midstream (hydrogen transport and storage infrastructure) and downstream (demand sectors), where midstream activities are usually the most labour-intensive.

Labour demand in the H_2 supply-chain



Total labour demand in the period 2024-2030

The largest share is in the midstream: construction of infrastructure and storage facilities

Upstream

Import and production

Especially technical knowledge needed on the development, installation, maintenance and associated safety procedures of receiving plants and electrolysers amongst others.

Midstream

Hydrogen backbone

Skills focused on structural engineering (design), industrial process engineering and area development.

Downstream

Mobility and industry clusters

Technical knowledge needed for different end uses of green hydrogen including regulations.

1. Research & development
- Researchers
- Engineers & construction experts
- ICT
- Legal, financial and policy staff

2. Manufacturing parts & machinery
- Assembly workers
- IT specialists
- Engineers
- HSE staff
- Purchasers

3. Transport and installation
- Logistics managers
- Installation technicians
- Construction workers
- Electricians
- Plumbers
- ICT staff

4. Operation & Maintenance
- Maintenance workers
- HSE staff
- Construction workers
- Electricians
- Engineers & structural engineers

Notes: fte = full time employment; ICT = Information and communication technology ; IT = Information technology; HSE = Health, Safety, and Environment.

Source: (Bachaus *et al.*, n.d.).

While advanced economies with well-developed industrial infrastructures can capture a large part of the clean hydrogen value chain, developing countries may only be able to capture a small part of this, for lack of R&D, OEMs and other factors. Herein also lies an opportunity in which developing countries could identify how to best use and develop their existing industrial and workforce capabilities to meet the needs of the nascent hydrogen economy.

As an example, a country with an existing manufacturing base could decide to invest in manufacturing components like pumps, tubes, cables and other equipment that is required for hydrogen infrastructure. It could thus capture a larger economic share and the related job creation. Table 6 provides an assessment of employment effects specifically for developing countries.

Table 6 Assessment of employment effects in developing countries

	EMPLOYMENT EFFECTS	ASPECTS TO CONSIDER
MANUFACTURING OF RENEWABLE ENERGY EQUIPMENT	Strong employment effects	• High market concentration (especially of solar PV). • Hydrogen technology patents (electrolysers and fuel cells). • Some inputs are more accessible for local production (*e.g.* steel structures, wind towers, pumps, cables), while others, such as PV cells, wind turbine components and blades, are often technology-intensive and rely on imports.
RENEWABLE GENERATION AND ELECTROLYSIS	Significant during construction, but weak in plant operation (depending also on type of renewable energy employed)	• Engaging in core activities requires substantial capital and scale. In most developing countries, foreign direct investment (FDI) and imported technologies are expected to play a leading role.
CONVERSION INTO DERIVATES	Significant during construction, but weak in plant operation	• This is capital- and scale-intensive, thus deterring new entrants. Core technologies are not mature. FDI and imported technologies are likely to play a leading role in most developing countries.
EXPORT (INFRASTRUCTURE)	Substantial during the construction phase, but the potential for forward and backward linkages and technological learning is fairly limited	• Requires large investments in ports, pipelines and storage capacities, as well as transport mode-specific investments (for ammonia synthesis, generation of LOHC and deep freezing hydrogen). • Most potential exporting countries will strongly depend on imports of industrial equipment, which may considerably reduce net export revenues. • Tax exemptions are often granted to investors (which are typically permitted to operate in special economic zones), thereby reducing the host country's tax benefits.
DECARBONISATION OF DOMESTIC INDUSTRIES	Strong employment effects	• There are high switching/start-up costs for clean technologies. Large subsidies for incumbent competitors. • It may be difficult to attract domestic customers due to initial price differentials between conventionally produced and "green" products.

Source: (UNIDO *et al.*, 2024).

The transition from current, megawatt (MW)-scale production to large-scale renewable hydrogen production will involve significant technological innovations. The impact of these on jobs is still to be assessed. As large-scale green hydrogen manufacturing processes become highly automated, for example, the potential numbers of jobs created is still unclear. Moreover, this complexity is compounded by developing countries' need of for infrastructure, materials, skilled labour and technology from other nations. Striking a balance between promoting imports, respecting the autonomy of the local economy and avoiding detrimental dependencies is of paramount importance. Social acceptance and community involvement are further critical factors, especially in the context of large-scale infrastructure development. This may also apply in building up supply structures to meet future green hydrogen demand. Peer learning from best practices could prove to be beneficial in addressing this.

Fostering a more inclusive workforce while addressing the urgency of the climate challenge is essential. Supportive policies and initiatives that enable individuals to acquire the diverse range of skills required in this evolving landscape should be prioritised.

6. HYDROGEN STRATEGIES OF POTENTIAL RENEWABLE HYDROGEN SUPPLIERS

The urgency of achieving net-zero emissions targets has led to a rapid growth in the number of countries developing hydrogen strategies, with more than 53 countries now possessing such plans. The private sector has also been active, with over 1 300 hydrogen-related projects being announced globally by mid-2023.

This marks the fourth wave of interest in hydrogen, following previous waves in the 1970s, 1990s and early 2000s. This wave is different in several ways, however, as outlined below.

