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Green hydrogen opportunities for emerging and developing economies

Identifying success factors for market development and building enabling conditions

By Joseph Cordonnier and Deger Saygin (1)

(1) OECD Environment Directorate

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Keywords: green hydrogen case studies; hydrogen roadmap; hydrogen value chain; industry decarbonisation; levelised cost of hydrogen.

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Contacts:
Joseph Cordonnier, CEFIM Policy Analyst
joseph.cordonnier@oecd.org

Deger Saygin, CEFIM Industry Programme Lead
deger.saygin@oecd.org

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Abstract

Hydrogen is a cross-cutting energy vector that can help to decarbonise various end-use sectors. At least two-thirds of the global hydrogen production is projected to be green hydrogen by 2050, supporting the transition to a net-zero emissions global energy system. This paper presents a value chain approach to identify priority areas for developing national hydrogen strategies, focussing on emerging and developing economies. Further, the analysis highlights success factors for green hydrogen projects, based on eight case studies covering applications in industrial, transport and power generation sectors. The paper summarises the enabling conditions and financing solutions that can spur the green hydrogen market creation and growth.

Keywords: green hydrogen case studies; hydrogen roadmap; hydrogen value chain; industry decarbonisation; levelised cost of hydrogen.

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Résumé

L’hydrogène, en tant que matière première et comme vecteur énergétique, est en mesure de soutenir la décarbonisation de nombreux secteurs. Au moins deux-tiers de la production mondiale d’hydrogène devraient être de l’hydrogène vert d’ici 2050, ce qui favorisera la transition vers un système énergétique mondial à émissions nettes nulles. Ce rapport présente une approche systémique de la chaine de valeur afin d’identifier les domaines prioritaires au sein de stratégies nationales pour le développement de l'hydrogène, en se focalisant sur les économies émergentes. En outre, l’analyse met en évidence les facteurs clés de succès de projets dédiés à l’hydrogène vert, à l’aide de huit études de cas couvrant les secteurs de l’industrie, du transport et de la production d’électricité. Enfin, le rapport résume les conditions favorables et les solutions de financement susceptibles de stimuler la création et la croissance du marché de l'hydrogène vert.

Mots-clés : études de cas pour l’hydrogène vert; feuille de route hydrogène; chaîne de valeur de l’hydrogène; décarbonation de l’industrie; coût actualisé de l'hydrogène.

Classification JEL : L20, O14, O25, Q42, Q48

Acknowledgements

The Clean Energy Finance and Investment Mobilisation (CEFIM) programme aims to support governments in emerging economies in South and Southeast Asia, Latin America and Africa to enable finance and investment in renewable electricity, energy efficiency and decarbonisation of industry ("clean energy").

Green hydrogen produced from renewable power and water is considered as one of the pivotal solutions to achieve net-zero emissions by 2050 worldwide. The majority of growth in industrial output, transport activity and power capacity is expected to take place in emerging and developing economies. While green hydrogen can contribute to lowering the carbon dioxide emissions of each of these sectors, identifying its most suitable applications will depend on national circumstances. Thus, this working paper provides the groundwork to better understand how to identify opportunities and create an enabling environment for green hydrogen development in support of CEFIM programme's activities in its partner countries.

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Abbreviations and acronyms

ADB	Asian Development Bank
AEC	Anion Exchange Membrane
AFD	Agence Française de Développement (French Development Agency)
ASU	Air Separation Unit
CAPEX	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon Capture, Use and Storage
CEFIM	Clean Energy Finance and Investment Mobilisation
CO_2	Carbon dioxide
COP	Conference of Parties
CUI	Common User Infrastructure
DAC	Direct Air Capture
DFI	Development Finance Institution
DKK	Danish krone
DRI	Direct Reduced Iron
DST	India Department of Science & Technology
EAF	Electric Arc Furnaces
EJ	exajoule
ESG	Environmental, Social, and Governance
EU-ETS	European Union Emissions Trading System
FCEV	Fuel Cell Electric Vehicles
FID	Final Investment Decision
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Corporation for International Cooperation)
GJ	gigajoules
GoO	Guarantees of Origin
Gt	gigatonne

GW	gigawatt
H2	Hydrogen
IFD	Innovation Fund Denmark
INR	Indian Rupee
InvIT	Infrastructure Investment Trust
IPO	Initial Public Offering
IPP	Independent Power Producer
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
LPG	Liquefied Petroleum Gas
MDB	Multilateral Developments Bank
MtG	methanol-to-gasoline
Mtpa	million tonnes per annum
NAMA	Nationally Appropriate Mitigation Actions
PPA	Power Purchase Agreement
SCDI	Southern Corridor Development Initiative
SDG	Sustainable Development Goal
SOEC	Solid Oxide Electrolyser Cell
SPV	Special Purpose Vehicle
RDD&D	Research, Development, Demonstration, and Deployment
TWh	terawatt-hour
UNDP	United Nations Development Programme
USD	United States Dollar
VRE	Variable Renewable Energy

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Executive Summary

International organisations and think tanks, as well as global, regional and national-level industry initiatives, are increasingly emphasising the role of green hydrogen in aligning the global energy sector with a net-zero pathway. As of today, over 30 countries have developed, or are in the process of developing, national hydrogen strategies to facilitate their climate action plans and to take advantage of the social and economic co-benefits offered by the green hydrogen value chain. This Working Paper is meant to create discussion in support of shaping an agenda on green hydrogen for the OECD's clean energy financing and investment work in emerging and developing economies. Drawing upon a large body of literature and using the green hydrogen value chain as a backdrop, it reflects on the opportunities to develop green hydrogen and its derivatives in emerging and developing economies, proposing a three-step approach.

- Understanding the value chain and overall country potential. The report highlights areas for consideration in the process of defining national hydrogen strategies by outlining the opportunities of various hydrogen usages. It provides a list of statements to support policymakers to carry out a preliminary self-assessment of their country's potential to develop green hydrogen. It also underscores the expected growing importance of the trade of green hydrogen and its derivatives at a global scale and the role of international collaboration.
- Understanding the business cases and economics factors. After assessing a country's potential and identifying its strength and blind spots along the green hydrogen value chain, an analysis of the benefits and risks, notably the parameters driving the costs, is a crucial step towards building robust business models and confirming suitable applications in a country. A checklist enables countries to pinpoint potential barriers to the creation of an enabling environment. Quantitative examples of green steel and green ammonia production underscore the importance of addressing the upstream, midstream and downstream components of the value chain.
- Identifying suitable policies to bridge the viability gap and develop the market. This Working Paper provides insights from case studies of green hydrogen projects, focusing mainly on emerging and developing countries, identifying commonalities and specificities of enabling market conditions and financing mechanisms that can foster the development of green hydrogen. Finally, it highlights how stakeholders can successfully initiate the growth of the green hydrogen market in their countries.

The value chain approach and the empirical analysis support the proposal for policy instruments that can help emerging and developing economies to create and drive the growth of a green hydrogen market.

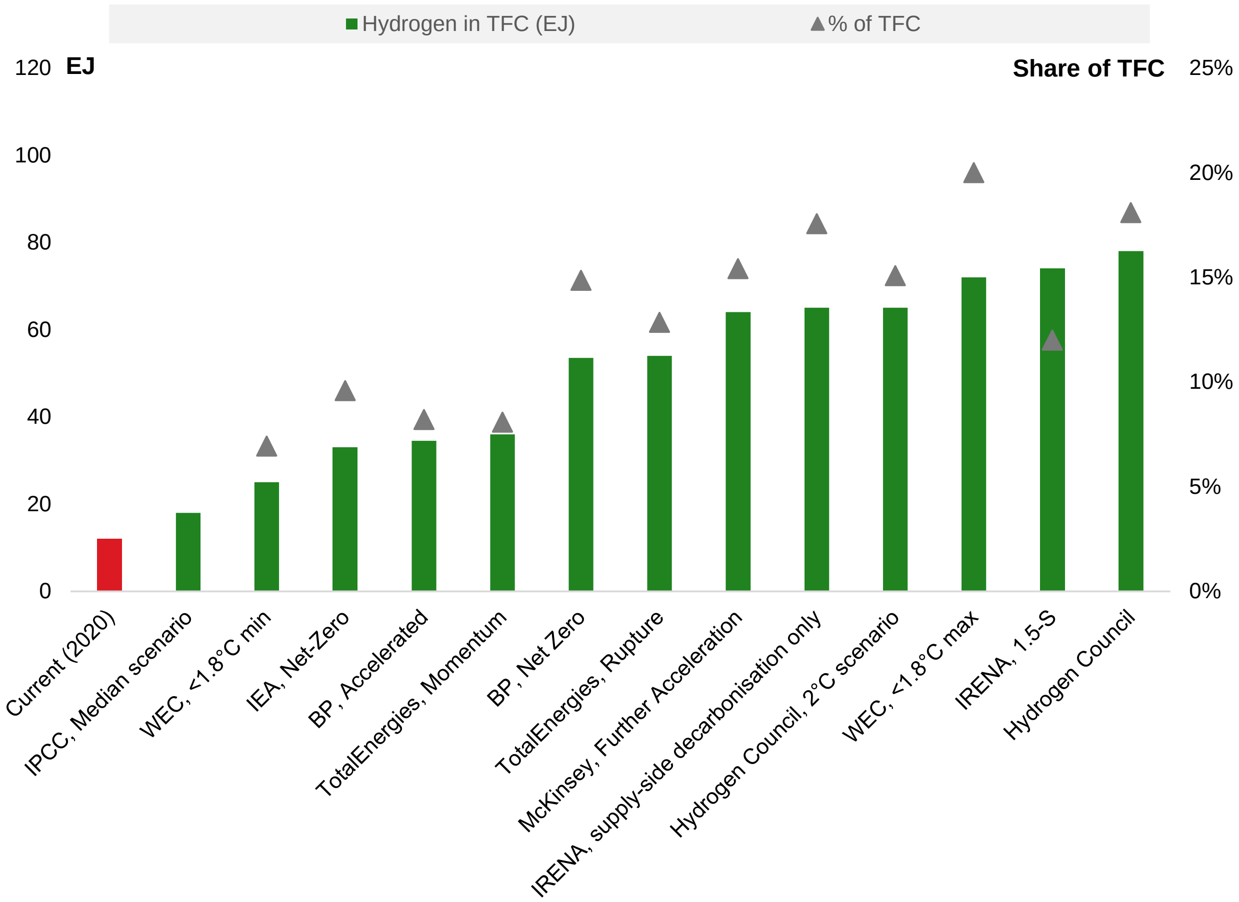
1 Green hydrogen potential for net-zero

Growing role of hydrogen in the global energy mix by this mid-century

Low-carbon hydrogen is projected to cover 12% to 22% of the global energy demand in 2050, estimated to be around 340-420 exajoules (EJ) (see Figure 1.1). The relative role of green and blue hydrogen differs between scenarios. IRENA's 1.5-S Scenario suggests that two-thirds of the 612 Mt of hydrogen needed by 2050 will be green (IRENA, 2022[1]). Green hydrogen's role in global energy transition scenarios vary for a wide array of reasons, including greenhouse gas (GHG) emissions reduction ambitions, underlying enabling policy assumptions, penetration rates of technology options across sectors and cost assumptions (Quarton et al., 2019[2]). As more net-zero emission scenarios are being released, the role of green hydrogen is becoming more prominent in these projections.

Green hydrogen, produced using renewable energy sources, has the potential to contribute to the low-carbon economic transition. As a cross-cutting energy vector, hydrogen can help decarbonise end-use sectors like heavy industry and integrate higher shares of variable renewable energy (VRE) sources (such as solar and wind) into the energy system. It can also be converted in derivatives, such as green ammonia or synthetic fuels, which can also contribute to mitigating GHG emissions. Hydrogen deployment will support the decarbonisation of nearly 140 countries that have pledged to achieve net-zero emissions within the coming decades, covering 83% of global emissions (Net Zero Tracker, 2022[3]).

Figure 1.1. Share of hydrogen in total final global energy consumption according to different scenarios in 2050

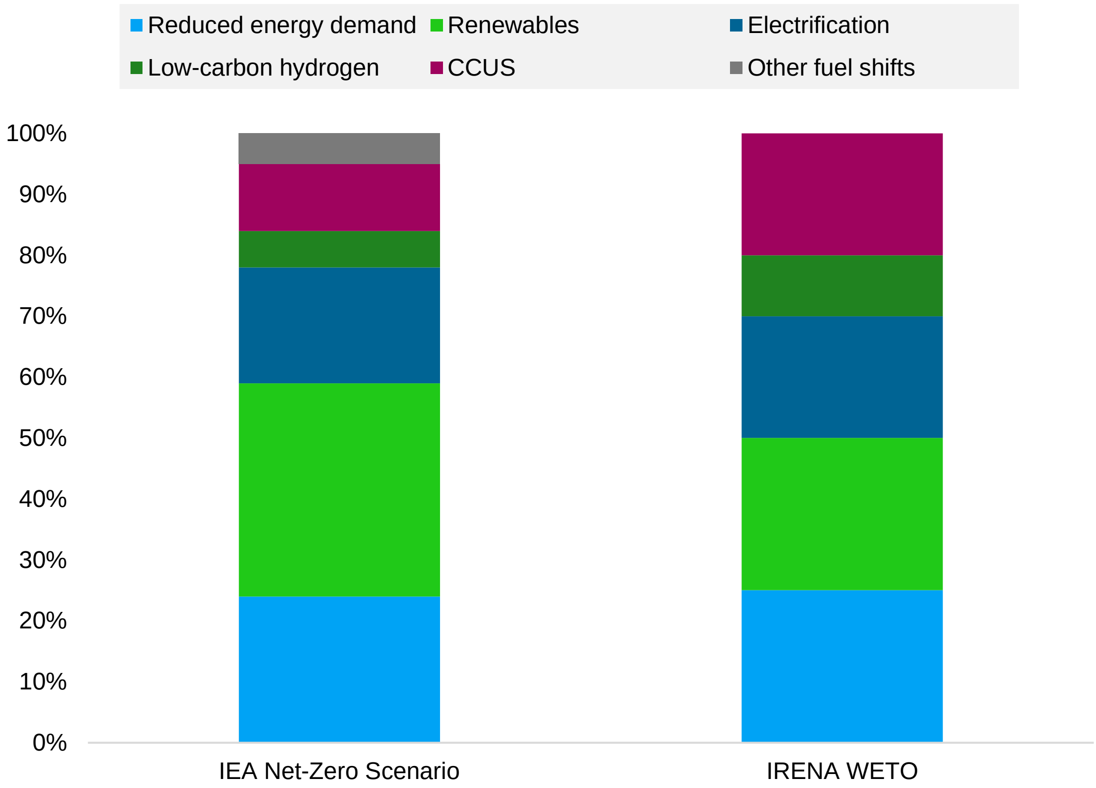


Note: The calculation for the percentage of the Total Final Consumption (TFC) is the ratio of the hydrogen production divided by the Total Final Consumption, except for the IRENA 1.5-S Scenario, in which the part of the hydrogen demand that is explicitly not part of the final energy demand (e.g. hydrogen use as feedstock for high-value chemicals) is excluded.
Source: Authors, based on (IEA, 2021[4]), (World Energy Council, 2021[5]), (IRENA, 2022[1]), (TotalEnergies, 2021[6]), (bp, 2022[7]), (Hydrogen Council, 2017[8]), (IRENA, 2022[9]), (Energy Transitions Commission, 2021[10]), (BloombergNEF, 2021[11]), (McKinsey, 2022[12]).

Emissions reductions potential of low-carbon hydrogen for net-zero transition

Achieving the objectives of the Paris Agreement will require a combination of various low-carbon technology solutions and approaches (see Figure 1.2). These will include reducing primary energy demand (through energy efficiency, increased material efficiency and recycling, and behavioural changes), decarbonisation of electricity supply coupled with electrification of end uses, and the direct use of renewable energy resources as fuel and feedstock. While mitigation measures to reach net-zero are well identified, their relative role in the net-zero path will vary depending on several factors, in particular the economic viability projections for carbon capture, use and storage (CCUS) and green hydrogen.

Figure 1.2. Contribution of low-carbon hydrogen (green and blue) to cumulative emissions reductions required to reach net-zero emissions by 2050



Source: (IEA, 2021[13]), (IRENA, 2022[9]).

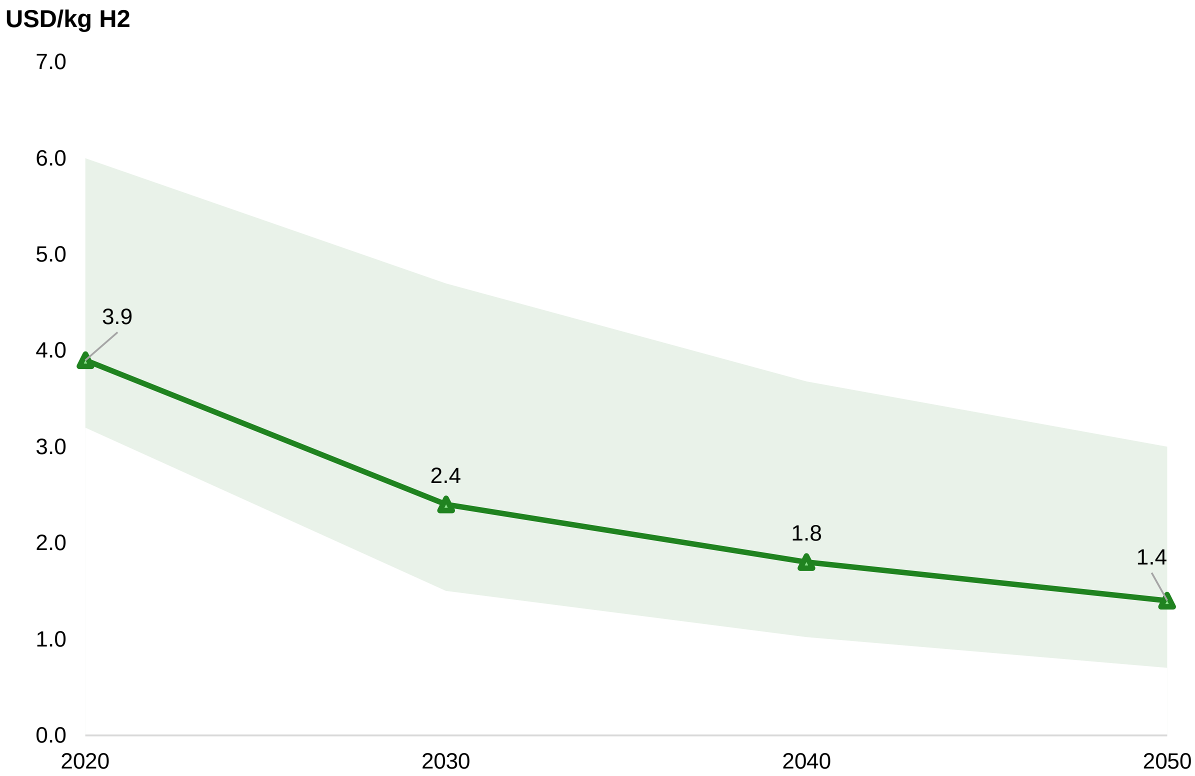
Profitability of green hydrogen by 2030/2050

Green hydrogen production costs are expected to decrease considerably in the next decade, driven by the falling costs of renewable power and improved learning curves in electrolysers due to capacity additions and continued innovation.