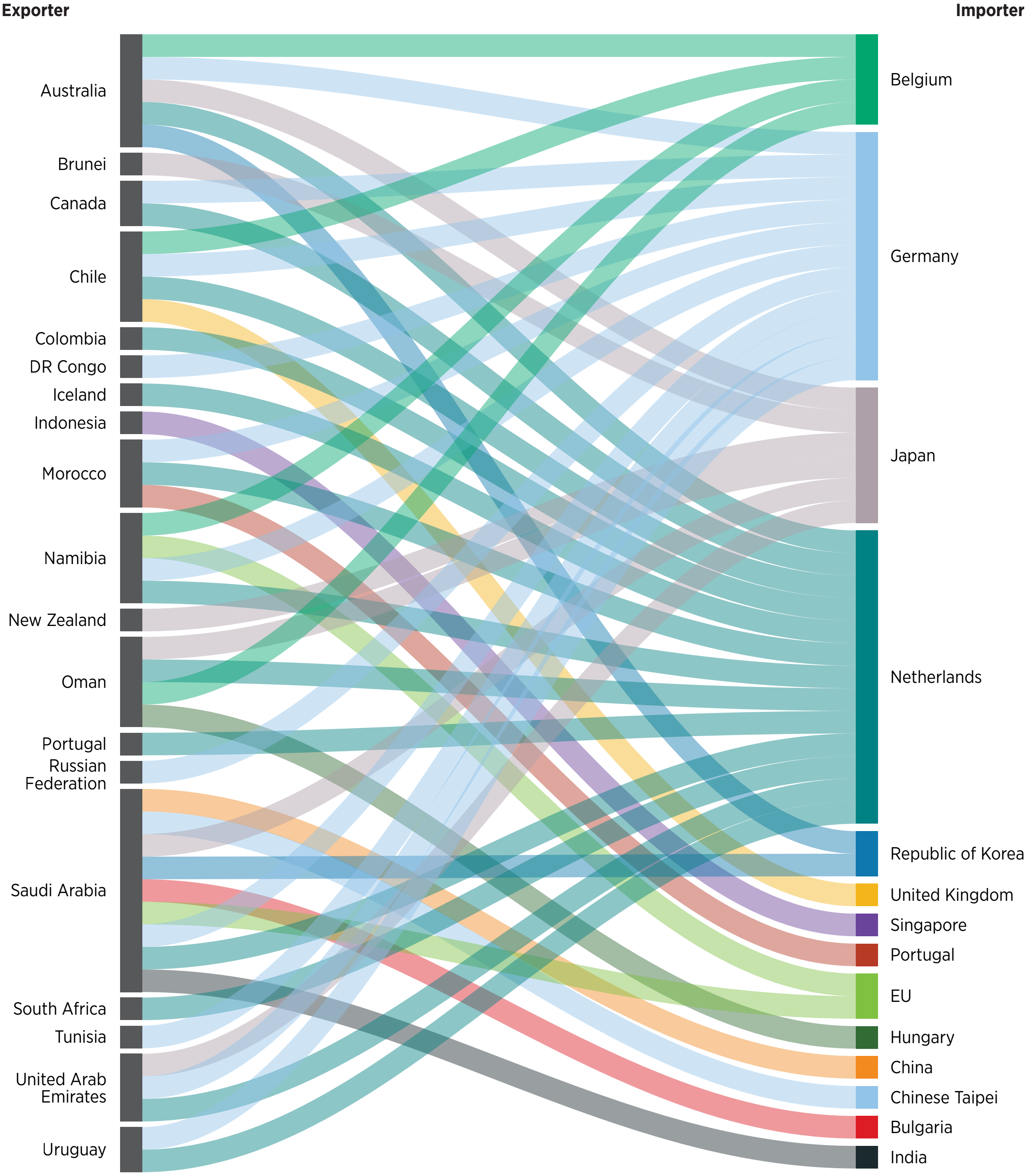
- Hydrogen strategies are now published much more frequently compared to previous waves. They are also being published by policy makers with precise policy targets – something missing in previous waves.
- The primary driver for investing in renewable hydrogen is now the energy transition, as opposed to past concerns about oil availability.
- The focus of most strategies is on hard-to-abate sectors, not the automotive industry.
- There is a heightened interest in renewable hydrogen due to the decreasing costs of electrolysis and renewable electricity.
- Lastly, there is a growing interest in trading hydrogen and its derivatives.

As already noted, the level of expected demand for renewable hydrogen in developed countries will not be completely met by local resources. Developed countries will therefore seek to import hydrogen from countries with a potential supply abundance. This has led to the signing of numerous MOUs, trade agreements and active diplomacy to facilitate hydrogen trade between Global North and South countries (UNIDO *et al.*, 2024).

Developing countries with high renewable energy potential are considered potential green hydrogen exporters due to their ability to produce low-cost green hydrogen, combined with their ample land availability. As indicated in Chapter 2, however, there will be just a few importing markets and many potential suppliers. It is therefore essential to investigate the strategic priority setting of future renewable hydrogen suppliers to gain a more comprehensive overview of the emerging international structure. It is also crucial to understand how socio-economic impacts that go beyond generating revenue from renewable hydrogen exports are being considered. Governments should also look at factors such as: the investment required to build and maintain the necessary infrastructure; the availability of skilled labour and technology; the overall investment climate; the existing infrastructure; the sustainability of government support; political stability; potential regional hydrogen demand; geopolitical stances; and the current energy mix and industry.

In the next section, priorities and policies announced by a selection of developing countries' hydrogen strategies are presented. The chapter analyses various plans that showcase country cases with distinct pre-conditions, such as diverse geographical features, location and size. These case studies help in comprehending the impact of different pre-conditions and how they influence the adoption of different policy approaches.

Figure 18 Hydrogen MOUs, as of October 2023



6.1 MAPPING SELECTED STRATEGIES

For this report, six national hydrogen strategies have been chosen from those published by Global South countries to provide an overview of policy plans across a diverse landscape. This complements previous analyses by IRENA of G7 member countries' strategy making.

The selected strategies come from three continents and include small island countries (Singapore and Trinidad and Tobago), desert areas (Morocco and Oman), and potential hydrogen hubs (Singapore). All the strategies were published in 2021 and 2022; Oman updated the strategy in May 2024 (DSI, 2021; Hydrom, 2024; IDB and National Energy, 2022; MEM Morocco, 2021; MEM Oman, 2022; MME Namibia, 2022; MTI, 2022).

With the exception of Singapore (see Box 8), one common characteristic among these countries is that they have significant potential for renewable energy generation, making them ideal for green hydrogen production and export.

These countries were also chosen as examples of different preconditions for green hydrogen production. The selection considered their varying distances from potential future demand centres for green hydrogen and its derivatives, as well as the existing infrastructure – a factor which plays a crucial role in facilitating the production, transportation and trade of green hydrogen.

Although these countries serve as illustrative examples, they do not include all Global South countries (excluding Singapore) aiming to accelerate hydrogen deployment and trade. From the analysis of the plans, it is possible to grasp the global dynamics at play and assess the different stances between Global North and Global South countries regarding hydrogen sector development.

Export orientation

All the selected countries have, in different ways, an export-oriented approach in their stated targets. While planning to produce hydrogen, much of the production would be dedicated to trade. Across the selected countries, the ratio between locally consumed and exported hydrogen varies between 2-to-3 and 1-to-9. More than half the foreseen electrolyser and VRE capacity is to be devoted to producing hydrogen and its derivatives for consumption in other countries. Table 7 provides an insight into the export orientation of the selected strategies.

Box 8

The case of Singapore

Singapore faces challenges in renewable hydrogen production due to its limited land and resources. To develop a hydrogen or ammonia sector, the country would need to make significant investments in new infrastructure. Despite this, the country has taken a unique approach, acknowledging its limitations and focusing on becoming a net hydrogen importer.

The country's strategy is centred on developing the midstream and downstream parts of the value chain, with a particular emphasis on the development of infrastructure for various end uses, such as industry, power, aviation and the maritime sector. The strategy also prioritises the development of ammonia bunkering for ammonia-fuelled ships.