Electrolyser shipments are expected to increase from 0.5 gigawatts (GW) in 2021 to 2.5 GW in 2022, with global capacity reaching 15 GW by 2026 and driving costs down (IRENA, 2020[14]). Green hydrogen supply is expected to achieve cost parity with grey hydrogen (derived from fossil fuels) in some regions by 2028, with costs as low as USD 1.5 per kilogram (kg) (see Figure 1.3) (Hydrogen Council, 2021[15]). Besides, the expected expansion of carbon emissions market for industrial sectors and its possible international price alignment under Article 6 of the Paris Agreement may act a key lever to bridge the cost gap between green hydrogen and its fossil fuel competitors (Natixis, 2021[16]).

Hydrogen production capacity is expected to reach 5 000 gigawatts (GW) by 2050, requiring a total renewable power production of 21 000 terawatt-hour (TWh) to contribute to the global net-zero emission efforts. This implies a total cumulative investment need of USD 11.7 trillion in renewable power, electrolysers and pipeline reconfiguration by 2050 (IRENA, 2022[1]).

Figure 1.3. Project developments in the levelised costs of green hydrogen production between 2020 and 2050

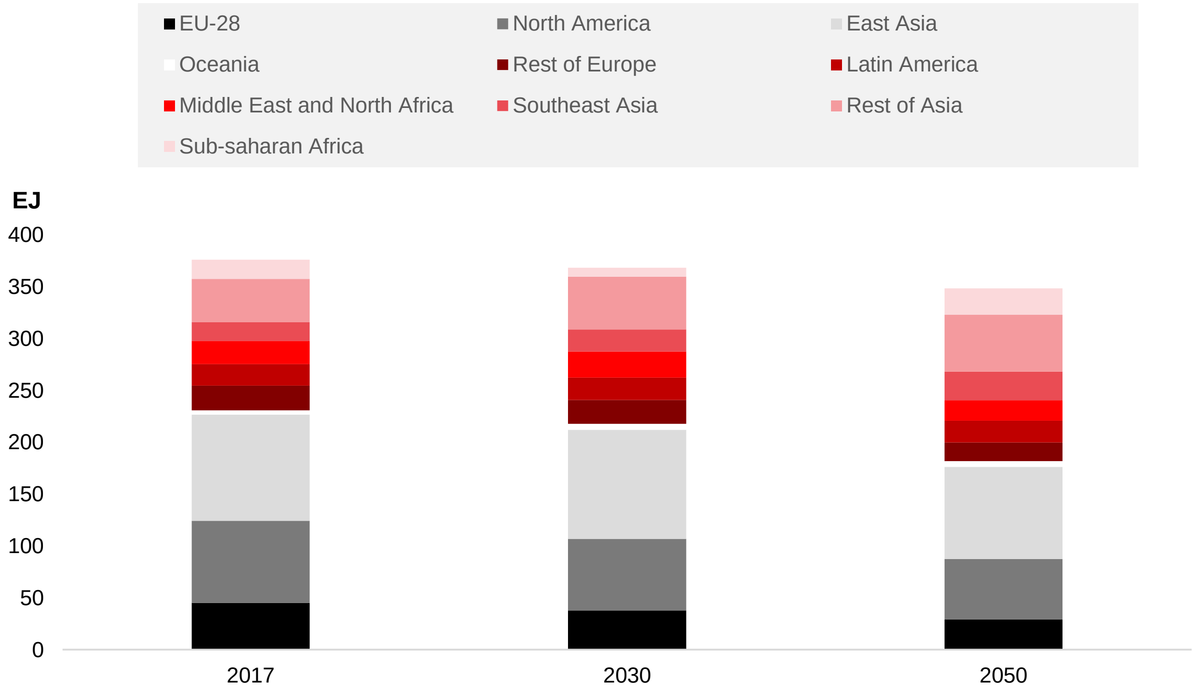


Source: Authors, based on (World Energy Council, 2021[5]), (Neuwirth and Fleiter, 2020[17]), (Hydrogen Council and McKinsey & Company, 2021[18]), (European Union, 2021[19]).

Growing importance of emerging and developing economies

By 2050, countries outside the Organisation for Economic Co-operation and Development (OECD), primarily comprising emerging and developing economies, could account for between 60% and 70% of the final global energy demand (EIA, 2021[20]). Energy demand is expected to increase markedly in Africa and Asia (except in East Asia), including in the ambitious scenario where global energy demand would slightly decrease between 2017 and 2050 (see Figure 1.4).

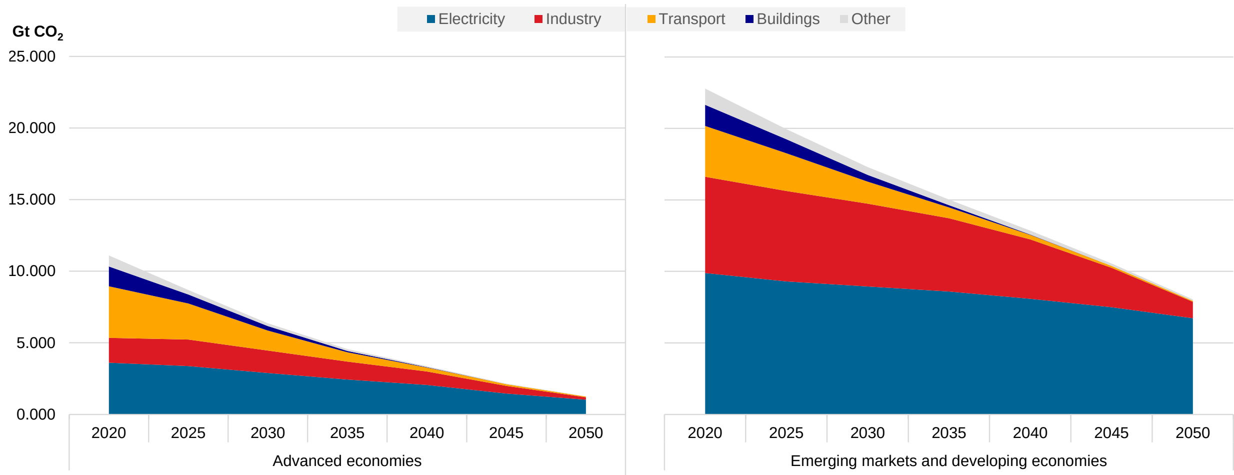
Figure 1.4. Energy demand evolution between 2017 and 2050



Note: Data from the Transforming Energy Scenario.
Source: (IRENA, 2022[21]).

While the industrial production in advanced economies is expected to remain stable or increase slowly between 2020 and 2050 (IEA, 2021[4]), the production of steel, cement and chemicals products is expected to increase in emerging and developing economies (World Economic Forum, 2022[22]). In the transport sector, new hubs will develop in these countries, especially as ports play a critical role to support international trade development. For instance, Mexico, Indonesia and South Africa have been identified by the P4G-Getting to Zero Coalition Partnership as regional hubs that could accompany the transition of international trade to green fuels and sustainable products. This increase in industrial and transport activities in these countries thus requires urgent decarbonisation solutions.

Figure 1.5. CO_2 emissions in the coming decades come mainly from emerging and developing economies



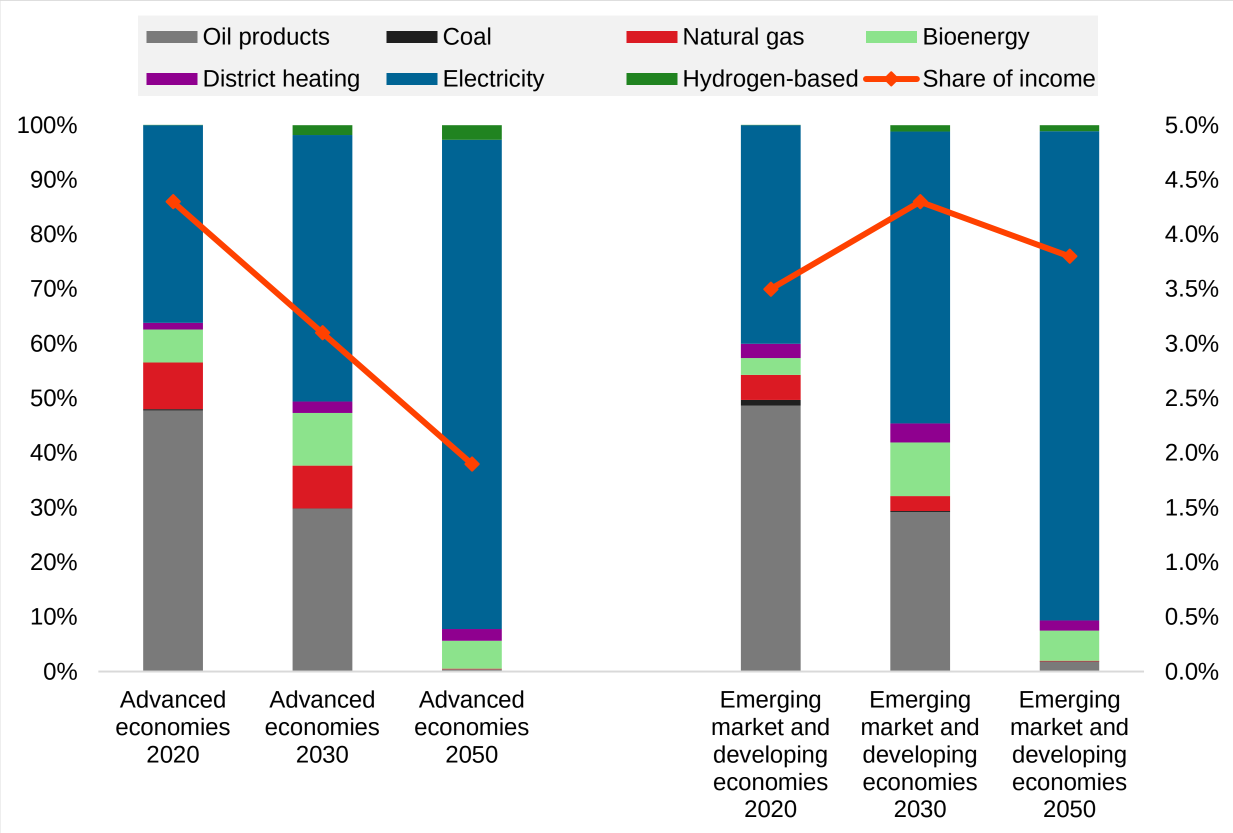
Source: (IEA, 2021[4]).

Fortunately, many emerging and developing countries are endowed with abundant low-cost renewable energy resources, thus making them major potential producers of green hydrogen. These countries are poised to reap the social and economic benefits brought by green hydrogen, such as improved energy security for countries dependent on fossil fuel imports and affordable clean energy access for remote regions. In larger grids, green hydrogen can support the integration of renewables, limit power supply interruptions and provide long-term energy storage. Green hydrogen can also accompany clean industrial growth in emerging economies with large industrial production capacity, for instance steel in India, ammonia and fertilisers in Egypt, and Trinidad and Tobago, or cement in Viet Nam and Indonesia. The deployment of hydrogen for these applications are at varying stages of commercialisation and their benefits will depend on the industrial process characteristics, the necessary process and equipment modifications, as well as the other decarbonisation options available.

Box 1.1. Opportunities to integrate green hydrogen development within a Just Transition approach

A just transition implies greening the economy in a fair and inclusive way, particularly by creating decent work opportunities and leaving no one behind (ILO, 2021[23]). Direct and indirect electrification, such as through the production and use of green hydrogen, will play a growing role to provide energy to industrials and households. Various end-users will compete to access the cheapest renewable sources. Overall, a lack of access to low-cost renewable energy could inflate the households' energy bills, as the share of renewable electricity increases their energy consumption. This is particularly relevant for emerging and developing countries, where energy bills are projected to account for 4% of household incomes in 2050 (see Figure 1.6). In these countries, it is critical to ensure that green hydrogen development will not jeopardise sustainable development goal (SDG) 7 pertaining to universal access to affordable, reliable, sustainable and modern energy services.

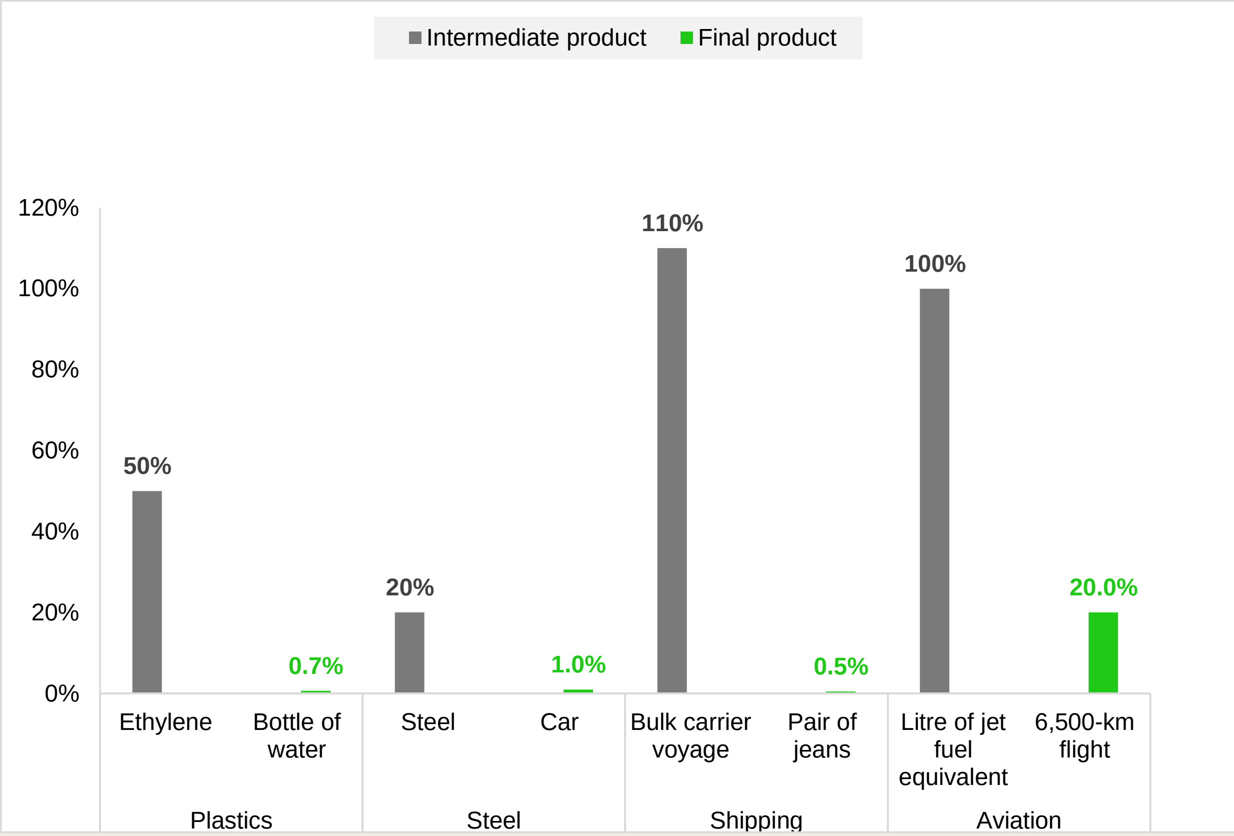
Figure 1.6. Average annual household energy bill in the IEA's Net-Zero Emissions Scenario



Source: (IEA, 2021[4]).

However, the impact of the potential cost increase due to the replacement of fossil fuels by green hydrogen and its derivatives will be different for consumers of industrial products (typically industrial companies) and for households. For instance, even though maritime shipping costs could double, the impact on the final price of transported goods, such as a pair of jeans, would remain limited (see Figure 1.7). Despite the potential limited impact on end-consumers, special attention should be paid to the fallout from cost increases, to ensure that the policies implemented for green hydrogen development are aligned with a just transition objective.

Figure 1.7. Impact of decarbonisation solutions on consumer prices - cost increase of intermediate and final products



Source: (Energy Transitions Commission, 2018[24]).

Increasing the role of green hydrogen in the economy can foster net job creation in the renewable energy sector (CE Delft, 2021[25]). As of the end of 2020, 12 million people worked in the renewable energy sector, with an average of 5.6 jobs per installed MW in solar and 1.7 jobs per installed MW in wind energy (IRENA, 2021[26]). By 2050, if green hydrogen accounts for 12%-22% of the total final energy consumption globally, up to 10 million jobs could be created to meet the renewable power needs for green hydrogen production. The net jobs creation related to green hydrogen development may be very sensitive to multiple parameters, in particular to the development of the associated infrastructures. Additional jobs will be created in the development, construction and operation of electrolysers. It is important to note that a significant share of these jobs will be one-off construction jobs and that the total jobs creation also spans over activities that are not classified as hard to abate, such as refuelling stations.

Estimates show that progress towards clean energy systems can also bring net job creation (ILO, 2018[27]). Major oil and gas organisations are evolving into energy companies by expanding their business portfolios into renewables and leveraging staff skills that are transferable between activities (DNV, 2022[28]). Thus, in emerging and developing economies where these industries are already active, new jobs can be created in the energy transition with minimal upskilling or reskilling. Moreover, the development of a market for green products may gradually shift the production of some industries to locations with access to cheap and reliable green hydrogen, skilled workforce, high productivity and political stability.