Singapore's initial focus will be on importing, managing, and using clean ammonia as a fuel for electricity production, or as a hydrogen carrier. The country will invest in R&D to address technological bottlenecks, collaborate with international partners to enable supply chains for clean hydrogen, and plan for long-term land and infrastructure needs. Workforce training will also be a key priority.

Table 7 Comparing the export orientation of selected strategies

NUMERICAL GOALS/TARGETS	MOROCCO	NAMIBIA	OMAN	SOUTH AFRICA	TRINIDAD AND TOBAGO
PRODUCTION OF HYDROGEN (Mtpa)		1.0-2.0 (2030) 5.0-7.0 (2040) 10.0-15.0 (2050)	1.0-1.5 (2030) 3.25-3.75 (2040) 7.5-8.5 (2050)	0.5 (2030)	1.5 (2052) 4.0 (2065)
ELECTROLYSIS (GW)			8.0-15.0 (2030) 35.0-40.0 (2040) 95.0-100.0 (2050)	0.001 (2024) 15.0 (2050)	
CONSUMPTION OF HYDROGEN (Mt)	0.09-0.2 (2030) 0.42-0.59 (2040) 0.62-0.64 (2050)				1.5 (2052)
EXPORT OF HYDROGEN (Mt)	0.22-0.46 (2030) 1.0-2.0 (2040) 2.5-5.0 (2050) PtL (GWh) 3.0-6.3 (2030) 13.3-26.7 (2040) 33.33- 66.7 (2050)	5.0-8.0% of expected international hydrogen equivalent trade volume		1.0 (2050)	2.5 (2065)

Sources: (DSI, 2021; MEM Morocco, 2021; IDB and National Energy, 2022; MME Namibia, 2022; MTI, 2022; Hydrom, 2024).

This proportion is not a result of the selection of these specific strategies: export orientation is a common trait in the hydrogen plans of many developing countries (IRENA, 2024; UNIDO *et al.*, 2024).

In these strategies, the export focus is justified by three main factors:

1. The demand expected from developed countries. Import targets, such as those set by Germany and Japan, are explicitly mentioned in several strategies (see, for example, that of Morocco).

2. Market analyses conducted by respected international organisations, such as IRENA and the International Energy Agency (IEA). Reports assessing the future market for hydrogen, such as IRENA's *Global hydrogen trade to meet the 1.5°C climate goal: Trade outlook for 2050 and way forward*, are explicitly mentioned in some programmes (see, for example the strategy of Trinidad and Tobago).

3. Strategies may have their own in-house projections of expected export markets, or rely on third party projections.

This export orientation impacts the way the strategies are designed. This is evident when assessing the priorities, policies and roadmaps.

However, it is important to acknowledge that the framework used for developing these strategies has become widely accepted and normalised, leading to the perception of value neutrality. Nevertheless, it is crucial to recognise that this framework rests upon several underlying assumptions.

The first underlying assumption is that the export market for hydrogen will undergo substantial expansion in a short time frame. This carries inherent risks. While it is true that many developing countries are incorporating an export-oriented approach in their hydrogen strategies and signing MOUs, there is no guarantee that the projected growth in the global hydrogen market will materialise as expected. Factors such as evolving geopolitical dynamics, regulatory uncertainties and the emergence of competing technologies could significantly impact the actual demand and growth potential of hydrogen exports.

In addition, the reliance on exogenous import targets introduces a risk of overshadowing alternative opportunities. By primarily focusing on meeting specific import demands, developing countries may neglect the exploration of domestic or regional markets, as well as potential avenues for technological innovation and value creation within their own borders. This narrow emphasis on export-driven strategies might limit the overall resilience and sustainability of a country's hydrogen sector.

It is important to recognise that the sources indicating the potential for imports in the hydrogen market utilise the same framework, a narrative that sees actors move in predetermined ways, often replicating current dynamics (industries in the Global North, resources from the Global South) and strategies tend to align to this story.

It is crucial to acknowledge that export-orientation is not the only possible scenario and the future is likely to diverge from these projections. It is therefore essential to exercise caution and not overly rely on a single framework or set of assumptions when designing hydrogen strategies. Embracing a more adaptable and flexible approach that considers multiple scenarios and allows for adjustments based on evolving market dynamics will better position developing countries to navigate uncertainties and seize opportunities that may arise outside the confines of the prevalent narrative.

Priorities

Countries focus on different ways of both producing and consuming hydrogen.

Production routes

On the production side, the selected countries strongly prefer green hydrogen. South Africa, however, is an exception within the selection, as it aims to transition from grey to blue to green hydrogen. the country plans to stimulate local demand for hydrogen with short-term projects to demonstrate commercial potential and prepare for the global market. Blue hydrogen is considered a structural part of the South African transition, structured to preserve asset value, allow for sustainable management of assets and conserve employment, while diversifying employment opportunities.

Trinidad and Tobago focuses its strategy on green hydrogen, planning to install 57 GW of offshore wind to feed 25 GW of electrolysers by 2065. However, it has also dedicated space to hypothetically reducing the impact of grey hydrogen production (1.7 Mt consumed yearly) earlier than anticipated by using blue hydrogen and retrofitting existing ammonia and methanol plants. This activity would be intended to position the country to compete for low-carbon products before transitioning to green products when renewable energy and green hydrogen developments are established. This hypothesis suggests that blue hydrogen production will peak in 2040, meeting 80% of the industry's hydrogen demand, before declining, as green hydrogen production expands. The strategy recognises, however, that additional assessments are required to determine the necessary investment in CO_2 infrastructure, the duration of operation of CO_2 capture facilities, the long-term availability of natural gas, and the policy and regulatory framework needed to support the blue hydrogen sector's development.

Transportation

Export orientation also impacts priorities in the midstream section of the hydrogen value chain. As the countries in this study primarily seek to export large quantities of hydrogen, a greater focus is placed on accelerating projects that facilitate intercontinental trade. For countries located far from the main expected hydrogen importers, such projects include shipping, while in the case of Morocco, on pipelines, with the country now looking at a retrofit of the Maghreb-Europe gas pipeline.

Developing energy infrastructure with a primary focus on its export potential should, however, be complemented by simultaneous investments in domestic infrastructure to support local industry. Failure to do so can lead to underdeveloped domestic infrastructure, impeding a country's long-term sustainable growth. While pursuing exports can bring economic benefits, it is important to consider the potential drawbacks associated with an exclusive focus on export-oriented strategies.

When a country heavily prioritises exports, there is a risk of diverting resources away from developing domestic demand. This diversion of resources can hinder the country's ability to build and strengthen its own energy infrastructure, limiting the potential for technology learning, innovation and cost reduction within the domestic market.