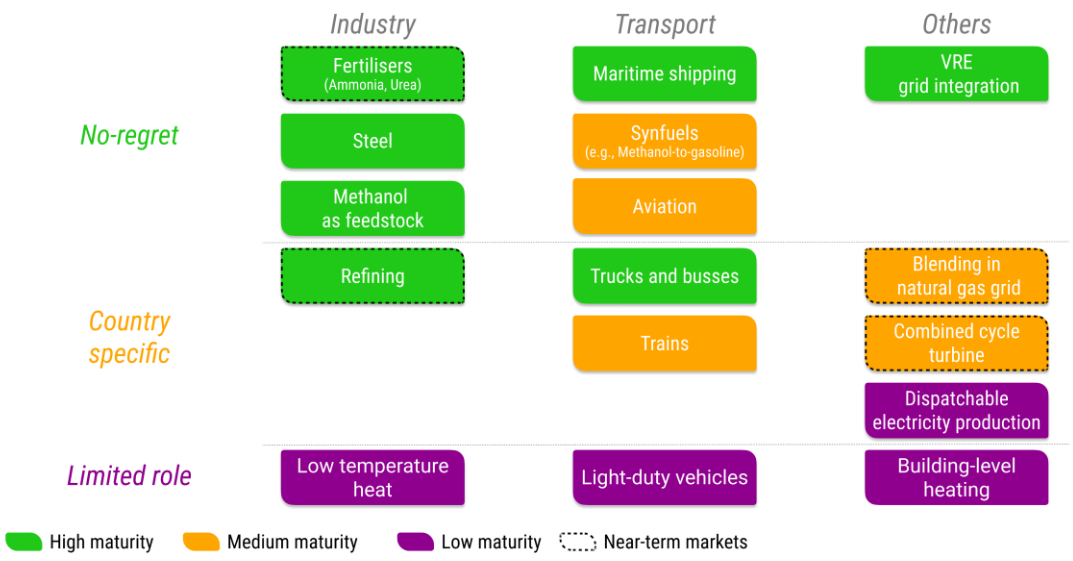
Potential applications and usages of green hydrogen

Global net-zero scenarios in recent years have emphasised hydrogen as a key decarbonisation solution. Available decarbonisation options are limited for sectors that are hard to abate, such as heavy industry, freight transport (particularly shipping) and aviation. Heavy industry currently emits around 7.0 gigatonnes (Gt) of carbon dioxide (CO_2) per year and long-distance transport modes around 4.0 Gt CO_2. Their direct CO_2 emissions represent around 30% of total global energy-related CO_2 emissions, which have ranged between 33 and 36 Gt CO_2 per year over 2017-2021 (IEA, 2022[29]). Green hydrogen and its derived products could be important enablers to align these sectors with the net-zero emissions goal. In net-zero scenarios, the use of hydrogen is generally prioritised for hard-to-abate industry sectors with high process heat requirements that cannot be met by other low-carbon alternatives. It is also prioritised in transport, notably in the maritime sector. Some countries at advanced stages of VRE deployment are also considering its use to enhance electricity system flexibility, since green hydrogen provides a medium for long-term seasonal storage, for instance through the production of synthetic fuels

Indeed, these choices are being driven by the scale of hydrogen production as well, depending on whether hydrogen is integrated into large demand centres in industrial regions or distributed across the country for multiple purposes. Nevertheless, there is no one-size-fits-all roadmap, and existing national strategies show that green hydrogen choices are based on local and national circumstances

Matching the supply of green hydrogen with consumption in a no-regret application can be challenging during the market creation and market growth phases. While the development of large-scale electrolyser capacity, shipping capacity and industrial facilities such as direct reduced iron (DRI) plants require 3 to 6 years, building the ports infrastructure, grid connection and geological storage requires 8 to 15 years (Beagle et al., 2021[30]). Yet, it is important to achieve a sustained growth in green hydrogen volumes to progress in the learning curve by utilising early market opportunities for developing green hydrogen production driven by availability of infrastructure, cost of incumbent processes and integration of hydrogen into existing systems with minimal or no modifications.

Figure 1.8. Potential applications and usages of green hydrogen and its derivatives



Note: Maturity corresponds to the maturity of green hydrogen compared to other decarbonisation technologies.
Source: Authors, adapted from (Agora Energiewende and Guidehouse, 2021[31]), (IRENA, 2022[32]), (IRENA, 2022[1]), (Hydrogen Council, 2020[33]), (Liebreich Associates, 2022[34]).

Potential consumers of green hydrogen

Large-scale consumers in industry and transport

Hydrogen is currently consumed mainly by the manufacturing industry as feedstock in chemical processes and as a reducing agent in steel plants. Around 95% of hydrogen production is based on fossil fuels (coal and natural gas) and produced on-site in petroleum refineries, ammonia and other chemical plants. Total hydrogen demand from industry was about 87 Mt per year in 2020 (Energy Transitions Commision, 2020[35]), (IEA, 2021[4]). With new markets and production routes, total green hydrogen demand in industry could reach around 320 Mt per year by 2050 (IRENA, 2022[9]).

By 2050, green hydrogen is projected to have a large market share in several sectors:

- Ammonia and methanol: to substitute the current fossil fuel-based hydrogen production in steam methane reformers or gasifiers, as well as to provide clean transport fuels for shipping.
- Olefins: to develop methanol-to-olefins and electro-synthesis production routes instead of steam crackers that use natural gas, naphtha, and gas oil.
- Iron and steel: to replace natural gas as a reducing agent for DRI production, which can subsequently be smelted with scrap in electric arc furnaces (EAF). The green hydrogen fuelled DRI-EAF route can replace traditional blast furnaces and eliminate coal use.

Commercialising and creating demand for low-carbon products can accelerate the decarbonisation of upstream sectors in the supply chain. For example, in Europe, the industrial strategy for climate-neutral industry by 2050, the European Green Deal and the European Union's High-Level Group on Energy-Intensive Industries support the creation of early markets for green steel. Promoting industrial consumption of green hydrogen to replace grey hydrogen as a feedstock and existing fossil fuels in refineries, methanol plants, ammonia plants and steel plants can allow manufacturing companies to label their production as "green products" and sell them to customers accepting a possible premium. For instance, customer pressures and social corporate responsibility can be major drivers for the adoption of green steel supply in automotive manufacturing (Muslemani, Ascui and Kaesehage, 2022[36]).

There are several early opportunities in the industry sector for green hydrogen. Brown and grey hydrogen used in petroleum refining processes and fertiliser and methanol production plants can be substituted with green hydrogen without modifying the current processes. More than 60 renewable ammonia plants (including technology demonstration plans) have been announced in 2020 and 2021. Planned capacity by 2030 amounts to 15 Mt per year globally with an additional capacity of more than 50 Mt after 2030 (IRENA and AEA, 2022[37]). Around 80 Mt of green steel production capacity is expected to be commissioned by 2030, including around 40 Mt of DRI, which could run on green hydrogen (Agora Industry, Wuppertal Institute and Lund University, 2021[38]). The impact on company competitiveness could remain limited in case hydrogen blending is partial or if their goods are domestically traded facing limited import competition. In the current energy crisis following Russia's invasion of Ukraine, natural gas prices have skyrocketed and can already make this option economically attractive.

Green hydrogen could offer the possibility for some developing countries to produce locally a renewable fuel or feedstock for their domestic industry, that could contribute to their industrial and economic development (ESMAP, 2020[39]). The conversion of existing large-scale industrial plants and transport systems to low-carbon solutions can be challenging due to their layout. As emerging and developing countries need to build greenfield infrastructures, this brings an opportunity to design new installations ready to use or easy to switch to green hydrogen.

Natural gas blending with green hydrogen

The blending of hydrogen with natural gas could offer an opportunity to address the potential imbalance of supply and demand of green hydrogen in the near-term by utilising the existing gas infrastructure. Indeed, gas blending would not require pipeline retrofitting nor adjustment on the end-consumer side, provided that the hydrogen blend is up to 20% on a volumetric basis. This would also not pose any risks to the operation of existing household appliances and heating equipment like boilers (Melaina M.W., Antonia O. and Penev M., 2013[40]). These solutions are currently primarily assessed in advanced economies, but they could also be a first transition solution to initiate the development of green hydrogen production in emerging and developing economies. At a local level, blending can be used as a back-up usage when green hydrogen production exceeds demand, and no options for storage and transport of that hydrogen are available. However, blending is expected to remain a partial and transitional solution, as applications in industry and transport seem to offer more efficient and economical uses of green hydrogen to reduce CO_2 emissions (IRENA, 2021[41]) (IRENA, 2022[42]).

Decentralised applications for small-scale and individual consumers

Hydrogen can also be consumed for decentralised applications. While electrification generally has a better yield across its value chain and the technology has already advanced well, green hydrogen uptake can foster in local public transportation, for instance for bus fleets. In areas where access to modern energy resources is a priority, policy makers need to choose between expanding the existing grid infrastructure and developing off-grid systems. Population in rural areas either do not have energy access or rely on expensive, polluting and inefficient diesel generators. A combination of renewable energy sources together with green hydrogen production can provide a dispatchable and competitive source of electricity to these populations.

The case of hydrogen valleys

The Hydrogen Valley concept has emerged in recent years to overcome the limitations of individual projects by building hubs and clusters. Nineteen countries (11 in Europe, four in Asia, two in South America, the United States and Australia) have identified hydrogen valleys in each geographical area to cover multiple steps of the hydrogen value chain and more than one end-use sector in large-scale projects (Hydrogen Valleys, 2021[43]). Combining various uses within the same area (e.g. an industrial cluster, a port or a city) can create synergies, help achieve economies of scale, optimise costs and reduce demand variation.

Grid integration of variable renewable energy resources

Electrolyser technology and green hydrogen production can serve as enabling technologies for integrating VRE into transmission and distribution grids besides commercial solutions such as battery storage and demand response (IRENA, 2022[9]).

As countries incorporate more VRE into their grids, balancing electricity demand and supply at all times has become a concern. While dispatchable renewable energy sources such as geothermal and biomass power plants can provide constant electricity supply, wind and solar energy supply are variable depending on resource availability. In the absence of power system flexibility, the output from VRE could be curtailed during hours of insufficient demand.

Hydrogen can be stored at large scale over long periods and provide a storage solution for renewable energy in seasons of high production (for instance, solar energy during summer). The hydrogen stored seasonally would subsequently be used in combined cycle turbines to produce electricity during times of low VRE output or high demand (such as during winter).

At a daily or weekly scale, electricity surplus during peak hours of solar or wind electricity production could be used to supply electrolysers. Electrolysers with ramp up times well below one minute to reach a nominal production rate can help balance the grid by absorbing surplus electricity and compensate for variations between supply and demand (thyssenkrupp, 2020[44]). As the round-trip efficiency of the power to hydrogen to power transformation is typically around 20 to 42% (Escamilla, Sánchez and García-Rodríguez, 2022[45]), batteries may be more efficient to smooth short-term spikes in consumption or production (IRENA, 2019[46]).

Priority areas for developing national hydrogen strategies

Many emerging and developing economies have huge untapped potential to produce renewable power at low cost, which can also be used as a feedstock for green hydrogen production. However, very few of these countries have yet assessed the extent to which these resources can be used for green hydrogen production, besides their primary role to decarbonise the power system. National hydrogen development roadmaps coupled with concrete targets are vital first steps (IEA, 2021[47]).

Table 1.1. Examples of country roadmaps and policies

Country	Initiative	Year
Japan	Basic Hydrogen Strategy	2017
Australia	National Hydrogen Strategy	2019
Korea	Hydrogen Economy Plan	2019
European Union	A hydrogen strategy for a climate-neutral Europe	2020
Chile	National Green Hydrogen Strategy Call for Financing of Green Hydrogen Projects	2020 2021
Colombia	Hydrogen Roadmap	2021
Egypt	Strategic announcements	2021
Morocco	Green Hydrogen Roadmap Green Hydrogen Strategy	2021
Namibia	Strategic announcements	2021
Uzbekistan	Measures to develop hydrogen energy	2021
India	Green Hydrogen/ Green Ammonia Policy	2022
South Africa	Hydrogen Society Roadmap	2022

Note: The list of countries' roadmaps is not exhaustive, and merely illustrates the momentum of the publication of national hydrogen strategies, in particular in emerging and developing economies since 2021.

Given the complexity of the competing usages and technologies in several sectors, embedding the hydrogen roadmap into a comprehensive national net-zero pathway enhances the credibility of mid-term and long-term targets. A systemic approach considering the entire hydrogen value chain would enable emerging and developing economies to design their strategy and roadmap, and identify projects, clusters and requirements to create and scale up a hydrogen market.

Policy makers may apply three basic concepts to set up policy priorities (IRENA, 2020[48]):

- Recognise that green hydrogen is one among many low-carbon technology solutions required to achieve a net-zero emissions energy system. The suitability of green hydrogen must be assessed against other low-carbon measures, depending on country capabilities and resource endowment, to ensure the selection of the most viable option for each application. For instance, more than five times more green electricity is typically required to heat a household with hydrogen produced from electrolysis than with a heat pump.

- Identify the highest-value applications for green hydrogen. In the market creation phase, this requires determining which sectors would be able to use green hydrogen rapidly. In the market growth phase, a country could also prioritise usages that enable the roll out of projects and economies of scale.
- Ensure additionality. Producing green hydrogen from renewable energy capacity should not impede the transition in the power sector by taking away renewable generation from the system, as it could in turn increase the risk of electricity scarcity or call for the use of fossil-fuel based power in the electricity production.

While analysis on a global scale helps to identify the most promising applications for the global hydrogen market, each country will have to develop its own specific roadmap. The possibility of developing activities within the green hydrogen value chain at the national level can vary according to country potential, key stakeholders, and potential barriers or main attention points. Available national hydrogen roadmaps cover a wide range of issues such as fossil fuel phase-out, local industrial integration and development or energy security, depending on national priorities and circumstances. Thus, there is no standard way of designing a national hydrogen roadmap and its content.

This Working Paper is accompanied by a digital *country self-assessment questionnaire* to help local policymakers identify potential "sweet spots" across the green hydrogen value chain. For each step of the value chain, a series of statements about country potential, key stakeholders and potential barriers and attention points can be graded from 1 to 4 points, where a four-points rating always corresponds to the most positive answer for the development of green hydrogen. The results are then aggregated and used to identify a country's opportunity to develop the upstream, midstream and downstream parts of the value chain, as well as possibilities to develop domestic or export usages. As the number of respondents grow, it will be possible to compare self-assessment results both within and across countries.

This survey aims to propose to stakeholders a simplified way to self-assess a country's potential for the development of green hydrogen. Its purpose is primarily to raise awareness of a few salient pre-requisites along the value chain, rather than providing an exhaustive list of all aspects to be considered to design a national strategy. It targets primarily policy makers, but also financial institutions, corporates, academia, NGOs and think tanks. The respondents are invited to give a grade from one to four stars to each of the proposed 27 statements (see Table 1.2).

Table 1.2. List of statements of the country self-assessment questionnaire

Value Chain Step	Statements
Upstream Resources	The country has regions/areas with favourable resource conditions for green hydrogen production (e.g. low-cost renewable power, abundant water resources, infrastructure)
	Actor(s) in the private and public sectors are able to develop, build and operate additional renewable capacity, and developing the storage, transport and distributions systems to deliver it to large industrial users
	There is sufficient land availability in regions with good resources potential, enabling both the development of direct electrification and green hydrogen
Electrolysers	The country has access to the critical materials and/or to the main components required for the production of electrolysers
	The domestic capacity to manufacture and supply electrolyser components, develop and commercialise electrolyser technologies exist or can be developed. [Alternatively: global leading technology developers are willing to establish capacities in the country.]
	The country can build a local electrolyser industry competitive against incumbent manufacturers in China, Japan, the United States and Europe
Hydrogen (H2) Production - Electrolysis	Oxygen (by-product of the electrolysis) could be consumed locally and generate additional revenue streams for operators
	Private companies and state-owned enterprises are in a position to invest, operate and innovate to develop electrolysis capacity
	The country is ready to establish technical, regulatory and financial ease for connecting electrolysers to the grid infrastructure (electricity transmission, gas network, industrial plants), and/or to develop off-grid projects
Conversion	The country has a significant presence of natural gas liquefaction plants, ammonia production and/or large-scale petrochemical plants
	Private and state-owned enterprises refineries, petrochemical and fertiliser plants are ready to adapt their processes and invest in green hydrogen conversion
	The country has identified opportunities for exporting green hydrogen and/or its derivates in the medium to long term, reducing risk of stranded conversion assets
Transport	The planning of future connection to green hydrogen production areas is foreseen in the development plan of the national and international electricity transmission grids, natural gas network and hydrogen pipelines
	The owners and operators of the natural gas network have included retrofitting or building hydrogen pipelines in their investment plans
	The existing natural gas infrastructures are well developed and could partially be repurposed for H2 [Alternatively: if existing infrastructures are limited, there is capacity to develop national hydrogen transportation corridors at limited costs]
Storage	The country has areas suitable for large-scale hydrogen storage (salt caverns, depleted gas fields or rock caverns), ideally located near areas with favourable resources for green hydrogen production
	The country already operates natural gas storage installations and can build on the know-how of domestic companies specialised in natural gas storage and extractive industries
	There is limited geological risk in the regions suitable for large-scale hydrogen storage
Domestic consumption	A mapping of the current and future hydrogen demand centres by sector is included in a broader national energy / climate plan
	(Current and future) consumers of hydrogen are engaged to define decarbonisation/net-zero roadmaps, confirming their technical and financial capacity to adapt their processes and equipment
	The country has identified and prioritised "no-regret"[a)] applications that would create significant demand for green hydrogen, either by large consumers or by a number of small modular, standardised projects.
Green Products	The country is willing to develop local production or improve its trade balance for the industrial materials/products that could be manufactured with green hydrogen
	Industrial and individual consumers are willing and ready to buy green materials/products instead of their fossil-fuel based alternatives
	The country has estimated that the green premium to manufacture green material/products for "no-regret" applications would have limited impact on end-consumers[b)]
Exports	The country has international gas pipelines, port infrastructures suitable for chemical storage parks and deep-water docks for tankers
	Public or private actors in neighbouring countries have expressed interest to import hydrogen
	The country has anticipated the risk that hydrogen exports may be detrimental for creating local markets and realising national decarbonisation / net-zero targets

Notes: a) Applications are "no-regret" depending on the country context and in particular the competitiveness of green hydrogen with other low-carbon options for decarbonisation; b) This can consider the regulations, market conditions and financing instruments that could also contribute to establish a level playing field.
Source: Country self-assessment questionnaire.

Development of hydrogen trade through international co-operation

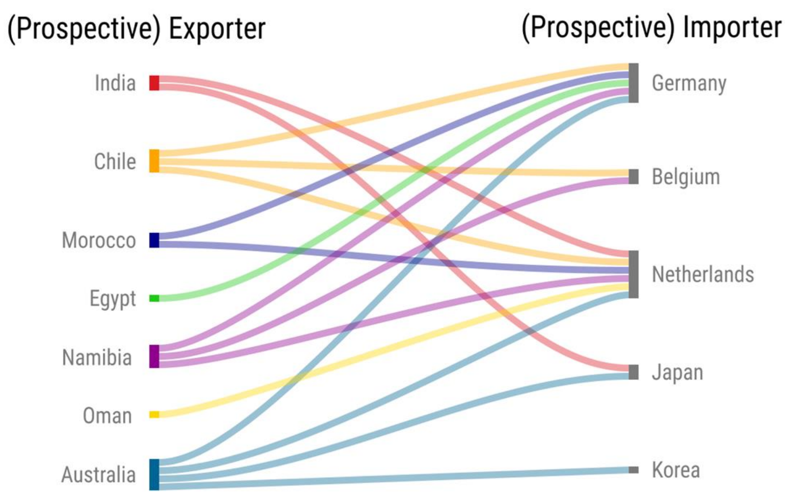
As achieving climate targets requires international collaboration to innovate and implement low-carbon technologies, the dynamic between co-operation and competition too needs to evolve. Governments, companies and academics must collaborate in technology research, development, demonstration and deployment (RDD&D) to limit the costs of the transition to a net-zero economy and accelerate the adoption of new technologies. A number of initiatives can be undertaken by the main countries developing hydrogen technologies on research and development, technical co-operation, investment facilitation and the development of trade routes (OECD, 2022[49]). In addition, international co-operation related to hydrogen will be key to harmonise definitions and standards.