Furthermore, a lack of focus on domestic infrastructure development can hinder the growth of local industries that could benefit from hydrogen technologies. By neglecting the development of local industries, a country may miss out on opportunities to create jobs, foster economic diversification and contribute to its overall socio-economic development. Investing in domestic infrastructure can support the growth of a local hydrogen industry, enabling technology transfer, promoting R&D, and fostering collaboration between academia, government and industry.

It is important to note, however, that the extent of this risk varies depending on the specific circumstances of each country. Some developing countries may have the necessary resources, capabilities, and market conditions to effectively pursue an export-oriented strategy without compromising domestic infrastructure development. These countries may have a robust industrial base, well-established domestic markets, and the ability to allocate resources effectively for both export and domestic infrastructure development.

End Uses

On end uses, hard-to-abate industries are part of the focus of the hydrogen strategies of all the selected countries, particularly the chemical industry. The export-oriented approach influences this decision. As hydrogen is difficult to transport, it is convenient to foresee a transformation process to transport renewable hydrogen carriers across the sea. Namibia, for example, aims to export hydrogen products – ammonia, methanol, synthetic kerosene and hot-briquetted iron – which have relatively lower shipping costs, to Europe, China, Japan, South Korea and other parts of the world. Table 8 provides an overview on the role of end-use within the different strategies.

On the other hand, Trinidad and Tobago, already an ammonia and methanol producer, is explicit in the desire to decarbonise its chemical industry before exporting hydrogen. Moreover, of the 1.7 Mt of local consumption, 0.2 Mt is allocated to steel and cement production. Whilst steel production facilities are currently mothballed, the 0.2 Mtpa allocated to them by the strategy would allow for the revival of this industry, as green steel gains traction in the market.

In South Africa, priority will be given to hard-to-abate sectors such as steelmaking, cement, mining, refineries and chemical production. Notably, South Africa also points toward decarbonising heavy-duty vehicles, shipping, aviation and rail. This aims to reduce the 11% share of national GHG emissions that come from the transport sector. Similar attention is sparser in other strategies.

Non-hard-to-abate sectors are of less interest in hydrogen strategies. Hydrogen for light-duty fuel cell electric vehicles (FCEVs), power generation and residential heating are sectors currently supported by few countries with fossil fuel reserves (IRENA, 2022e). In general, countries with fossil gas availability have a more flexible approach, aiming to use hydrogen in any end-use where fossil gas is used today, while countries that are likely to import hydrogen in the future have a more focused approach. At the same time, potential exporting countries are not concerned about using hydrogen for otherwise electrifiable end uses, in order to maximise their exports.

Table 8 Comparing the end-use priorities in selected strategies

CATEGORIES	MOROCCO	NAMIBIA	OMAN	SINGAPORE	SOUTH AFRICA	TRINIDAD AND TOBAGO
Value chain priorities (+/-)						
Production segment (upstream)						
Renewable/green	++	++	++	+	++	++
Blue				+	++	·
Transportation segment (midstream)						
Hydrogen pipelines	+		++			
Distribution by road/railway					++	
Shipping		++	++	++	++	++
Storage options	+			++	+	
Off-taking (downstream)						
Chemical Industry	++	++	++	++	++	++
Steelmaking		++			++	++
Cement					++	++
High temperature heating	+			++		+
Other industry		++		++	++	
Long haul aviation	+			+	++	·
Long haul shipping	+			++	++	
Long Haul trucks	++				++	+
Train	++				++	
Bus	++					+
Ferry						+
FCEV cars				·		·
Other mobility (specify)	+					
Power generation (fuel cell / turbines)	++			++	++	·
Residential	+					
Export	++	++	++		++	+
Import				++		

Notes: ++ = High priotiry; + = Low priority; · = mentioned

Policy tools

All the strategies present some policy measure that is going to be undertaken by the government. It should be noted, however, that hydrogen strategies differ substantially in terms of commitments made. In their strategy documents, South Africa and Namibia present many measures that will be undertaken soon or are already being undertaken, accompanied by the roles of public bodies and timelines. In other cases, commitments maintain a more high-level description, with only a few focused examples of committed policies.

Comparing the Global South strategies with those of the G7 members, it is possible to note some differences. Given their limited state budgets, the countries considered here only commit funds for direct incentives in a few cases. Instead, the policy packages proposed are designed to give information about the openness and ease of the hydrogen business in the specific jurisdiction. In Global South strategies, public funds are not allocated to green hydrogen projects, nor are specific, direct policies mentioned. Instead, enabling policies for businesses are highlighted. Examples include policies on fiscal incentives, infrastructure, land permits, knowledge and skills availability and transfer. These policies are undertaken with the intention of de-risking investment in the country in order to attract (often foreign) finance.

One peculiarity of this “open for business” approach are the land auctions, as designed in Namibia and Oman (see Box 9).

In many cases, strategies are explicit in their attempt to attract foreign investments. In line with its sustainable development goals (SDGs), the 'SDG Namibia One Fund' was launched at COP27 with a goal of reducing green hydrogen production costs. The fund is a partnership between the Environmental Investment Fund of Namibia, Climate Fund Managers and Invest International. It will use blended finance structuring to attract public and private capital to invest in high-impact sectors in emerging economies.

The Namibian government has commissioned the fund to manage all renewable hydrogen financing in the country on its behalf. The anchor investor – the government of the Netherlands working via Invest International – will provide EUR 40 million. The intention is for other donors and investors to join the fund in the future, increasing the fund size EUR 1 billion. Table 9 assesses the chosen policy tools to support the development of the renewable hydrogen sector in the respective country.

Box 9

Land auctions in Oman

Oman is offering 50 000 square kilometres (km^2) of land, with the potential to host 500 GW of renewable energy generation capacity, or the production of 25 Mtpa of green hydrogen. Hydrom, a new state-owned company, offers the land to investors in auctions. Oman expects the winning developers to deliver integrated projects covering the full green hydrogen value chain. For renewable production, developers are expected to propose a wind/solar mix that ensures a competitive Levelised Cost of Hydrogen (LCOH), with the technology mix evolving over time. In terms of hydrogen production, developers can choose their preferred electrolyser technology and end-product, whether hydrogen, ammonia or methanol. Furthermore, developers are expected to secure the offtake for their projects. They are anticipated to bid as consortia and partner with a government-owned entity post-award.

In December 2022, a request for proposals was issued by Hydrom, the state-run company established to support the development of green hydrogen in Oman. The first phase of auctions is divided into two bid rounds, aiming to meet the 2030 production target of 1 Mt. In Round 1, two land blocks were awarded in Duqm in June 2023. Round 2 plans to award up to three additional blocks in Dhofar by mid 2024.

In the first phase, five significant projects have been awarded in the Duqm area, for a total expected production of 750 kt per year. Three additional projects have been awared for the region of Salalah, for a total of 1.38 Mt.

Source: (Hydrom, n.d.).

Table 9 Comparing the policy tools of selected strategies

CATEGORIES	MOROCCO	NAMIBIA	OMAN	SINGAPORE	SOUTH AFRICA	TRINIDAD AND TOBAGO
Policy						
Grants	+				++	+
Mobilisation of finance	+	++	+		++	+
Taxation	+		++		++	
Hydrogen and non-hydrogen infrastructure creation	+	++	+	+	++	+
Production support mechanism						
Demand side support	+				++	
Regulation, standards and certification	+	++	+	+	++	+
Land permits		++	++	+		
Skills		++		+	++	+
Local content manufacturing		++			++	
Knowledge creation	++			+	++	+

Notes: ++ = Policy mentioned with details like governance and timelines; + = policy mentioned

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Box 10 Mini-grids for islands

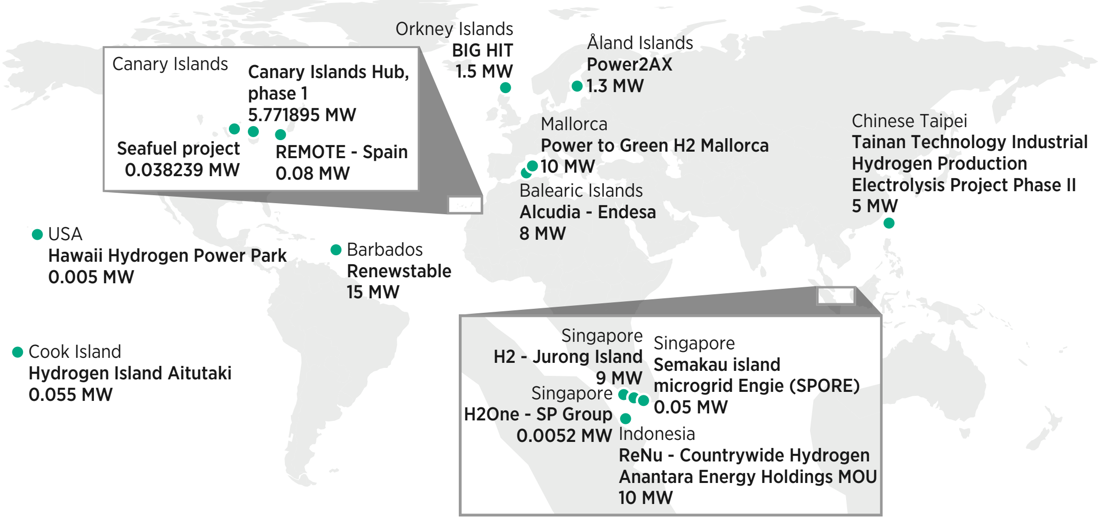
Mini- or micro-grids are electric power grids that can function independently. They consist of a self-reliant fusion of distributed energy sources (including generators and energy storage appliances) and interconnected loads. These can operate in parallel with the main grid, off-grid or in islanding mode providing reliable and efficient energy services to the final users.

Mini-grids are a necessity when the remoteness of locations and the limited demand load make the expansion of the grid something with little economic sense. Most islands operate with mini-grids, relying on fossil fuel imports (typically diesel fuel) for power generation. They, therefore, need to develop alternative solutions for their power needs when pursuing decarbonisation.

Generation on islands must be, in the absence of storage, as load-following as possible. VRE technologies, therefore, need to be paired with flexibility solutions. Storage allows a renewable mini-grid to use power at a different time than when it is produced and is a critical functionality for increasing the amount of renewable energy that can be used. Additional benefits include: an increase in the share of energy from renewable sources; the ability to provide continuous power; a reduction in demand for power during peak times; ramping and smoothing of load and generation; and a lessening of the impact of long-term and short-term fluctuation of renewable energy.

Various storage technologies exist today, ranging from mechanical to chemical solutions. Storing hydrogen produced during hours (and seasons) of excessive VRE production is an additional source of flexibility. Hydrogen is particularly interesting for its potential for seasonal storage. It can accommodate seasonal cycles in electricity demand and variable solar or wind, as it is durable, efficient and not affected by charging cycles. This could make it an instrumental part of a smart power system that stabilises the micro-grid and ensures full energy independence from fossil fuels.

Hydrogen could also complement daily-to-weekly storage of energy from other solutions. Currently, storage represents a significant portion of the costs associated with deployment and operation of renewable mini-grids, due to high upfront costs and replacement needs, which vary with each storage option. This cost can represent between 20% and 40% of the cost of a renewable mini-grid today (IRENA, 2016). Electrolyser technologies and other power-to-gas applications are increasingly being considered as storage solutions. At the moment, few projects are being developed on islands, with those that are still being at rather small scale.



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Hydrogen is best suited when it has a lower cost than regular electricity storage batteries. For hydrogen generators in the context of mini-grids, cost is mainly influenced by two factors: first, the cost of the fuel cell and tank system; and second, the cost of hydrogen production and its distribution.

The Asia Development Bank (ADB), for example, estimates that cost competitiveness for hydrogen storage in Maldives may arrive toward the end of the decade (ADB, 2020). Another potential advantage of hydrogen usage is the stimulation of sector coupling and the wider array of options to decarbonise end-use sectors, for example, by adopting hydrogen-fuelled ferries.

Producing hydrogen in small electrolysers using excessive energy only would, however, be more expensive than in centralised hydrogen production from regions with large VRE availability and higher capacity factors. For this reason, another opportunity for small islands comes from importing hydrogen produced elsewhere. This could be used when VRE, batteries and load-following resources are not available. While this would reduce energy independence, the hydrogen sector is less likely to become a cartel, leading to fewer opportunities to control prices, or to become used for geopolitical reasons. Indeed, hydrogen can ensure diversification of energy supply (IRENA, 2022e).

Phases of deployment

As the penetration of green hydrogen technologies increases and costs come down, a phased approach is used to reflect the expected evolution of the hydrogen sector, its policy needs and the increased deployment of green hydrogen. Five of the G7 members explicitly mention such a phased approach in their strategies, with explicit mid-term targets and forecasts for hydrogen's market growth (IRENA, 2022g).

Three of the selected strategies have a similar phased approach and are outlined in the table below.