Several developed economies like the EU and Japan have implemented large subsidies to support the development of green hydrogen and to scale-up pilot projects. While relying on large state subsidies is not feasible in most developing and emerging economies, international collaboration can stimulate timely investments. For example, assisting emerging and developing economies in deploying hydrogen projects could help phase out fossil fuels, thereby making hydrogen part of a just transition effort and supporting industrial development (IRENA, 2022[1]).

Opportunities of hydrogen trade for emerging economies

Many governments envisage partnerships to establish cross-border hydrogen trade. For instance, Germany estimates a total hydrogen demand of around 90-110 TWh/year by 2030, but its available renewable energy resource potential falls short of this demand. Thus, the German government has initiated bilateral talks with several countries (such as Angola, Morocco, Namibia and Turkey) to explore hydrogen imports through international gas pipelines or in the form of hydrogen-derived products. For future importers like Europe, green hydrogen can also help diversify energy sourcing and mitigate geopolitical risks. To deal with the consequences of the global energy crisis following Russia's invasion of Ukraine, the European Commission presented the REPower EU plan to accelerate its hydrogen-based transition and to diversify clean gas supply through green hydrogen and its derivatives like green ammonia. This plan sets a target of 10 Mt of domestic production of green hydrogen and 10Mt of imports by 2030, corresponding to 2% of the region's total final energy consumption by the same year.

Figure 1.9. Examples of official discussions and agreements for international green hydrogen trade



Source: Adapted from (IRENA, 2022[1]).

The announced agreements hint that, after prioritising domestic use to the extent possible for their decarbonisation, some emerging and developing economies may become exporters, catering to developed countries that cannot meet their transition goals with domestic hydrogen production. These partnerships could create local value chains and contribute to improving exporting countries' trade balances, thereby supporting sustainable and local development. Scaling up production for exports can also facilitate the creation of local demand. Thus, it will be key to find a suitable balance between domestic priorities and export opportunities. Partnerships can also create a window of opportunity for technology transfer in exporting countries, which typically have limited public resources to create local hydrogen value chains. Thus, at the national level, setting targets and defining a green hydrogen roadmap will depend on the country "archetype", either as a hydrogen importer, self-sufficient producer, or hydrogen exporter (Hydrogen Council, 2021[50]).

Today, about 85% of hydrogen gas is produced and consumed on-site within a facility (IEA, 2019[51]), and the remainder is mostly commercialised locally. To align with a net-zero energy system, hydrogen will need to become an internationally traded commodity.

Developing trade routes between potential low-cost hydrogen producing countries and potential consumption zones calls for reinforced international collaboration. It is necessary to develop clean, affordable, secure and reliable supply chains to support the development of effective hydrogen trading markets. This requires, for instance, the development of a global network of transportation and storage technologies for a standard hydrogen quality and for the alignment of handling procedures to guarantee safe end-to-end delivery.

International dialogue and climate targets

At the 26th Conference of Parties (COP), 21 countries and several development banks pledged to end new international public finance for fossil fuels. Advanced economies have also made financial commitments to support emerging and developing economies to adapt to climate change, which will further facilitate the emergence of green technologies worldwide. The OECD's latest data published in July 2022 shows that a total of USD 83.3 billion finance was provided and mobilised for climate in 2020. This is USD 16.7 billion short of the pledge. Between 2016 and 2020, the energy sector accounted for one-third of the total climate finance provided and mobilised. During the same period, more than half of the total climate finance provided and mobilised in the energy sector was targeted for renewable power. New technologies such as green hydrogen are not yet benefitting from such climate finance (OECD, 2022[52]).

In addition, specific compensation mechanisms to alleviate the economic impact of emerging economies giving up their fossil resources can strengthen international collaboration in alignment with the transition to a low-carbon economy.

The first Hydrogen Energy Ministerial Meeting, held in Tokyo in 2018, gathered representatives from 21 countries. Although participants came mainly from developed countries, this initiative reaffirmed the value of collaborating at an international level to accelerate progress in hydrogen technologies. International organisations can also use their convening power and neutrality to co-ordinate and participate in international dialogue.

A hydrogen workstream has been created in several broader initiatives, such as the Clean Energy Ministerial led by the IEA, and Mission Innovation, initiated by 22 countries and the European Commission. Several leading international organisations have set up dedicated programmes, such as the Collaborative Framework on Green Hydrogen led by IRENA, or the Global Programme for Green Hydrogen in Industry by UNIDO.

Technical assistance and sharing best practices

IEA's Tracking Clean Energy Progress 2021 report finds that more efforts are needed for hydrogen development to be on track with their Net-Zero Emissions by 2050 Scenario (IEA, 2021[53]). Sharing best practices can help identify suitable technologies, business cases, knowledge gaps and successful projects for replication. It also helps design suitable training and technical assistance to support capacity building, skills development, knowledge-transfer and innovation required for local value chain development.

For example, the first workgroup of the International Partnership for Hydrogen and Fuel Cells in the Economy focuses on education and outreach. The India Department of Science & Technology (DST) and the Innovation Fund Denmark (IFD) project to fund Indian and Danish researchers on joint development of green fuels (including green hydrogen) is another example of international co-operation. IFD will allocate a total of DKK 20 million (USD 3.0 million), and DST will allocate a total of INR 200 million (USD 2.7 million) to fund three to five joint research and innovation projects up to three years.

Advanced economies lead in the number of low-carbon hydrogen projects across the value chain (Hydrogen Council and McKinsey & Company, 2021[18]). As this remains a nascent market, the steep learning curve of the first projects will play an essential role to roll out future capacity. Drawing upon the knowledge accumulated in the first projects to support technology adoption and diffusion in emerging and developing economies will facilitate the global scale up of green hydrogen. Capacity building and skills development will be critical to develop local value chains and manufacturing capabilities that could be major drivers to build a resilient, competitive industry. Countries who already have an industrial footprint of refineries, fertiliser plants and steelmaking can build on the expertise of the current hydrogen producers and consumers and expand their skills to green hydrogen handling across the value chain.

Investment facilitation

Aligning the hydrogen sector with global net-zero emissions by 2050 requires early investments of USD 1 200 billion between now and 2030 (IEA, 2021[54]), covering the manufacturing of upstream and downstream equipment, green hydrogen production and infrastructure for hydrogen end-uses, each with its own challenges and specific risk profiles. Additional investment in the renewable power generation capacity to supply the electrolyser will be required. Although public finance institutions can provide guarantees and grants in early stages of development, the scale of investment will require crowding in private finance, especially in emerging and developing economies with limited access to capital.

A growing number of asset managers are increasingly focused on Environmental, Social and Governance (ESG) criteria and many industrial companies and banking institutions have announced sustainability-linked financing frameworks. However, the lack of a long-term strategy for decarbonisation and a credible process for monitoring, verification and reporting can hinder investor confidence. Given the size and anticipated growth of the existing hydrogen market, the development of green hydrogen projects could present a significant investment opportunity for investors in emerging and developing economies.

Co-ordination among all stakeholders to provide concessional financing and mobilise private capital will be essential for the rollout of green hydrogen. Innovative blended finance could play an essential role to support green hydrogen projects in emerging and developing economies, in particular for technologies with no track record, while commercial financing could be used for renewable power projects with proven business cases (De Sisternes, Fernando and Jackson, 2020[55]). The use of blended finance facilities for green hydrogen should focus on de-risking near commercial deployment, for instance through a viability gap fund, and can mobilise more financial resources by ensuring that the funded projects meet environmental imperatives (OECD, 2022[56]). Various financing vehicles could foster the investment in these required infrastructures, such as Infrastructure Investment Trusts (InvITs).

Regulations, Codes, Standards

Regulations and standards for hydrogen are currently well covered for existing production and usages, i.e. mainly for on-site production and consumption of fossil-fuel based hydrogen. However, reliable data and analyses on hydrogen, including environmental impact assessments, are required to enable the creation of a global low-carbon hydrogen market.

Countries often lack institutionalised mechanisms to track the production and consumption of hydrogen and to credibly certify its quality and climate neutrality (IRENA, 2022[1]). (Velazquez Abad and Dodds, 2020[57]) provide a stocktake of initiatives currently under development and identify that the main differences between these relate to definitions for green or low-carbon hydrogen, system boundaries (point of production, point of use, or well-to-wheel basis), and emission intensity thresholds.

Currently, there is no standard definition of green hydrogen based on a transparent and universally accepted methodology. Several tracking systems can thus be implemented,[1] such as guarantees of origin (GoO), which have been successfully implemented to track renewable electricity generation. Such tracking schemes would need to be based on a simple and replicable tracking system, with hydrogen product labels providing clear information on production routes.

The expected prominence of developing and emerging economies in the green hydrogen market in the next decade afford grounds for their involvement in the definition of regional or global standards. Some of these countries can increase their credibility to weigh in the international discussions, for instance by referring to their green taxonomies. Indeed, using green finance criteria and agreeing on internationally recognised rules will make it easier for export markets to understand how GHG emissions for the traded green hydrogen are calculated, facilitating their placement in the market (IRENA Coalition for Action, 2022[58]).

[1] Traceability of green hydrogen in order to certify products can follow various procedures, such as track-and-trace, mass balance or book and claim approaches (Ecofys, 2012[89]).

2 Understanding the drivers and factors for green hydrogen investments and business models with a value chain backdrop

Green hydrogen value chain

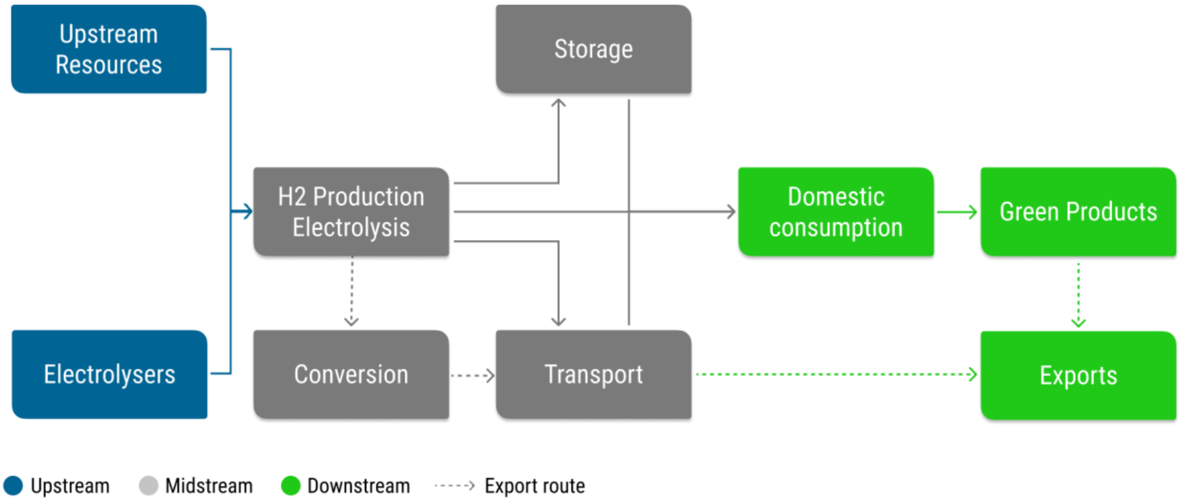
Hydrogen can be produced and supplied in multiple ways and has applications in several end-uses. Countries can tap into opportunities at various stages of the green hydrogen value chain depending on their strategic priorities and learnings from global experiences. However, developing national hydrogen strategies requires local contextualisation. Emerging and developing economies are often at early stages of developing their hydrogen plans and may require support to understand its most effective uses and economy-wide implications.

Several potential factors could drive green hydrogen development in emerging and developing economies:

- decarbonisation of hard-to-abate sectors (such as heavy industry, road freight, maritime transport and aviation)
- grid integration of VRE
- modern energy access
- diversifying energy supply and reducing import dependence
- improving trade balance
- supporting local economic growth
- creating new and high-skilled jobs
- developing technology expertise and knowledge.

Given the complexity of hydrogen production and the diversity of national circumstances, a systems approach encompassing the entire hydrogen value chain is required to identify its benefits and prioritise applications (see Figure 2.1). Indeed, focusing only on the electrolysis process can minimise the overall impact on developing the entire value chain. For instance, (Beagle et al., 2021[30]) estimate that for a project in the steel sector (including investments in the renewable energy capacity, an electrolyser and a new steel plant), the electrolyser only represents 1/8th of the total investments and generates 1/30th of the total jobs created across the entire value chain.

Figure 2.1. Green hydrogen value chain



Notes: A wide range of green products for both the domestic markets and exports can be produced without green hydrogen, e.g. through direct electrification of industrial processes.
Source: Authors

Factors influencing investments across the hydrogen value chain

All the steps of the green hydrogen value chain need to come together to bring projects to fruition, and a single missing piece could deter financial institutions from investing. A value chain lens enables countries to apprehend the drivers of the economics, from the upstream resources to the domestic consumption or exports of green hydrogen and its derivatives.

Countries are rapidly utilising new opportunities to position themselves in the global green hydrogen landscape. However, unplanned hydrogen choices may bring risks and additional challenges for fast-growing emerging and developing economies. For instance, green hydrogen development for transport and industry sector end uses requires access to renewable power, which may slow down the clean energy transition in the power sector and for direct electrification. Lack of sufficient infrastructure (e.g. transmission grid) for renewable power generation could further hinder green hydrogen projects. Costs and benefits of the various uses of hydrogen also will differ significantly depending on the geography and the energy system structure. Hydrogen choices will therefore need to consider the opportunities and limitations within the overall energy and climate strategies of countries.

The OECD organised an online stakeholder consultation meeting on 14 June 2022, bringing together 100 experts from governments, industry, financial institutions, think tanks, research organisations and other stakeholder groups. The consultation, supported by preparatory desk-based research, pointed to key areas that are important for the green hydrogen value chain and the creation and growth of the green hydrogen market at the country level:

- **Strategy, governance and standards**, including elements such as the existence of a roadmap, a regulatory framework (that is aligned with national targets), and the quality of the licensing and permitting process.
- **Technology and industrial development**, corresponding to technical know-how, experience, and capacity-building.

- **Enabling market measures**, highlighting the potential to achieve a sustainable green hydrogen market that would not rely on support and subsidies in the long-term, for instance through the presence of demand for green products.
- **De-risking investment mechanisms and financing solutions**, elucidating factors that could affect financial risk perception among investors and describing the ability of the financial ecosystem to invest in local green hydrogen projects.

Based on these categories, a checklist comprising 45 questions along the value chain was prepared to support policy makers in identifying the main barriers to investment in green hydrogen projects, considering their national circumstances (available on: www.oecd.org/cefim). This can be used as a starting point during the preparation of a country roadmap to ensure that it addresses potential key barriers to establishing an enabling environment.

Table 2.1. List of questions in the checklist

Value Chain Step	Category	Questions
Upstream Resources	Strategy, governance and standards	Is there an integrated national energy roadmap that encompasses the development of renewable power for electrification including other usages such as green hydrogen?
	Technology and industrial development	Are current industrial actors in capacity to scale up renewable electricity production (and water desalination plants)?
	Enabling market measures	What is the current and projected cost of renewable power from solar and wind energy resources (if available also from geothermal and hydropower)?
	De-risking investment mechanisms and financing solutions	Are there feed-in tariff, auctions and other measures to accelerate the uptake of renewable power capacity?
		Do local renewable energy developers have a sufficient access to capital to develop their projects and are there financing instruments to mobilise private capital?
Electrolyser technology	Strategy, governance and standards	Does the country position itself as an electrolyser manufacturer or an importer?
	Technology and industrial development	Is there sufficient technology know-how and human capacity in the manufacturing industry or would re/upskilling be required to deploy a local electrolyser manufacturing capacity?
	Enabling market measures	How does the country manufacturing competitiveness compare with regional and international standards, and what are the most competitive sectors?
	De-risking investment mechanisms and financing solutions	What type of incentives and financing models have been used to implement large-scale manufacturing projects in the last decade?
		Are local banks and international finance institutions active in financing the manufacturing industry in the country?
Electrolysis	Strategy, governance and standards	Did the country release a green hydrogen production/demand target? Is this part of a broader energy / climate plan and is the target voluntary or mandatory?
	Technology and industrial development	Do local companies have experience on electrolysis operations and hydrogen safety standards?
	Enabling market measures	What is the current and projected cost of green hydrogen in the foreseen production sites compared to fossil-fuel based routes?
	De-risking investment mechanisms and financing solutions	Are long-term utilities contracts (electricity, water) for industrial players well developed to ensure both good pricing visibility and security of supply?
		What are the typical WACC for low-carbon technology investments and the typical country risk premium asked by investors?
Conversion	Strategy, governance and standards	Does the country have a specific interest in selecting any of the individual options among hydrogen liquefaction, or the production of ammonia or liquid organic hydrogen carriers?
	Technology and industrial development	What are the experiences of chemical and petrochemical companies in hydrogen liquefaction, or the production of ammonia and liquid organic hydrogen carriers?
	Enabling market measures	How does the green hydrogen price (and price outlook) compare with the green hydrogen price in other countries and with currently used fossil fuels?

	De-risking investment mechanisms and financing solutions	Were specific incentives required to implement large chemical plants projects in the last decade?
		Which investors have financed >USD 100 million projects in the last decade?
Transport	Strategy, governance and standards	Are the future responsibilities of hydrogen transport and distribution between public and private actors been defined?
	Technology and industrial development	Is there local capacity with building and operating gas networks? Are local companies certified and have skilled manpower to retrofit or build H2 pipelines and transport system?
	Enabling market measures	Does the national natural gas code already include aspects of hydrogen transportation?
	De-risking investment mechanisms and financing solutions	Are there specific financing and business models in place for the development of infrastructure in the country?
		Is the hydrogen transport capacity development part of the national infrastructure project budget?
Storage	Strategy, governance and standards	Is there a roadmap assessing energy, gas or hydrogen storage capacity needs at national and regional levels?
	Technology and industrial development	Is there a mapping of suitable areas for large-scale storage and a permitting process in place?
	Enabling market measures	Is the cost of investing and operating storage facilities for specific projects already assessed?
	De-risking investment mechanisms and financing solutions	Can a natural gas storage revenue model be replicated for green hydrogen, or can specific revenue models be developed, for instance as a flexibility option to integrate VRE?
		Is the storage capacity development part of the national infrastructure project budget?
Domestic consumption	Strategy, governance and standards	Do the line ministries in charge of energy, industry and transport co-ordinate the national green hydrogen priorities?
	Technology and industrial development	Have academics and the companies undertaken projects to demonstrate the feasibility of hydrogen use in priority sectors?
	Enabling market measures	Are there enabling market conditions to manage the additional increase from green hydrogen on production costs>
	De-risking investment mechanisms and financing solutions	Are there financial incentives and de-risking measures for consumers of green raw materials/fuels?
		Do public and private financial institutions have specific funds and investment vehicles for the decarbonisation of the industry?
Green Products	Strategy, governance and standards	Are there specific green products identified and promoted by the government for their production and/or use?
	Technology and industrial development	Can future industrial and individual consumers of green products (e.g. green steel, green fuels) use them directly in their current assets, or do they need to adapt their process and equipment?
	Enabling market measures	Could a green premium impact the profitability of companies and/or the income of end-users?
	De-risking investment mechanisms and financing solutions	Are there financial incentives and de-risking measures for consumers of green products?
		Are there financial instruments to offset the green premium and incentivise customers to buy green products?
Exports	Strategy, governance and standards	Has the country developed a trade strategy for green hydrogen and/or green products?
	Technology and industrial development	Are standard operating procedures, hydrogen quality and infrastructures harmonised at international level, and does the country have corresponding international pipelines or port infrastructures?
	Enabling market measures	Are international markets and trade rules facilitating the global circulation of green hydrogen and green products?
	De-risking investment mechanisms and financing solutions	Has the country engaged into discussions and agreements with large foreign off-takers?
		Are international investors committed to investing in large projects locally through concessional or traditional financing?

Parameters influencing benefits and risks across the value chain

For each part of the value chain a brief discussion is provided below to put its relevance into the context of the value chain and to provide a rationale to the questions in Table 2.1.

Upstream Resources

Electricity

Depending on VRE load factors, which typically range between 15% and 30% for solar and 30% and 50% for wind, each installed GW of VRE-based electrolyser capacity may require between 2 to 6 GW of renewable power capacity to provide electricity volumes corresponding to its full loading capacity.[2] In these cases, the upfront capital cost of dedicated renewable energy capacity may be two to six times higher than the upfront capital cost of the electrolyser itself.

Land and Water

Land and water requirements may constrain site selection for green hydrogen projects. Significant land areas may be required if renewable energy assets and electrolysers are to be built in the same location to avoid the cost of transporting power. Similarly, lack of access to water in certain regions may require selecting areas next to the coastline, relying on a desalination plant to provide the water required for green hydrogen production. The electrolysis process requires between 9 to 30 litres of fresh water per kg of hydrogen produced, depending on the level of treatment required to achieve a suitable water quality (Blanco, 2021[59]); (Al-Qahtani et al., 2021[60]). Water availability is likely to be a significant barrier to green hydrogen production in water-stressed countries and regions. Countries that have abundant renewable energy resources, but limited freshwater resources have a lower likelihood of becoming major green hydrogen exporters (De Blasio and Pflugmann, 2021[61]). The energy and cost contribution of water supply to green production is marginal.

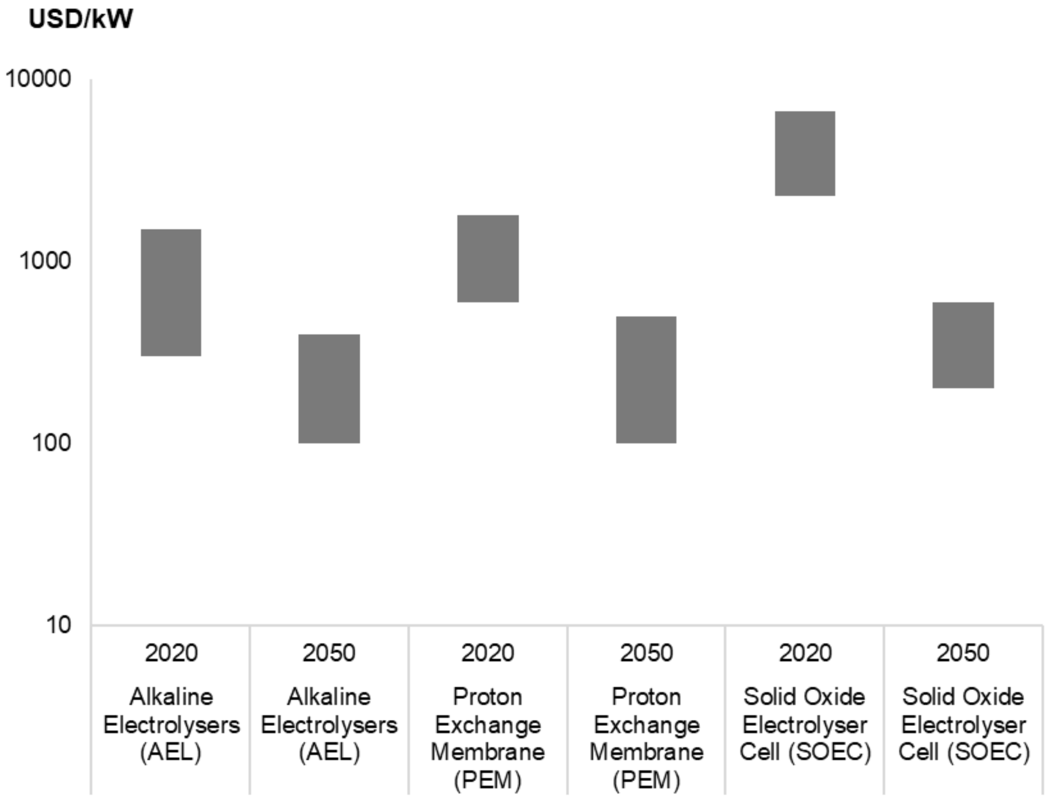
Electrolyser technology

The three main types of electrolyser technologies are Alkaline and Proton Exchange Membrane (PEM), Solid Oxide Electrolyser Cell (SOEC) and Anion Exchange Membrane (AEM). Alkaline and PEM technologies have already been commercialised, while SOEC and AEM are at early stages of development. Alkaline electrolyser is the most common and mature technology.

Global electrolyser is a nascent market, with more than 90% of electrolyser manufacturing capacity being located in Europe and China in 2021 (IEA, 2021[54]). While emerging and developing economies can already purchase electrolysers from incumbent companies in these regions, there is also great potential for them to develop local manufacturing capacities.

[2] The economic optimum for green hydrogen production will not necessarily require running at full capacity, and it would depend on the investments and operational costs all along the value chain.

Figure 2.2. Capital cost of electrolysers in 2020 and 2050 (logarithmic scale)



Source: Adapted from (IRENA, 2020[14]), (Oxford Institute for Energy Studies, 2022[62]), (Agora Energiewende and AFRY Management Consulting, 2021[63]), (World Energy Council, 2021[5]), (IEA, 2020[64]).

Electrolysis

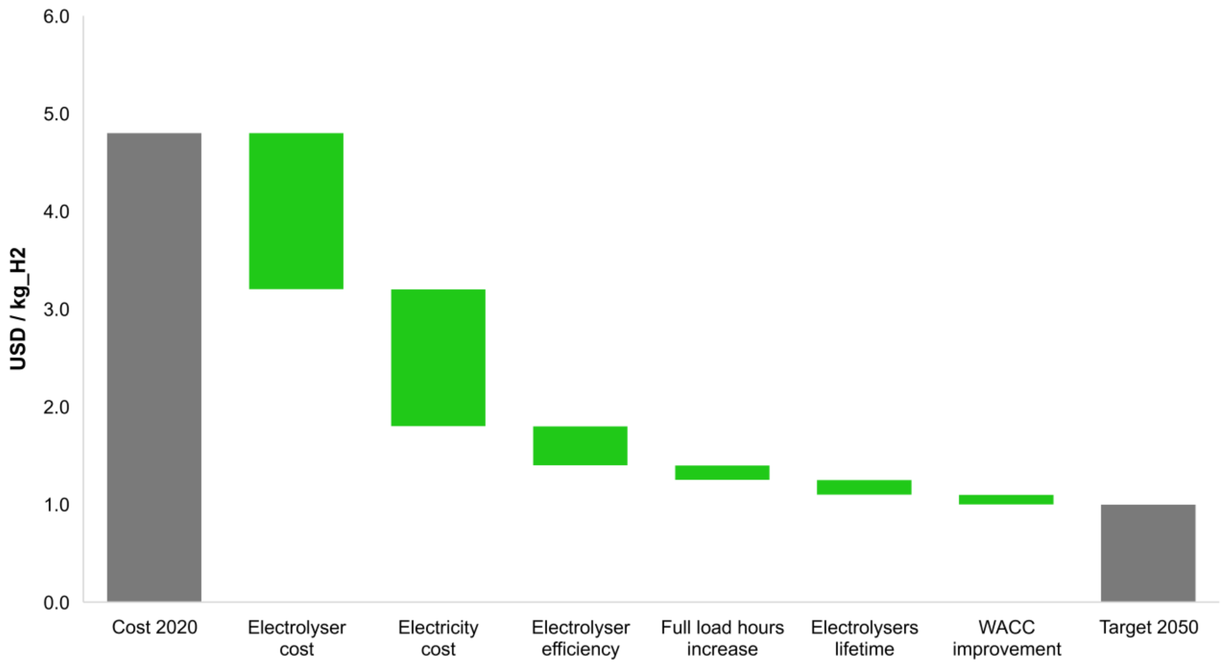
Electricity sourcing

Electricity required to produce green hydrogen through electrolysis can be supplied from the national grid, local mini-grid, or dedicated renewable energy assets either co-located with electrolysers or connected through power transmission lines (for instance, offshore wind assets connected to onshore electrolysers). Building off-grid electrolysers co-located with dedicated renewable energy assets can lower the total cost of the project by eliminating transmission and distribution costs and enabling consumption of direct current without using inverters. On the other hand, grid-connected electrolysers run at a stable load, although they would require Power Purchase Agreements from well-identified assets or GoOs to certify hydrogen production from renewable sources.

Levelised Cost of Hydrogen (LCOH)

The cost of producing hydrogen using natural gas without Carbon Capture, Use and Storage (CCUS) amounts to USD 0.9-1.8 per kg of hydrogen, split between USD 0.34 for CAPEX, USD 0.17 for OPEX, and USD 0.4-1.3 for natural gas price (IEA, 2018[65]). For electrolysis-based production, analysis suggests that the LCOH is largely impacted by electricity generation costs and electrolyser capital costs. The electrolyser load factor can impact production costs, especially during the early phases of market creation when electrolyser capital costs remain high.

Figure 2.3. Main drivers to lower production costs of green hydrogen



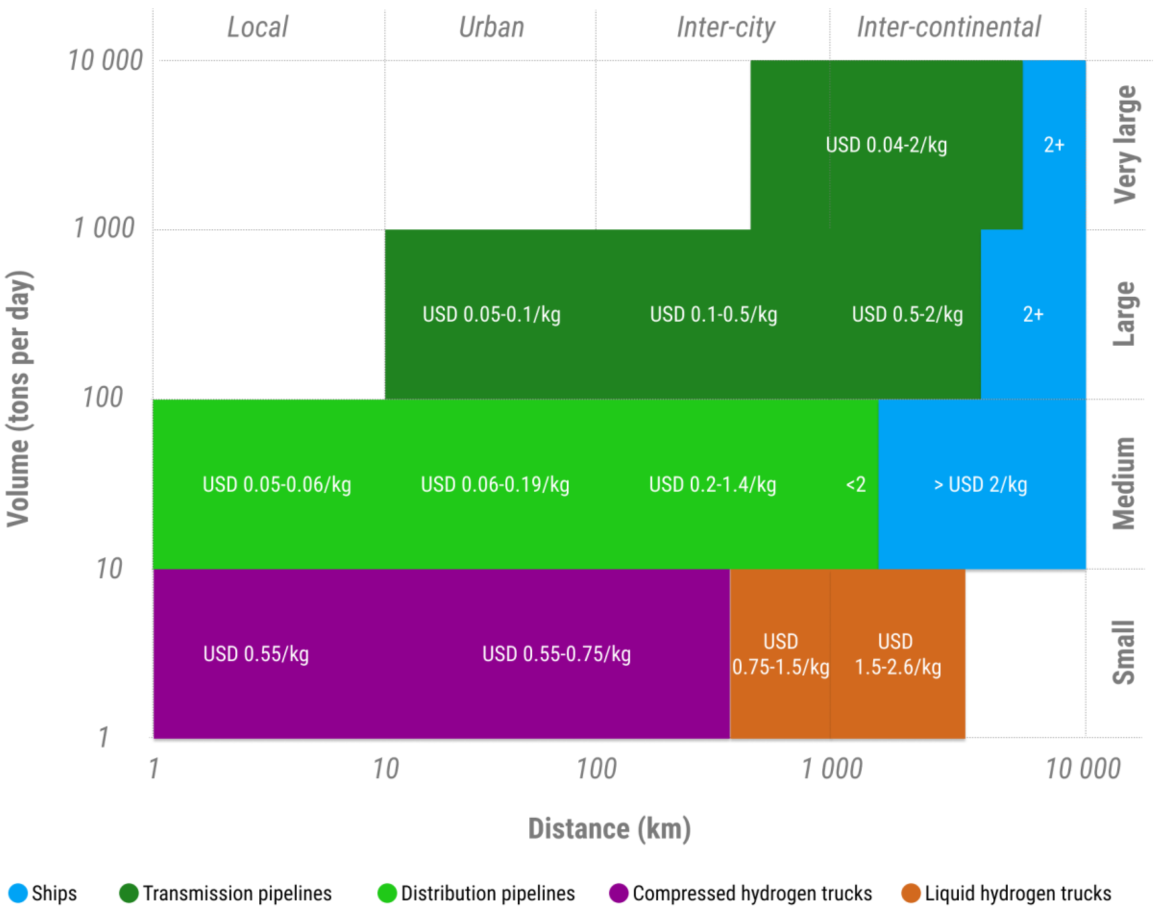
Source: (IRENA, 2020[14]).

Transport

Most hydrogen consumption currently occurs at the point of production at the on-site production facilities of large refineries and ammonia plants. While this avoids transportation costs, developing trade routes between countries with favourable production conditions and large demand centres with unfavourable production conditions can further reduce landed costs of hydrogen.

Green hydrogen can be transported in three main forms: in gaseous form by pipelines, trucks and ships (see Figure 2.4). While truck transport is suitable for limited quantities over short distances (such as for refuelling stations), pipelines and ships are optimal for transporting large volumes over long distances within and across borders.

Figure 2.4. Hydrogen transport cost based on distance and volume



Source: (IRENA, 2022[42]).

Retrofitting existing natural gas pipelines costs less than building new ones. However, large demand is required to justify the development of pipeline transport infrastructure, including compression stations, valves, metering stations and possibly a distribution network. Some emerging and developing economies have limited natural gas infrastructure, such as the least industrialised countries or countries predominantly using coal power. A new natural gas grid may be expensive and difficult to finance in the near term. However, designing a hydrogen transportation and distribution network with less legacy infrastructures can be an opportunity to leapfrog. The development could also start with local or regional uses in hydrogen hubs, valleys or highways, and then follow a step-by-step approach for potentially larger integration.

Ships are technically and economically suitable for very long-distance transport (such as exports), typically above 3000 km (IEA, 2021[54]), or in cases where there is a wide maritime distance between the production point and demand centres (as in archipelagic countries). There are three main technology solutions to transport hydrogen by ships:

- Liquid hydrogen. As hydrogen has a very low density by volume, it can be stored by liquefaction at -253ºC. This is an energy intensive process and there is a risk of boil-off during the transportation. This leads to a yield loss of more than 30%, thereby increasing the cost of hydrogen (Van Hoecke et al., 2021[66]).
- Ammonia. The energy density of liquid ammonia is higher than that of liquid hydrogen and the transport of ammonia over large distances is a mature industrial solution. Several applications for

direct use of ammonia are being investigated, as the decomposition of ammonia to hydrogen at the arrival terminal would incur additional costs.

- LOHC are molecules that can be reversibly hydrogenated (at the point of exports) and dehydrogenated (at the point of import). These can be transported in liquid form without cooling.

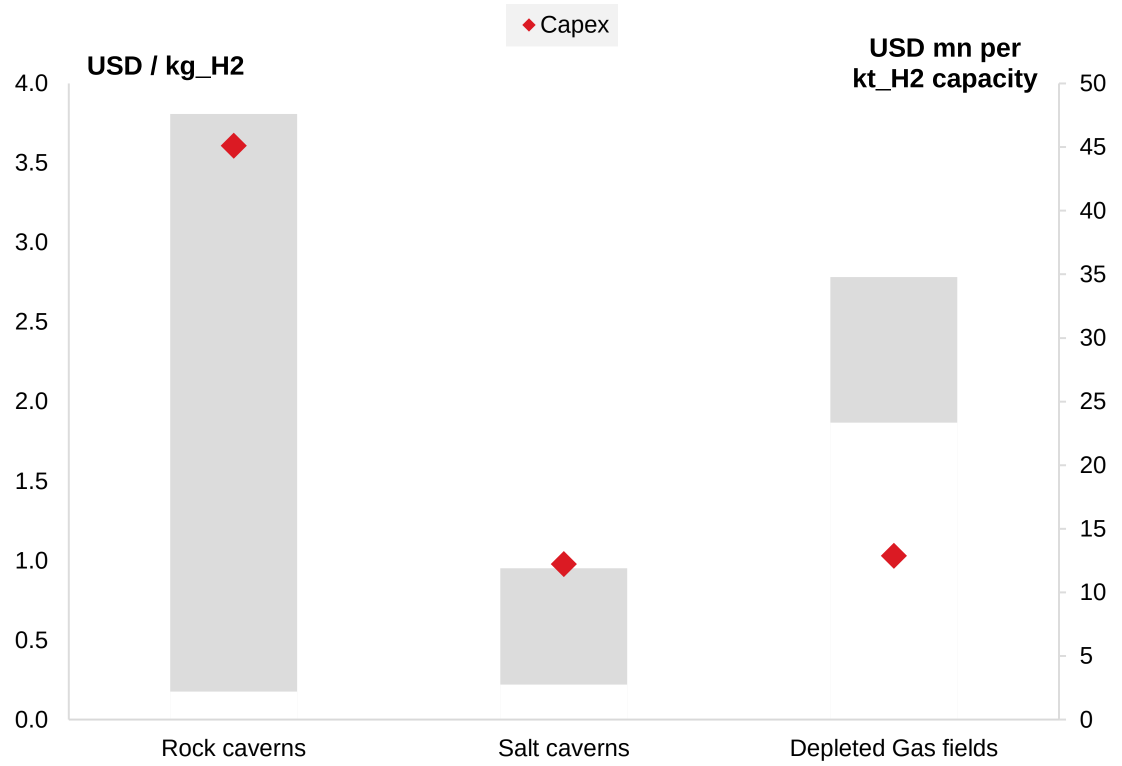
While converting hydrogen to ammonia or LOHC may facilitate transportation by ship, the reconversion into green hydrogen leads to losses, which can for instance amount to 15% in the case of ammonia (IEA, 2020[64]).