CATEGORIES	MOROCCO	SOUTH AFRICA	TRINIDAD AND TOBAGO
Phases			
Phase 1	2020-2030	2021-2024	2022-2028
Phase 2	2030-2040	2025-2030	2029-2044
Phase 3	2040-2050	2030-2040	2045-2065

All the G7 strategies see the years around 2030 as the beginning of the last phase, when a rapid hydrogen market expansion is expected. This is not the same for Trinidad and Tobago and Morocco, which instead forecast maturity phases in 2045 and 2040 respectively. In addition, G7 import-oriented strategies earmark 2030 as the year when hydrogen imports will have already achieved significant size (notably, the 10 Mt EU import target is set to 2030). This date does not align with the selected strategies. Trinidad and Tobago foresee exceeding local demand for green hydrogen in 2045, when international trading could start. Morocco, meanwhile, predicts exports already having begun by 2030, but for limited quantities – between 10.3 terawatt hours (TWh) and 21.7 TWh of hydrogen and its derivatives. By 2050, this is predicted to increase up to tenfold.

In South Africa's first phase, there is a concentration on regulation and innovation that enables the hydrogen sector. The second phase aims to achieve 0.5 Mt of green hydrogen production by 2030 and implement an export strategy, including negotiating purchasing commitments, establishing partnerships and commencing exports. During the third phase, by 2040, South Africa aims to achieve a total installed capacity of electrolyser of up to 15 GW. By then, it also aims to be implementing an export strategy, including commercial export and increasing market size.

Harmonisation of expectations between the Global North and the Global South can lead to a clearer investment environment and boost investor confidence. By aligning expectations, countries can create a more predictable and stable framework for investment in the hydrogen sector, worldwide. This, in turn, can attract more investors and promote the flow of capital, technology and expertise, which are crucial for the development and scaling up of hydrogen technologies. In this, it is important to recognise the varying levels of readiness and prioritise capacity building, knowledge sharing and targeted investment, in order to support the growth of the hydrogen sector in the Global South.

Socio-economic and environmental aspects

As mentioned in Chapter 4, hydrogen (and the energy sector) do not exist in a vacuum. They have deep ties with the economy, society and ultimately the Earth. Historically, energy planning has had the tendency to disregard these aspects, but more recently it has evolved and now integrates more and more socio-economic and environmental aspects. In particular, these include job creation, environmental protection and decarbonisation. Hydrogen strategies do not differ and often include an evaluation of their impact on jobs – as can be seen, for example, in the Italian and Dutch strategies.

Water impact

In the strategies selected, the water aspect is considered in a variety of ways. It is worth noting that all the strategies mention desalinated water as the main source of water for electrolysis. Morocco and Oman present evaluations of the investments needed, including saltwater treatment.

The South African strategy recognises that the production of green hydrogen requires significant amounts of water. Given the water-scarce nature of the Northern Cape, where e-fuels are intended to be produced, this will most likely require the desalination of sea water.

In its strategy, Trinidad and Tobago highlight the challenge of limited water resources and emphasise the importance of desalination in green hydrogen production. The current desalination plants in the country have a limited capacity and cannot meet the additional water demand required for hydrogen production. Therefore, Trinidad and Tobago acknowledges the need to invest in new desalination facilities to accommodate the significant increase in water demand. Additionally, the strategy emphasises the importance of considering the environmental impact associated with increased brine production by desalination plants, highlighting the need for sustainable practices in water management.

Energy access

The only country with energy access issues in the selection is Namibia. The country faces challenges in terms of electricity access, with the national electrification rate estimated at around 45% (IEA, IRENA, UNSD, World Bank, WHO, 2023). This implies that more than half of Namibia's population lacks access to electricity and clean fuel sources for cooking. Namibia’s hydrogen strategy emphasises the potential of economies of scale in larger plants to reduce the cost of greening the domestic grid. Access to a stable and cost-effective green power supply is considered crucial for expanding affordable electricity access across the country, aligning with Namibia’s developmental goals.

In 2021, Hyphen was announced as the preferred bidder for a green ammonia plant in the Namib Desert, Tsau Hyphen. Hyphen’s shareholders include Enertrag, which is headquartered in Germany. The plant, to be built in phases, is set to produce 2 Mt of green ammonia by 2030. Currently, a study is underway to evaluate the integration of Hyphen's facilities into the Namibian grid through the establishment of new transmission lines.

Additionally, Hyphen is exploring options for temporary energy storage to facilitate smoother integration into the grid, with a capacity of up to 2 TWh to 4 TWh per year (see Box 5).

Industrial relocation

Industrial relocation is not a part of hydrogen strategies, with the attraction of new industries using cheap and large-scale hydrogen production not considered a priority. Indeed, South Africa explicitly mentions the decarbonisation of energy intensive industries as a priority, with the only new industry seen as viable to attract being the sustainable aviation fuel industry.

For Namibia, the development of a renewable energy grid, as a consequence of the deployment of hydrogen projects, has the potential to attract new energy-intensive industries. These could include aluminium and glass production, fostering the country's green growth. Namibia's comparative advantage in renewable energies presents an opportunity to produce goods that leverage these resources, thereby attracting FDI into new and emerging sectors. In addition, Namibia is considering exporting reduced iron briquettes. In its strategy, however, it is not considering attracting those industries that the exported hydrogen would serve, such as the fertiliser and steel industries.

Jobs and a just transition

Jobs are mentioned in some of the selected strategies. Oman, for example, foresees 70 000 new jobs, 17 000 of which are to be managerial (MEM Oman, 2022). In the latest strategy, Oman foresees green hydrogen as a catalyst for significant local industrialisation, as well as substantial local production of various raw materials and components. Furthermore, the transition will spur new industries, including local manufacturing of solar panels, wind turbines and electrolysers, supporting green steel and e-fuel production The deployment of wind turbines, solar panels and electrolysers will require corresponding increases in the local production of steel, concrete, plastics, glass, aluminium, copper, silicon and nickel.

This industrial expansion is expected not only to support the development of green hydrogen but also stimulate adjacent industries - from mining to green steel production - resulting in positive feedback loops. For example the growth of the mining sector, powered by renewable energy is seen to support the renewable energy value chain. In agriculture, excess electricity and water trickling from green hydrogen production is seen to boost output, enabling increased crop and cattle production. These developments are set to enhance Oman's business ecosystem, driving economic diversification and sustainability (Hydrom, 2024).

In Namibia, the hydrogen industry is expected to create 85 000 direct jobs by 2030 and 185 000 by 2040. Most of these are to be in construction, business services, transportation and durable manufacturing. Namibia also forecasts 60 000 indirect jobs by 2030, rising to 130 000 in 2040. By 2030, however, only between 35 000 and 40 000 skilled and qualified people are expected to be in the Namibian job pool. Indeed, in contrast to most Global North countries, Namibia faces the problem of a "talent gap".