Transporting hydrogen via ships thus requires developing several additional industrial facilities for the conversion of hydrogen. Countries with existing large ports can convert them into hubs. Emerging and developing economies with existing knowledge and resources in the Oil and Gas industry (notably for Liquefied Natural Gas) can deploy this experience to similarly develop hydrogen exports via tankers. At the port of import, additional facilities for ammonia cracking, vaporisation of liquefied hydrogen or dehydrogenation of LOHC will need to be developed by the countries off-taking the hydrogen. The development of infrastructure dedicated to a given energy carrier in some locations may also limit the options of trade routes.

Storage

Hydrogen can be stored at various steps of the value chain. A storage capacity near the electrolyser production enables the use of hydrogen storage as a buffer in order to deliver a constant hydrogen volume round-the-clock. In case large transport infrastructures are built, the volume of gas maintained in a pipeline network (the linepack) can be used to meet peak demand, as is the case today for natural gas networks. Hydrogen can also be stored in various forms to facilitate transport or at a smaller scale near the consumption point (e.g. at an industrial site or a refuelling station). Large-scale storage of gaseous hydrogen relies on three main solutions, all linked with geological storage capacity in salt caverns, depleted gas fields and rock caverns. This means that when decoupled production and consumption of hydrogen occur at the same location, the availability of such geological formations in the vicinity can be a success factor for the project.

Figure 2.5. Levelised cost of underground storage of hydrogen and initial capex costs



Source: Adapted from (European Union, 2021[19]), (Agora Energiewende and AFRY Management Consulting, 2021[63]), (BloombergNEF, 2020[67]).

Hydrogen consumption

The diversity of potential hydrogen applications will require carrying out specific analysis depending on the hydrogen consumers. The understanding of operational constraints and economic consequences for the end-user is paramount to evaluate the risks and benefits of a project.

Choice of location

Industry may favour on-site green hydrogen production rather than connecting plants to centralised large-scale electrolysers via pipeline. New industrial production plants using green hydrogen can thus locate in territories with low-cost renewable power integrated with efficient electrolysers. This could enable emerging economies with growing industries to optimise the location of future plants in line with a net-zero pathway.

Continuous operations

Industrial production processes require a continuous supply of energy and feedstock to ensure that plant operation hours are not disrupted. DRI plants operating with natural gas typically operate around 8000 hours per year. Maintaining such a high load with green hydrogen based on variable renewable energy may require significant renewable power capacity and hydrogen storage, although industrial companies are investigating how to improve their process flexibility (Heffron et al., 2020[68]), (European Commission, 2021[69]).

Impact on production processes

Some industrial subsectors like fertilisers already use pure hydrogen, but others will need to adapt their production processes for the same. Several related technologies, such as pure hydrogen DRI, are still at a demonstration phase. R&D efforts and demonstration through first-of-a-kind projects must be implemented to confirm the feasibility of new production pathways and better estimate the impact on the production processes. When new processes are proven, existing plants may have to undertake massive retrofitting to adapt.

Competitiveness

Early switch to green hydrogen can increase production costs where profit margins are already constrained due to high competition. Additional costs need to be covered by specific support measures to ensure a level playing field for transitioning energy-intensive industries and enable the first movers to thrive in the energy transition.

Green products

Definition of green products

Building a common understanding of the definition of green products and materials is a critical issue, notably to avoid the risk of greenwashing. Sound carbon and emission accounting methodologies will be necessary to reach a globally comparable classification.

Creation of a market for green products

Expanding the role of green hydrogen in the economy can help lower costs and support the development of major downstream consumers. The resulting value chains could enable a country with abundant and affordable green hydrogen to promote production of green steel and fertilisers.

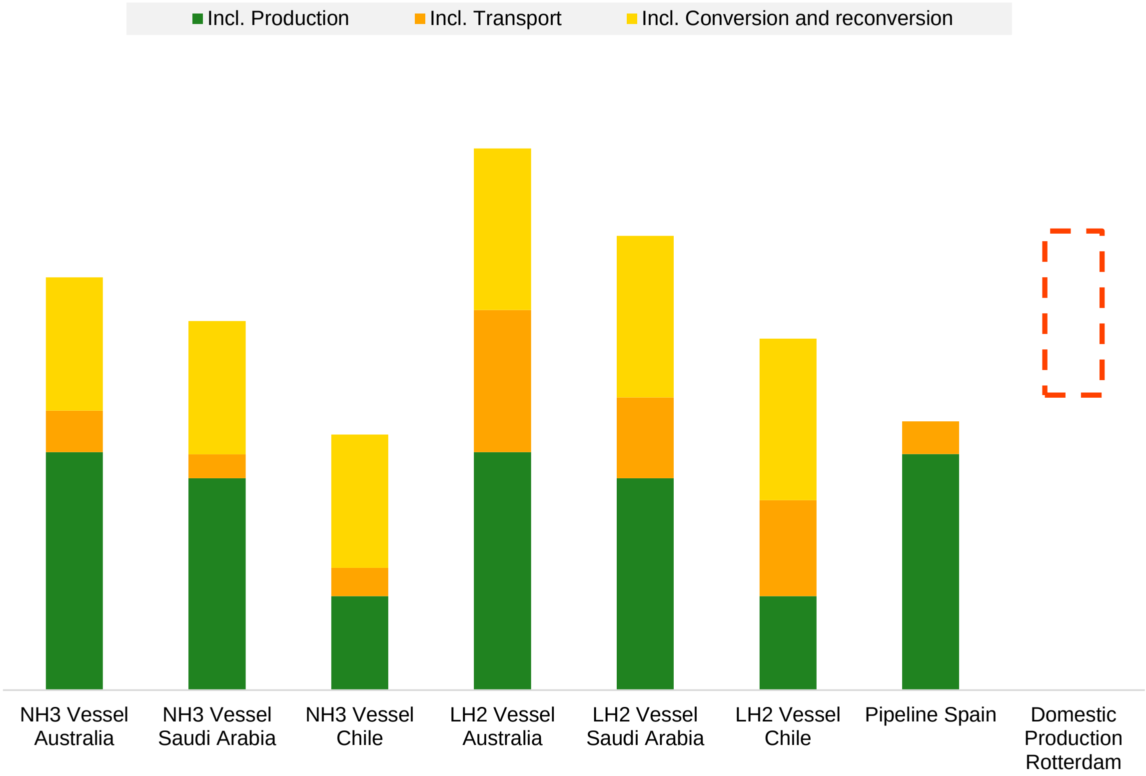
Creating a market reflecting carbon value is required to incentivise investments in projects covering the entire value chain of green hydrogen. Synthetic fuels or products manufactured with clean energy sources usually have a green premium over products manufactured through polluting routes. Factoring in negative externalities as carbon costs or implementing market conditions enabling green products to be competitive will boost the demand for green products. Conversely, uncertainty on carbon price may be an important hindrance for customers to commit to buying green products.

Exports

Global scenarios point to the potential of hydrogen and its products to reshape global energy trade and the balance of power. By 2050, hydrogen could account for more than one-third of the total international energy trade. Around 25% of the worldwide production would be traded globally (IRENA, 2022[9]), representing a market of close to USD 300 billion, with green hydrogen accounting for more than half of this total.

Countries with low-cost renewable energy potential as well as sound enabling environments (such as strong infrastructure and skills base) can become major exporters of green hydrogen, on top of decarbonising their domestic energy system. Other countries can become self-sufficient in green hydrogen and reduce their exposure to internationally traded fossil fuels (IRENA, 2022[1]). Creating sustainable hydrogen trade routes requires the fulfilment of several preconditions, such as accounting for life cycle impacts and measuring carbon content of commodities according to international standards, which may affect the landed cost of green fuels and green products depending on their embedded emissions.

Figure 2.6. Comparison of trading routes and landed costs for imports to and domestic production in Northern Europe



Note: Although the routes displayed in the chart do not emphasise the opportunities for emerging and developing economies, the figure underscores the potential for countries that can produce low-cost green hydrogen to export at competitive prices to certain regions such as Europe. The red scored box at the right side represents the price range of domestic production of green hydrogen in Rotterdam.
Source: Adapted from (European Union, 2021[19]).

Box 2.1. The impact of cost of finance on countries' competitiveness for green hydrogen production

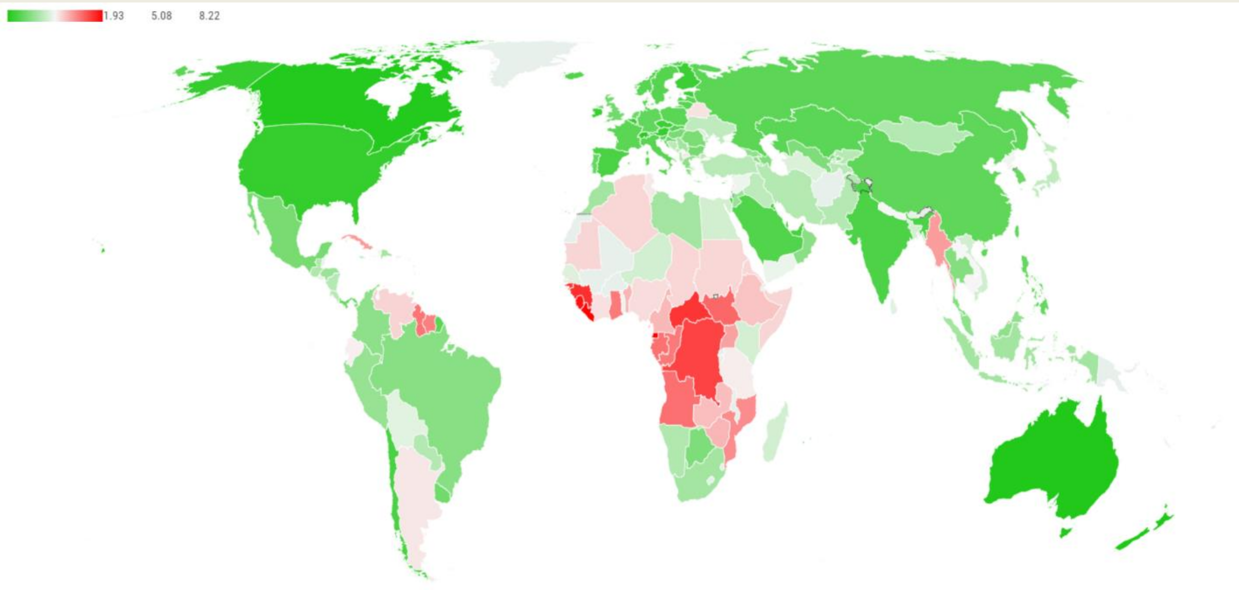
Green hydrogen production is capital-intensive, mainly driven by the cost of renewable electricity capacity and electrolysers. Thus, the cost of finance may influence greatly the levelised costs of production and may be critical for emerging and developing economies to reap the opportunities of green hydrogen (IRENA, 2022[70]). The following maps (Figure 2.7, Figure 2.8, Figure 2.9) display an assessment of the LCOH in various countries, with different assumptions on the countries' discount rates, energy prices, capacity factors and capital costs of technologies to the extent data availability allows.

The assessment assumes a mix of solar, onshore and offshore wind to supply power in maintaining a 50% capacity factor for electrolysers. The solar and wind resources have been estimated based on the best 10% location of each country (ESMAP, Vortex and DTU, 2021[71]), (ESMAP and Solargis, 2022[72]). The capital costs of renewable power plants have been adjusted for several countries, based on the current level of capital expenditures (IRENA, 2022[73]). All findings refer to the current situation.

The three maps illustrate the impact of the cost of finance on two key elements of the green hydrogen economics worldwide. First, the sensitivity of the absolute production costs of green hydrogen when the cost of finance decreases, as one can see in the upper range of the worldwide costs scale in the top-left corner of the figures. Lowering the absolute price level of green hydrogen can be critical to achieve cost parity with competing fuels, such as grey hydrogen, blue hydrogen or natural gas. The production costs of grey hydrogen (derived from fossil fuels) are as low as USD 1.5 per kilogram, although the current energy crisis has driven the prices up significantly (Jaller-Makarewicz and Flora, 2022[74]). Blue hydrogen is produced via the same process as grey hydrogen but where CO_2 is captured and stored, which typically adds USD 0.30 to 0.50 per kilogram of hydrogen produced on top of grey hydrogen prices (Oni et al., 2022[75]). Second, the sensitivity of regional and global competitiveness of a given country to the cost of finance can be observed by comparing its colour on the different figures. For instance, the colour of several countries in North Africa evolves from a light pink in Figure 2.7 to a green shade in Figure 2.9, along with the decrease of the applied discount rate.

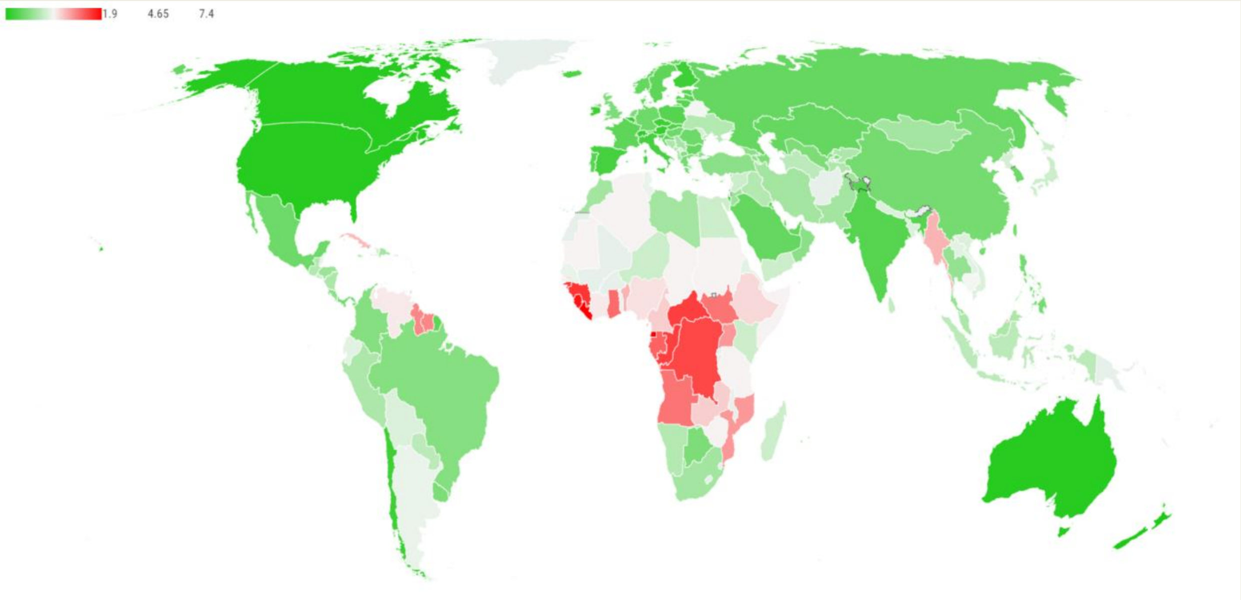
The coloured maps are based on a limited set of assumptions. For instance, as this market is still nascent, a single investment cost has been considered worldwide for electrolysers, although some countries may build domestic manufacturing capacity which may bring them an advantage in the coming years. In addition, the discount rate is applied as an indicator based on the credit rating of countries, but the assessment does not provide any insights on the model financing structure. For a given project in an emerging economy, the cost of capital could be lowered, for instance if private investors are willing to invest with a limited return on equity, if concessional finance is provided through specific programmes, or if special de-risking measures for the project are implemented by the policymakers. For these reasons, and because production costs are not the single criteria to finance a project, the maps do not aim to reflect the investors' decision.

Figure 2.7. Estimation of the cost of production of green hydrogen based on a mix of 50% solar and 50% wind power, adjusted with country-level discount rate



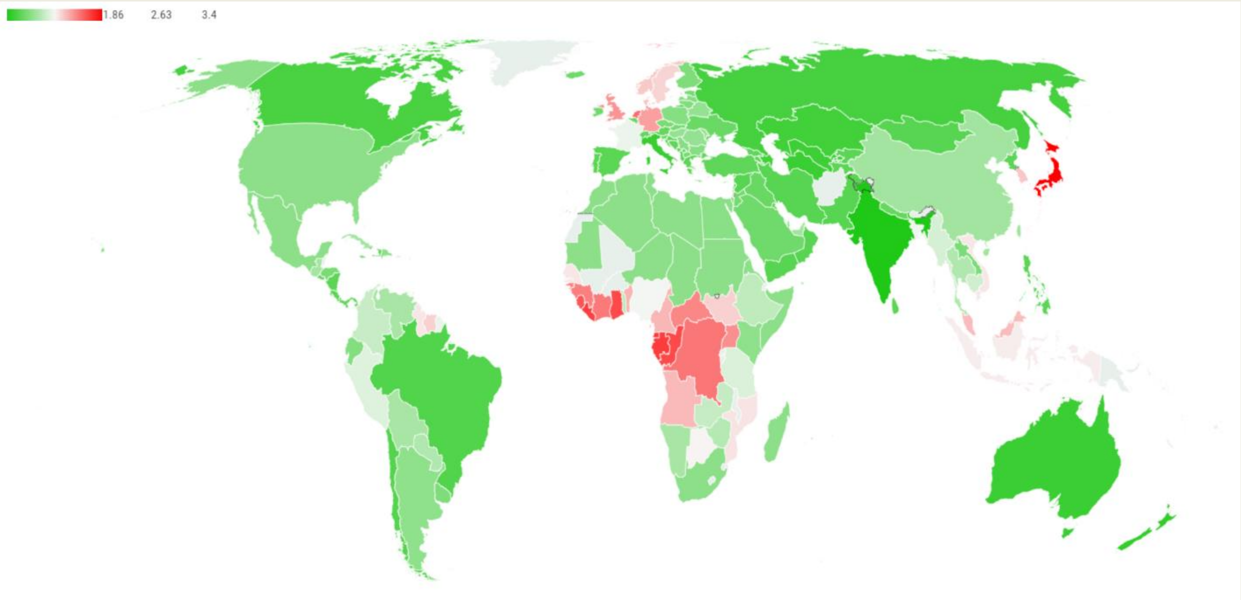
Note: The discount rate in this map has been assessed based on the credit rating of countries, and ranges between 5% and 22%.
Source: Authors

Figure 2.8. Estimation of the cost of production of green hydrogen based on a mix of 50% solar and 50% wind power, adjusted with a two-level discount rate



Note: The discount rate in this map has been set at 5% for OECD and EU 27 countries and 10% for the rest of the world.
Source: Authors

Figure 2.9. Estimation of the cost of production of green hydrogen based on a mix of 50% solar and 50% wind power, adjusted with a single discount rate applied to all countries



Note: The discount rate in this map has been set at 5% for all countries.
Source: Authors

Illustrative business cases

Green steel and green ammonia production are hard-to-decarbonise activities for which green hydrogen is identified as a key lever for reducing emissions. These industries will likely be major consumers of low-carbon hydrogen, especially in scenarios aligned with a net-zero economy (IEA, 2021[54]). These two products are particularly important for emerging and developing economies where their production is increasing, driven by economic and population growth, enabling these economies to achieve socio-economic targets.