The country's skills development and labour supply strategy aims to address this, however, by mapping out the resources, skills and programmes necessary to fill the gap. By 2025, a sizable portion of lower-skilled jobs, such as those done by technicians, might be filled by re-skilling the passive labour force through vocational programs for the unemployed and recent graduates. In addition, immigration could be a significant supply of highly skilled labour, with this then imparting skills to the local labour force. Projects for developing hydrogen will be carefully planned out in order to handle peaks in labour demand and maintain employment.

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The government of Singapore, meanwhile, is set to work with industry, unions and the education sector to support workforce development. This aims to equip Singaporeans with the skills and knowledge needed to thrive in the hydrogen sector.

In South Africa, that sector is expected to create 30 000 jobs by 2040. The country's strategy anticipates that there may be some job losses during the transition to a net-zero carbon economy, despite the fact that this is predicted to support a net growth in jobs. A "Just Energy Transition Centre" is planned, with an emphasis on retraining particular marginalised groups so that they can take advantage of opportunities in the energy transition, including hydrogen. This centre will be expected to conduct studies with relevant research chairs to predict market demand for particular skills. It will also inform policy in order that it can respond with appropriate interventions.

The South African strategies emphasise the gender aspect as well, imposing on governing bodies a number of actions and targets in order to ensure a just and inclusive energy transition that empowers women. This involves actions such as: investing in training and capacity-building initiatives for female green industry professionals; encouraging equal access to promotions, management and leadership roles; and the development of a pipeline of female talent with the technical skills and knowledge required to secure green-industry jobs and advance to senior levels.

As mentioned in Chapter 5, the real impact of the hydrogen transition on the job market is still uncertain. To address this uncertainty in these early stages, it is advisable for countries to transparently share assumptions about job creation. This practice can lead to a better understanding of the potential economic impact of hydrogen production and facilitate informed decision-making for the industry's development.

6.2 NAVIGATING THE STRATEGIC OBJECTIVES OF POTENTIAL IMPORTING AND EXPORTING COUNTRIES

The rapid rise of hydrogen as a crucial element in the energy transition highlights its potential for reducing emissions in hard-to-abate sectors. It also highlights its growing significance in the worldwide energy trade, particularly between countries in the Global North and South.

As different countries around the world develop and implement hydrogen technologies, especially in the Global South, a collective effort towards utilising renewable energy sources has become apparent. Indeed, with many strategies focusing on exporting hydrogen, with an emphasis on its production using renewable energy, a global shift towards sustainable energy systems is highlighted. These strategies also come with inherent challenges, however. These include market dependence, the need for substantial infrastructure and skilled labour development, and the geopolitical risks.

This chapter has outlined the export-oriented approach adopted by many countries. In this, a significant portion of the planned capacity for hydrogen production will be allocated to international trade. More precisely, over 60% of projected electrolyser and VRE capacity is to be earmarked for export to third countries. These targets are in line with the strategic objectives of key markets such as Japan, South Korea, and the EU, which anticipate substantial reliance on imported hydrogen to meet their consumption needs. However, for this export-oriented approach to be successful, the projected growth in the global hydrogen market needs to materialise as expected.

As an example, incentive schemes like the EHB aim to stimulate the external production of green hydrogen and import it to the EU, providing temporary certainty. However, if EU producers become competitive, demand from overseas could be smaller than anticipated. Therefore, it is advisable for exporters to develop an internal market for green hydrogen and derivatives to balance out this uncertainty.

The analysis of hydrogen strategies across the Global South reveals a critical need for flexibility, adaptability, and comprehensive consideration of socio-economic and environmental impacts. While exporting offers economic benefits, it is crucial to balance these with investments in domestic infrastructure and industries to foster sustainable growth and resilience.

The evolving hydrogen sector presents both opportunities and challenges for countries worldwide. Strategic planning, international collaboration, and a focus on sustainable and inclusive growth are imperative to harness the full potential of hydrogen in the global energy transition.

As the hydrogen sector continues to develop, it will be crucial for countries to navigate the complexities of the market, infrastructure needs and socio-economic considerations to achieve their energy and environmental goals effectively. The dynamic nature of the hydrogen sector, marked by slow technological advancements and uncertainties regarding costs, underscores the importance of maintaining a flexible and adaptive approach to hydrogen strategy development.

As clarity emerges, and the economics of hydrogen production, storage, and transportation evolve, it becomes critical for countries to regularly review and update their hydrogen strategies. This flexibility ensures that policies remain aligned with the latest developments and cost efficiencies, enabling countries to swiftly capitalise on technological breakthroughs and cost reductions. By staying attuned to these changes, countries can adjust their strategic priorities, scale up successful initiatives and recalibrate their focus as needed. This approach not only maximises the economic and environmental benefits of hydrogen, but also safeguards against the risks associated with market shifts.

7. CONCLUSIONS AND RECOMMENDATIONS

This report has examined the important factors that contribute to the development of sustainable renewable hydrogen value chains. It has explored the various environmental, infrastructural, socio-economic and governance aspects that are associated with renewable hydrogen production in developing countries, along with its transportation to meet future demand. The report has highlighted the opportunities and potential risks associated with shaping international hydrogen value chains. Based on this analysis, the report can now provide some key recommendations and action points for stakeholders to consider.

7.1 COMPREHENSIVE SUSTAINABILITY FOR RENEWABLE HYDROGEN VALUE CHAINS

The renewable hydrogen sector presents a unique opportunity for first movers to demonstrate the potential of a sustainable and equitable energy transition, both locally and globally. The hydrogen value chain is one of the most critical factors in achieving climate goals, with the emissions levels throughout the chain playing a key role in this regard. To ensure that renewable hydrogen and hydrogen-derived commodity value chains are sustainable and equitable, a comprehensive approach that considers economic, environmental, social and governance aspects beyond emissions intensity alone is also necessary. This approach will help to address the challenges that arise from the production, transportation and consumption of renewable hydrogen and hydrogen-derived commodities.

The economic aspect considers the cost-effectiveness of renewable hydrogen production, transportation and storage. The environmental aspect deals with the impact of renewable hydrogen production on the environment, such as water consumption and land use. The social aspect covers the impact of renewable hydrogen production on communities, such as job creation and training. Finally, the governance aspect contains the regulatory framework and the strategic target-setting of stakeholders in the renewable hydrogen value chain.

In summary, the renewable hydrogen sector has tremendous potential to contribute to a global energy transition that is both fair and sustainable. A comprehensive approach that considers all aspects of renewable hydrogen production and consumption is necessary, however, to ensure that the emerging renewable hydrogen and hydrogen-derived commodity value chains are truly sustainable and equitable.

ACTIONS SUGGESTED:

- In order to ensure that the emerging hydrogen sector is beneficial for both producer and consumer countries, it is important to have a shared understanding of sustainability. This involves working towards a common understanding on the strategic and project level, which includes considering environmental, economic and governance aspects. A just and sustainable renewable hydrogen sector can be fostered by creating a shared understanding of sustainability.