With significant green hydrogen potential at low cost (see Box 2.1), some emerging and developing economies may become regional or global market leaders in green steel and green ammonia. However, a successful development will need to de-risk and invest in all steps of the value chain, as a single missing block may prevent projects from coming to fruition.

Understanding the breakdown of investment and annual costs across the value chain scale is a necessary step to identify where policy and financial support will be needed to reduce costs. This can eventually lead to identifying whether a country is well positioned to prioritise parts of the value chain or certain sectors in its national hydrogen strategy.

The two following business cases provide orders of magnitude, based on generic assumptions. Whilst assumptions may vary depending on each country and on the market prices evolution, this analysis can help to draw general conclusions on challenges associated with building profitable business models and create an enabling environment for green steel and green ammonia production.

Green steel[3]

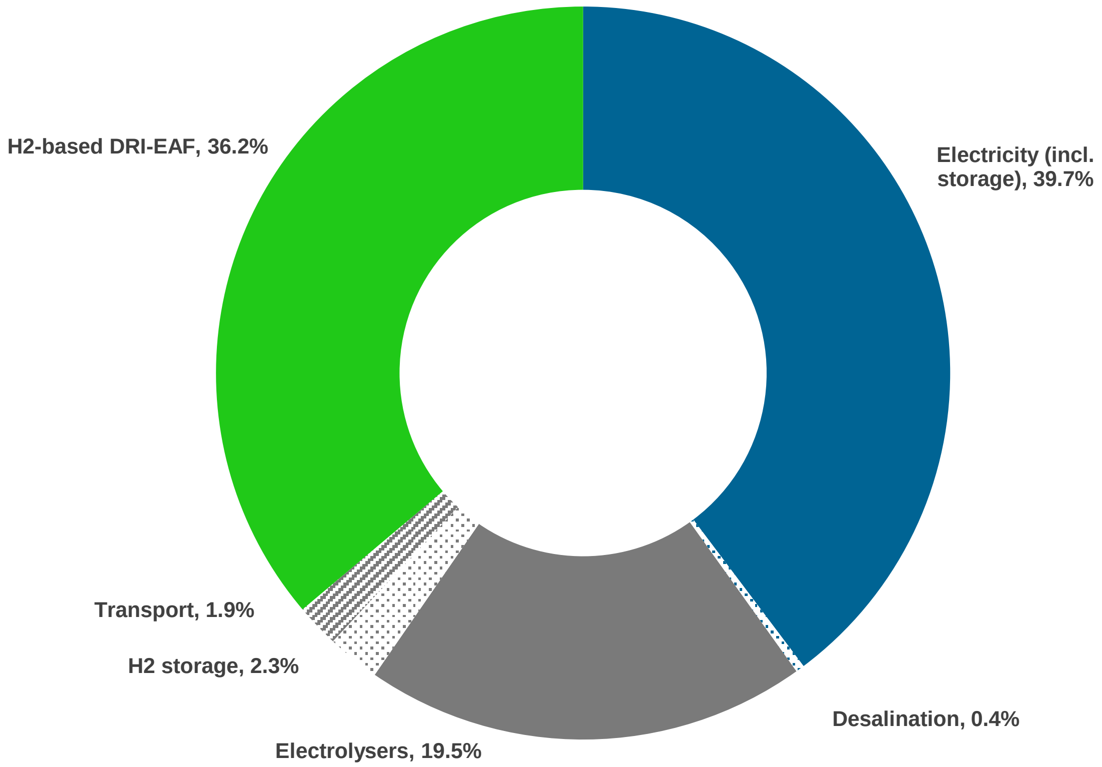
The steel industry is one of the largest emitters of CO_2, contributing to 7% of global CO_2 emissions. While 30% of global steel production is done by recycling steel scrap in EAF, almost 65% relies on blast furnaces (BF) using coal to reduce iron ore, thereby generating about 2 tonnes of CO_2 per ton of steel. Steel can also be produced from iron ore in direct reduction plants fuelled with natural gas, emitting around 1 tonne of CO_2 per tonne of steel. Scrap availability being limited compared to steel demand, the steel industry will continue to rely predominantly on the iron ore-based production route in the foreseeable future.

Various solutions are envisaged by steelmakers to reduce their carbon emissions, among which direct reduction of iron ore using green hydrogen is promising. This route involves an intermediate product called DRI, which can be subsequently melted with a flexible amount of scrap in an EAF. When renewable power is used, the emissions of this route would approach virtually zero.

The analysis of a co-located project of an H2-DRI-EAF steel plant with a capacity of 1 million tonnes per annum (Mtpa), combined with dedicated renewable electricity generation, desalination water plant and electrolysis production demonstrate the interest of a holistic approach to apprehend the economic drivers of developing a green steel plant. An illustrative breakdown of the capital expenditures (CAPEX) of such a project is described in Figure 2.10.

[3] There is currently no official definition for green steel, although various initiatives are underway to define standards of greenhouse gases emissions for green steel and net-zero steel (ResponsibleSteel, 2022[88]). In this section, we will use the term “green steel” to mean simply the steel produced by H2-DRI-EAF plants.

Figure 2.10. Illustrative CAPEX breakdown for a co-located project of VRE, electrolysis and green steel

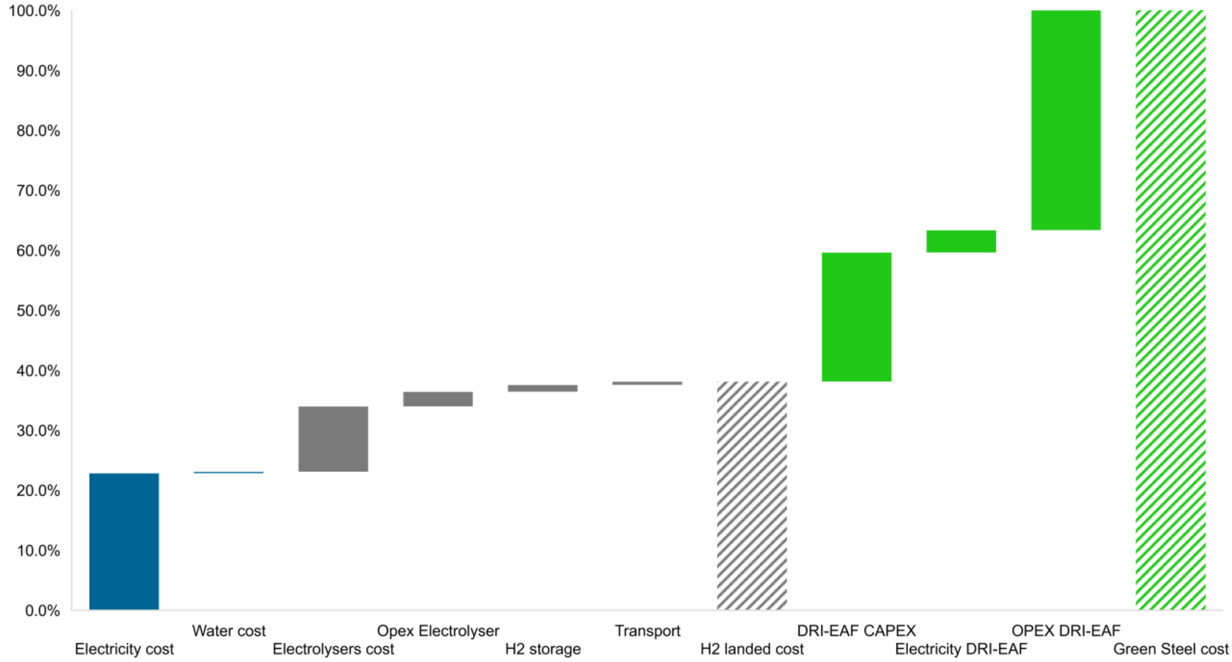


Note: Illustrative calculation based on 50% solar and 50% onshore wind in a favourable location (Levelised Cost of Electricity (LCOE) of USD 30/MWh), USD 550/kW electrolyser costs, 50% capacity utilisation rate for the electrolyser, and availability of geological storage for H2.
Sources: Authors, based on (IEA, 2020[64]), (Patonia and Poudineh, 2022[76]), (OECD, 2021[77]), (IRENA, 2022[78]), (Hydrogen Council and McKinsey & Company, 2021[18]), (European Union, 2021[19]), (Agora Energiewende and AFRY Management Consulting, 2021[63]), (Chevrier, Lorraine and Michishita, 2020[79]).

The breakdown is sensitive to various parameters, such as access to renewable electricity sources, the corresponding electricity storage needs, or the availability of geological storage for hydrogen. Such projects would thus require a case-by-case analysis, considering local conditions. Nevertheless, as the total investment for a similar project could vary between USD 1.5 and 4.0 billion per Mtpa, it is critical to share the investment risks among investors. Steel is a globally traded good facing market overcapacity; higher cost H2-DRI-EAF steel is less attractive to consumers than cheaper steel produced from other domestic or foreign plants. The calculation of the green steel annualised cost in Figure 2.11 sheds light on the relative weight of each component of the value chain in the final production cost.

Since electricity costs represent nearly 20% of the final steel production cost, locations with abundant renewable energy sources would have a competitive advantage for cheap green hydrogen and, in turn, green steel production. Similarly, the expected learning curve for electrolyser production should drive prices down and strengthen the economic viability of H2-DRI-EAF steel plants compared to conventional blast furnace-based production routes relying on coking coal. Given that the prices of electricity and coking coal are not correlated, the "tipping point" enabling H2-DRI-EAF plants to be competitive should be achieved first in locations with access to low-cost renewable electricity.

Figure 2.11. Example of the breakdown of the contribution of each step of the value chain to the annualised cost of production of green steel



Note: The annualised costs include both capital expenditures, amortised throughout the lifetime of the asset, and operational expenditures. The operational expenditures (OPEX) include cost of iron ore pellets, scrap, energy (except for electricity, counted separately), labour, electrodes, alloys and refractories.

Sources: Authors, based on (IEA, 2020[64]), (Patonia and Poudineh, 2022[76]), (OECD, 2021[77]), (IRENA, 2022[78]), (Hydrogen Council and McKinsey & Company, 2021[18]), (European Union, 2021[19]), (Agora Energiewende and AFRY Management Consulting, 2021[63]), (Chevrier, Lorraine and Michishita, 2020[79]).

Green ammonia

183 Mt of ammonia is produced globally every year. More than two-thirds of all ammonia production is via the steam reformer methane route, where natural gas is first used to produce hydrogen, which is then fixed with nitrogen produced via air separation to utilise ammonia. Most of the remaining one-third of the total global ammonia production is largely from coal in China, and a small share is produced from oil via the partial oxidation route.

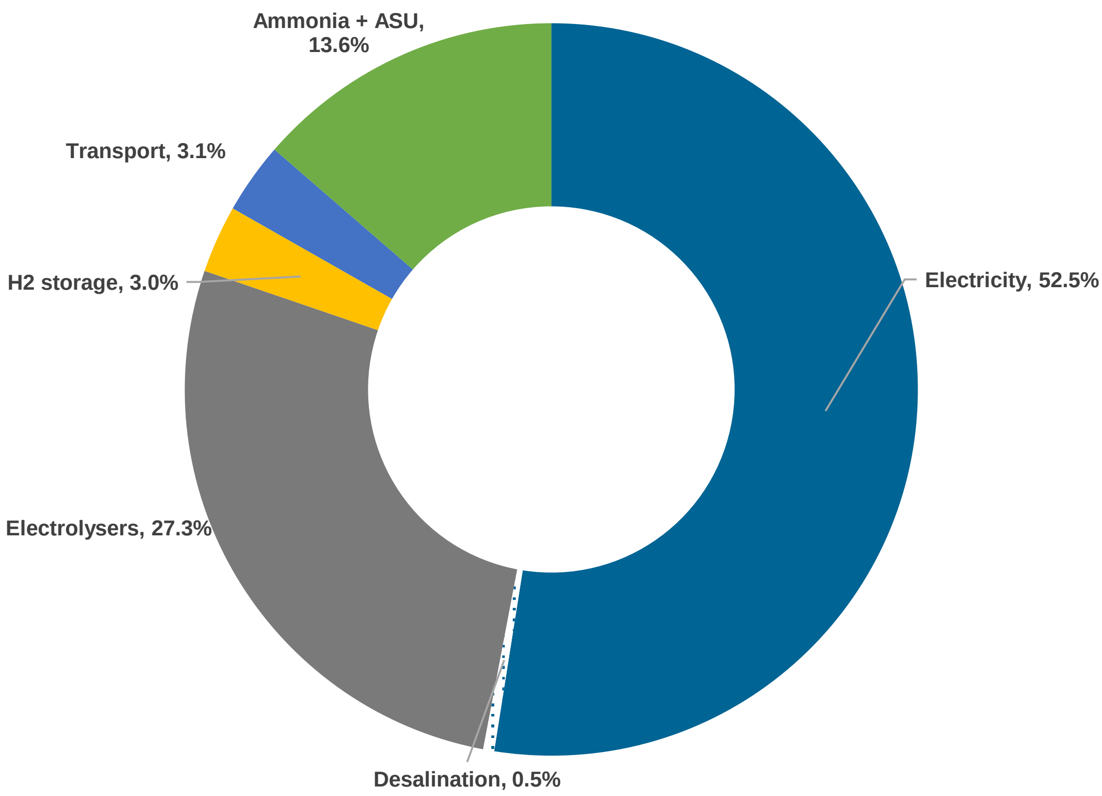
The traditional Haber-Bosch route for producing ammonia from natural gas has an efficiency of about 60% resulting in a total energy requirement of less than 30 gigajoules (GJ) per tonne in modern reformers. The coal-based route is less efficient where modern gasifiers require just above 40 GJ of final energy per tonne of ammonia. The resulting energy demand for ammonia production is about 2% of the total final global energy consumption, directly releasing a total of 0.5 Gt CO_2 emissions.

Fertiliser is the largest market for ammonia today. In the future, ammonia can be used for transporting hydrogen as a transport fuel and for electricity generation. As its uses expand, the global ammonia market is projected to grow by a factor of three to four times by 2050, driven by low-cost green hydrogen production.

Green ammonia presents an early opportunity market, as the steam reforming process can practically be replaced by green hydrogen production from electrolysis where subsequently this can be synthesised with nitrogen from air. The emissions of this route could be close to zero compared to the natural gas-based production that emits around 1.6 tonnes CO_2 per tonne of ammonia, before the capture of CO_2 for urea production.

The largest contributor to the total capital costs along the green ammonia value chain would be related to renewable power and electrolysers, which would collectively account for 80% of total costs. The contribution of the ammonia synthesiser and the air separation unit (ASU) to total costs is around 14% (see Figure 2.12).

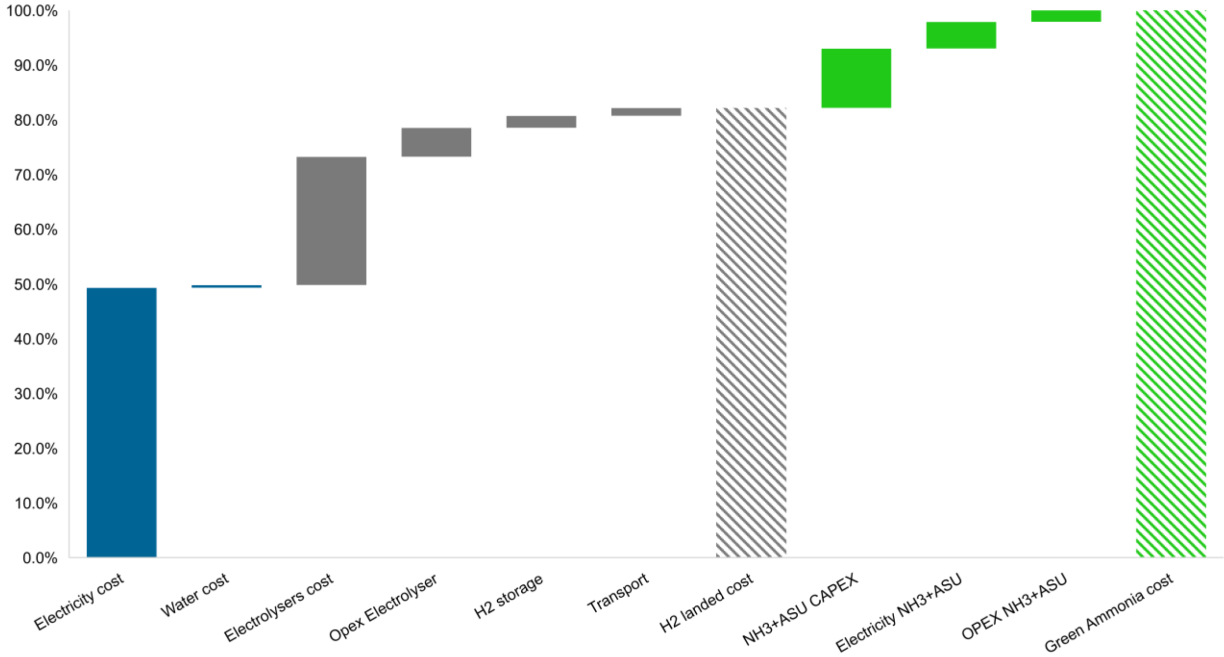
Figure 2.12. Illustrative CAPEX breakdown for a co-located project of VRE, electrolysis and green ammonia



Note: Illustrative calculation based on 50% solar and 50% onshore wind in a favourable location (LCOE USD 30/MWh), USD 550/kW electrolyser costs, 50% capacity utilisation rate for the electrolyser, and availability of geological storage for H2.
Sources: Authors, based on (IEA, 2020[64]), (Patonia and Poudineh, 2022[76]), (OECD, 2021[77]), (IRENA, 2022[78]), (Hydrogen Council and McKinsey & Company, 2021[18]), (European Union, 2021[19]), (Agora Energiewende and AFRY Management Consulting, 2021[63]), (Neuwirth and Fleiter, 2020[17]).