- The renewable hydrogen market is still in its early stages. There will be many challenges to overcome during the scale-up phase. To support a rapid scale-up, it is important to share best practices and lessons learnt by first movers, especially those that have assessed and addressed the impact on sustainable development. This will help to ensure the mutual benefit of the sector.

7.2 MITIGATING ENVIRONMENTAL RISKS AND MAXIMISING OPPORTUNITIES

The shape of any product's value chain varies depending on the technologies selected, efficiencies and whether the final product is locally consumed or transported over long distances. With hydrogen, there will be multiple derivatives available on the market, all of which may be traded. To contribute towards achieving climate goals, it is essential to minimise the emissions intensity throughout the entire value chain. This requires a focus on rapid renewable energy deployment. A robust quality infrastructure is necessary to minimise potential risks, ensuring that renewable hydrogen and its commodities can be traded globally, while also being sustainable and safe.

When it comes to emissions intensity, renewable-based electrolytic hydrogen holds the least amount of uncertainty in the full market of production options. It is also likely that major importing markets in the future will prefer renewable hydrogen and its derivates. By producing these, access to more importing markets can be achieved, reducing uncertainty. This further enables alignment with achieving the SDGs.

ACTIONS SUGGESTED:

- Renewable hydrogen production requires the rapid deployment of renewable energy. The deployment of renewable energy should not be limited to just meeting the needs for renewable hydrogen production. To ensure that the development of the hydrogen economy in exporting regions also drives the wider energy transition, it is important to support renewable energy deployments beyond those required to power production facilities – both locally and in areas with abundant resources.

- Developing high-quality infrastructure for the production and transportation of renewable hydrogen and its derivatives can help ensure that it can be traded globally while still being sustainable and safe. Co-operation in developing a strong quality infrastructure can ensure the safe use of hydrogen at both the national level and internationally through intergovernmental forums.

- To ensure that renewable hydrogen and derivative production maximises opportunities for reaching climate goals, it is crucial to champion initiatives that emphasise environmental impact, resource efficiency and water management. It is also important to avoid offloading negative impacts in resource-rich areas.

7.3 CONSIDERING THE ROLE OF HYDROGEN DERIVATIVES IN BUILDING MARKETS

Hydrogen carriers allow the transport of hydrogen over long-distances from resource-rich countries to future demand centres. Ammonia and methanol are two examples of hydrogen carriers, each with different technical implications. However, both ammonia and methanol are not only hydrogen carriers, but also hydrogen-derived commodities, as chemical feedstocks and with potential functions in the energy system. Future demand hubs – including the G7 countries – could meaningfully support the development of derivative value chains in developing countries as well as in addition to historic and existing support for the development of renewable hydrogen projects.

The merit of such an approach bridges two aspects discussed in this report. First, there is an opportunity here to support local market development of renewable hydrogen and hydrogen derivative value chains in developing countries. Nurturing a local market first provides the knowledge needed to participate in the global market. Second, from an efficiency perspective, energy losses can be minimised by building value chains around the direct use of the derived commodities themselves. It is also likely to be more convenient to transport derivative commodities than hydrogen itself across long distances – for example, from developing country producers to import markets in Europe, Japan and elsewhere.

ACTIONS SUGGESTED:

- G7 countries could invest in market development, research, development and demonstration activities, and capacity building initiatives, which specifically target the derived commodities of ammonia and methanol. The intent here could be two-fold: this support could help to develop efficient export capacity for the commodities, while there is also an opportunity to support deep decarbonisation and industrial development by growing production capacity and local use of the commodities in the developing countries themselves. In their emerging hydrogen strategies, developing countries are increasingly recognising these opportunities. The G7 countries should support these initiatives, while also facilitating the development of future export capacity.

- Support local decarbonisation and sustainable industrial development in developing countries while in parallel facilitating the development of future export capacity.

7.4 COLLABORATING ON LOCAL VALUE CREATION WITH A FOCUS ON DEVELOPING COUNTRIES

Many developing countries have the potential to produce significant amounts of renewable energy, which is an opportunity for economic growth and sustainable development.

One way to take advantage of this potential is by producing and exporting renewable hydrogen and its derivatives. This can lead to various co-benefits, such as job creation, increased access to clean energy, and the promotion of green industrial development. However, achieving these outcomes requires careful planning, including the development of a skilled workforce in both the public and private sectors. G7 countries can enable developing countries by supporting capacity-building that focuses on renewable hydrogen technologies and sustainable energy practices. This will help equip the workforce in these countries with the skills necessary to participate effectively in the global hydrogen sector. By investing in capacity building, risks associated with the ramp-up of green hydrogen production can be mitigated. This investment can also ensure that developing countries can sustainably and equitably harness their renewable energy potential.

ACTIONS SUGGESTED:

- There are several aspects that need to be explored in order to understand the implications of renewable hydrogen and its derivatives production. These include identifying the kind of jobs that will be created, as well as determining how to provide education and skills development for this new sector.

- Different countries have already developed approaches to tackling these issues. Sharing these experiences can help accelerate progress. It is important to exchange insights on the potential benefits of this new industry, including assumptions about job creation.

- Capacity building and education initiatives are particularly important for developing countries, where the growth of this sector could create significant job opportunities. Therefore, it is crucial to invest in capacity-building to develop a skilled local workforce in these areas.

7.5 PROMOTING STRATEGIC PARTNERSHIPS – BOTH GLOBAL AND INTER-REGIONAL

Encouraging the formation of strategic partnerships between potential suppliers of green hydrogen, demand centres and technology providers is crucial in accelerating the adoption of advanced technologies across the hydrogen and commodity value chains – and to scale up production capacities.

Front-runner countries can play a pivotal role in facilitating technology transfer, sharing best practices and leveraging financial and technical resources to support the hydrogen sector in developing countries. For instance, social acceptance and local community involvement remain mostly overlooked, but can significantly contribute to preventing harm and to maximising the benefits of renewable hydrogen production.

These strategic alliances are vital to overcoming technical and economic barriers, enabling more rapid deployment of renewable hydrogen projects and ensuring that the benefits of the hydrogen transition are shared widely. Further formats for South-South co-operation can support exchange between developing countries that face similar barriers and challenges when developing their hydrogen sectors.

ACTIONS SUGGESTED:

- Transferring knowledge and sharing best practices are crucial in various fields, particularly in areas such as social acceptance and community involvement. Learning from each other’s perspectives can be very beneficial. The green hydrogen sector in developing countries needs resources and support to facilitate the transfer of knowledge and sharing of best practices. Intraregional co-operation should also be encouraged to help developing countries facing similar challenges.

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