As with green steel production, maintaining low-cost electricity will be critical, perhaps even more important, as they are estimated to represent more than half of the final ammonia production cost. This is followed by the electrolyser capital costs which would account for another 20% of the total production cost. As opposed to the green steel production cost breakdown, the contribution of the capital and operation and maintenance costs of the downstream production processes, namely the ammonia synthesiser and the air separation unit, have a much lower share (see Figure 2.13).

Figure 2.13. Example of the breakdown of the contribution of each step of the value chain to the cost of green ammonia



Note: The annualised costs include both capital expenditures, amortised throughout the lifetime of the asset, and operational expenditures.
Sources: Authors, based on (IEA, 2020[64]), (Patonia and Poudineh, 2022[76]), (OECD, 2021[77]), (IRENA, 2022[78]), (Hydrogen Council and McKinsey & Company, 2021[18]), (European Union, 2021[19]), (Agora Energiewende and AFRY Management Consulting, 2021[63]), (Neuwirth and Fleiter, 2020[17]).

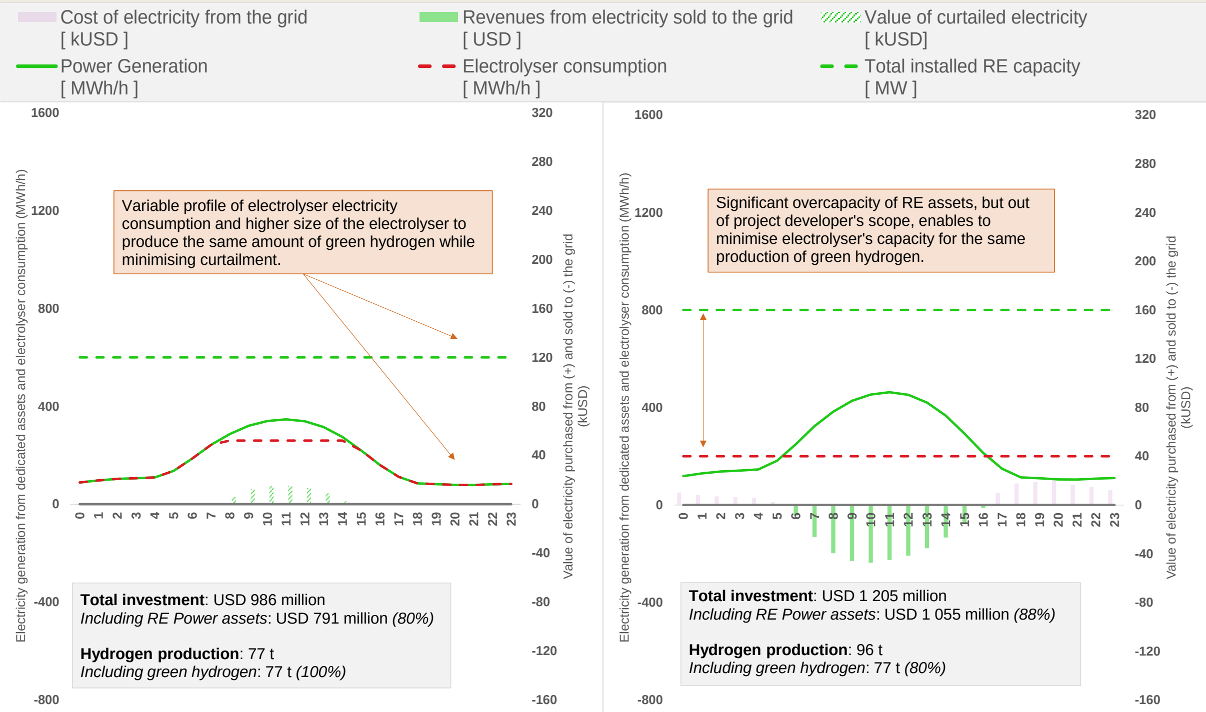
Box 2.2. Influence of using stand-alone renewable power capacity dedicated for hydrogen production or grid-connected electricity

When designing a project for green hydrogen production, it is critical to understand how power will be supplied. Project developers can rely on stand-alone renewable power capacity dedicated for hydrogen production or allow for a mix of consumption including from the power grids.

This decision impacts the project scope and upfront investment costs, and its detrimental for the actual production volume of green hydrogen. Grid-connected electricity enables the minimising of the CAPEX for the electrolyser and attain higher utilisation rates of the electrolyser capacity, but the share of hydrogen produced from electricity from the grid that can be labelled as green may vary in each jurisdiction. Moreover, the hydrogen production cost would be exposed to the market prices of electricity, which can be volatile and reach very high levels, as observed in many countries during the current energy crisis. Conversely, the choice of using stand-alone renewable power capacity would affect the load factor of the electrolyser but would guarantee that all the hydrogen produced is green.

Figure 2.14. Illustration of the impact of using stand-alone renewable power capacity or grid-connected electrolyser

In the left-hand chart, a typical day of operations of an electrolyser relying on stand-alone renewable capacity is depicted, with oversizing of renewable power capacity assets compared to the electrolyser, and a variable hourly production of electrolyser. In the right-hand chart, the connection to the grid enables the buying of electricity from the grid or selling of the excess of power generation and maintenance of a constant production of hydrogen.



Note: Illustrative charts showing one day of operations. Each model could be further optimised based on project-level sensitive assumptions. Calculations based on a renewable electricity generation mix of 40% solar photovoltaic (CAPEX: 800 USD/kW), 40% onshore wind (CAPEX: 1800 USD/kW) and 20% offshore wind (CAPEX: 3739 USD/kW), and electrolyser CAPEX of 750 USD/kW.

3 Enabling conditions and success factors of green hydrogen projects

Overview of case studies

In order to shed light on the success factors of pioneer green hydrogen projects, eight case studies were carried out with companies that have developed demonstration projects and/or are in the process of developing large-scale projects. Case studies were selected from emerging and developing countries wherever possible, or from developed economies where the former can take advantage of key learnings. Selected projects and companies cover several end applications for green hydrogen, including industry, transport and energy applications (see Table 3.1).

The company case studies have been informed by background desk-based research covering the companies' publicly available information. In order to gather additional information and insights on the green hydrogen projects, semi-structured interviews were conducted with the relevant company representatives. Subsequently, the case studies prepared by the OECD were vetted by the companies ahead of their publication. Insights and lessons learnt from the case studies are incorporated in the main text of this paper. Updates on these first case studies and further examples will be posted on the CEFIM website as the projects develop (www.oecd.org/cefim/).

Table 3.1. Case studies illustrating the governance model, enabling conditions and financing structure of green hydrogen projects

Case studies selected by the author based on the level of maturity, geographical location, and replicability potential of similar projects in emerging and developing economies.

Company	Country	Green Hydrogen application
Ad Astra	Costa Rica	Trucks and buses
H2 Green Steel	Sweden	Steel
HIF Global	Chile	E-fuels
HDF Energy	French Guiana / Indonesia	Dispatchable power
Hychico	Argentina	Power
Hyphen Hydrogen Energy	Namibia	Ammonia
Port of SOHAR	Oman	Hydrogen, Ammonia, Steel
The Green Solutions	Viet Nam	Ammonia

Note: e-fuels (also called synthetic fuels or electrofuels) are liquid fuels manufactured by combining captured CO_2 and green hydrogen; HDF: Hydrogène de France.

Case studies

Ad Astra, Costa Rica, trucks and buses

Basic description

Founded in 2007, Ad Astra Energy and Environmental Services explores the application of green hydrogen and fuel cells in e-mobility. It builds on the expertise of its parent company, Ad Astra Rocket Company, in similar technologies for space applications.

Ad Astra's first demonstration project, the "Costa Rica Hydrogen Transportation Ecosystem", began operations in 2018 in the Guacanaste province. Green hydrogen was produced with electricity generated from its own solar farm (78 kW) and wind turbine (5 kW) and a 5.9 kW Proton Exchange Membrane (PEM) electrolyser. This green hydrogen was then used in a "Nyuti" bus, the first hydrogen-based transport unit in Costa Rica. The Nyuti bus runs on a hydrogen tank with a capacity of 38 kilograms (kg) of compressed hydrogen, can transport 35 passengers, has a 338 kilometers (km) range and a speed limit of 110 km per hour. Since 2019, the green hydrogen project has been feeding a fleet of four Toyota Mirai that operate in the tourist areas of Guanacaste.

The Costa Rica Hydrogen Transportation Ecosystem project was developed over the past 10 years with a total investment of USD 8.8 million (49% investment from Ad Astra, 35% from the Costa Rica government, 9% from NGOs, 7% from other investments and sponsorships), including end-of-cycle electrolyser replacement and an H70 (for 70 megapascal) hydrogen dispenser in 2019. It is a small-scale pilot project built to test the technology and to learn by doing. Learnings from this project are fundamental in understanding how to operate green hydrogen infrastructure in tropical climates and to mitigate risks related to high temperatures.

Figure 3.1. Simplified process of Ad Astra

Note: 1: Renewable electricity generation; 2: Electrolyser; 3: Storage; 4: Hydrogen dispenser.
Source: Company's communication document.

Project rationale

Costa Rica's power generation relies entirely on renewable electricity, with hydropower being the main energy source (70 to 75% of power generation), followed by wind and geothermal energy. Transport share in the total final energy consumption is just above 50% (80 petajoules (PJ) per year), and this sector consumes the lion's share of the country's fossil fuels. As Costa Rica depends highly on imported fossil fuels, developing local clean fuels will not only decarbonise the transport sector and achieve the country's net-zero targets, but also improve its trade balance.

Business model

As transport is the targeted market segment for the first project, the main challenge is to aggregate demand by identifying strategic areas to develop user recharging hubs. This will reduce infrastructure and distribution costs, which is especially important when the size of the project is around a few MW for the electrolysers, thus limiting economies of scale for green hydrogen production.

The first location was chosen strategically, at a convenient area for city buses and less than 10 km away from logistics centres to enable demand from trucks or on-site vehicle fleets.

Collection of letters of intent from potential off-takers secures demand for the first project(s), although it is complex to commit to long-standing contracts in the transport sector. Thus, under a pay-per-use model currently under discussion, Ad Astra / ProNova Energy plan to lease vehicles (including the fuel) at a given tariff per km.

On the supply side, Ad Astra plans to rely on grid electricity possibly with a minor share of on-site solar panels, as grid electricity is already fully decarbonised and Costa Rica has upside potential to build additional clean power generation capacity. Given the size of the project and the large share of dispatchable renewable energy in Costa Rica's power mix, the project will not affect the grid's operations.

Fossil fuels are rather expensive in Costa Rica, hence the price gap between diesel and green hydrogen is not a barrier. This is especially so because some companies are ready to pay a small premium, as long as the pay-per-use price does not significantly affect their cost structures.

Governance

The Costa Rica Hydrogen Transportation Ecosystem project began in 2011 as a public-private partnership between Ad Astra and the state refinery Refinadora Costarricense de Petroleo to understand the process of producing, compressing and storing hydrogen at 700 bars.

Ad Astra is a technology integrator, which aims to integrate the engineering, equipment design and project development for green hydrogen infrastructure deployment across Latin America. For this initial pilot project, a public-private collaborative effort was led by Ad Astra and involved Air Liquide, Cummins Inc, Sistema de Banca para el Desarollo, Relaxury S.A., and US Hybrid Corporation. For instance, Cummins supported the process of integrating the renewable energy sources and the hydrogen bus into the Ecosystem and Air Liquide provided the hydrogen fuelling equipment.

In order to move from demonstration to commercial operations, Ad Astra launched a joint venture with a Latin American renewable energy investment firm called Mesoamerica. The joint venture, ProNova Energy, is positioned as a large-scale green hydrogen project developer for Latin American markets. Its first project will be developed in Costa Rica to expand the electrolyser capacity of the current pilot project to 1 MW through a special purpose vehicle (SPV). This project, expected to cost USD 6 million and become operational in 2024, will produce 450 kg of hydrogen per day and operate a fleet of around 10 buses or trucks. Future projects are also expected to be developed through SPVs.

Enabling market conditions and investment de-risking

Costa Rica's power market is dominated by the national power company Instituto Costarricense De Electricidad. A new green hydrogen bill, currently under discussion, would offer a special electricity tariff and/or power purchase agreements at above-market conditions to green hydrogen producers. The allocation of carbon credits could also provide an additional revenue stream to de-risk the first green hydrogen projects.

The main risk for applications in trucks and buses is on the demand side. So far, there is no national policy or mandate that guarantees a sufficient market size. Aggregating demand, proposing an offtake guarantee, or setting vehicles emissions targets could thus mitigate the demand risk.

Financing

The Costa Rica Hydrogen Transportation Ecosystem project has been financed mostly through private equity, with an important share of public seed funding at the beginning. The project expansion to 1 MW electrolyser capacity with ProNova Energy will also rely on private equity, which has already been secured.

In addition, Ad Astra participates in a consortium sponsored by the government of Costa Rica under a grant from the Nationally Appropriate Mitigation Actions (NAMA) Facility. This Facility proposes a two-step approach over five years: *(i)* a pilot phase including a new transportation pilot project and an industrial demonstration; and *(ii)* the design of a full-scale financial mechanism to make green hydrogen projects in Costa Rica economically viable.

Ad Astra has identified MDBs, including the World Bank, and climate funds as key financiers for the next projects. The International Finance Corporation is in fact the key financial partner of Costa Rica's green-hydrogen NAMA proposal. The InterAmerican Development Bank will also play a key role through direct investment of credit lines for green hydrogen project developers and producers, as well as by supporting the country on policy development. Similarly, the Central American Bank for Economic Integration and the Climate Investment Funds will be privileged financing stakeholders.

While the company is currently focusing on the first project, scaling up in the future will require accessing the debt market, particularly with the use of green bonds. Financing from commercial banks will also be needed to increase leverage.

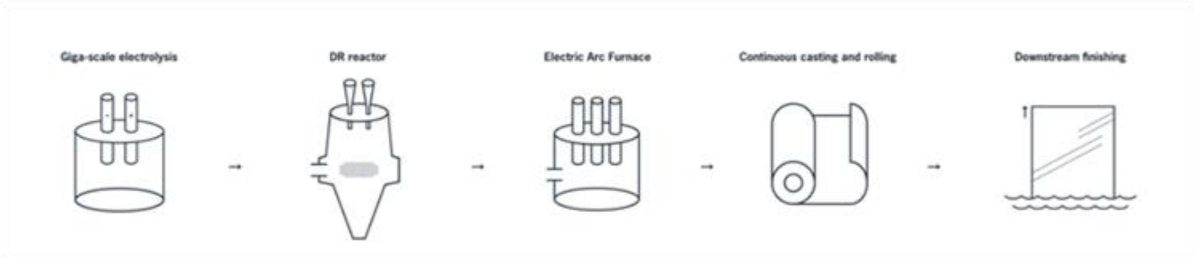
H2 Green Steel, Sweden, steel

Basic description

H2 Green Steel, headquartered in Stockholm, was founded in 2020 by Vargas. It aims to build a large-scale green steel production facility in Boden in northern Sweden, using a combination of renewable electricity and green hydrogen, thus eliminating almost all the CO_2 emissions from the traditional steelmaking process. The company's mandate is to decarbonise heavy industry with green hydrogen, and the construction of its first green steel plant ensures offtake for its future green hydrogen production.

The project consists of a 700 MW capacity of alkaline and PEM electrolyser capacity, a direct reduced iron (DRI) plant with a nameplate capacity of 2.1 million tonnes (Mt) per year, a steel melt shop to combine the DRI with steel scrap and downstream production lines to produce 2.5 Mt of finished steel products annually prior to a planned second-phase capacity expansion.

Figure 3.2. Simplified production process of H2 Green Steel



Source: Company's communication document.

Project rationale

While the purpose of the company is to decarbonise heavy industry, the choice of green steel as a first application was driven by its large-scale technical and commercial readiness compared to other uses. Given its strong ties with several end customers of steel, including in the automotive sector, H2 Green Steel matches Sweden's large resources of cheap hydropower with customer appetite for green steel. Although the green steel premium was unknown at the inception of the company, this market has started to emerge over the last couple of years.

The choice to locate in Europe stems from the high risk facing the European steel industry, as free allocations within the European Union Emissions Trading System (EU-ETS) are expected to decrease in the coming years. There is also growing consumer demand for decarbonised products in Europe. The combination of a possible carbon border adjustment mechanism (CBAM) and high EU ETS prices is expected to drive up costs of producing steel via the blast furnace route. As this route emits around 2 tonnes of CO_2 per tonne of steel, H2 Green Steel estimates that steel production costs will exceed EUR 100 per tonne of steel by 2031, leading to a strong increase in steel market prices. Green steel production costs will not be affected by these developments, thereby assuring sufficient margins for green steel producers.

Business model

Producing steel based on green hydrogen is more expensive than producing it via the traditional coal-based blast furnace route. Thus, the business model relies on demand from first-mover customers willing to pay a premium for green steel. In May 2022, H2 Green Steel announced that long-term contracts with volume commitments over 5 to 7 years have been signed with customers from various industries. The aggregated pre-sold volumes reached 1.5 million tonnes (Mt) per year of steel, corresponding to 60% of the plant's future production capacity.

The optimisation of the raw material mix in the Electric Arc Furnace (EAF), in particular the use of high-quality scrap, can ensure better production costs and low CO_2 emissions. Pursuing this objective, H2 Green Steel has secured a reverse flow of 40 percent of the pre-consumer steel scrap from the car manufacturer BMW.

Moreover, in principle more than 70% of the European blast furnace capacity will need to be relined[4] over the next decade as they reach the end of their operating lifetimes. H2 Green Steel aims to minimise the production cost premium of its greenfield plants, thanks to the availability of cheap and stable renewable electricity in north Sweden. It announced a 7-year contract with Statkraft in June 2022, securing 2 terawatt-hour (TWh) per year of renewable electricity supply for its green steel facility.

Governance

H2 Green Steel has a standard governance structure found in industrial sectors, with a holding company acting as an investment vehicle for equity investors and individual project companies for each new project. As the company does not envision owning future assets along the entire value chain, it could focus more on hydrogen production, possibly in vertically integrated projects, for instance with green electricity suppliers and green hydrogen off-takers.

[4] Blast furnaces operate for 20 to 25 years after which the refractory lining has to be renewed. Steel companies usually carry out refurbishing activities and upgradation in parallel **to** the relining process.

Enabling market conditions and investment de-risking

Access to cheap and stable renewable electricity throughout the day and the year is the main prerequisite for the H2 Green Steel project. Building an energy-intensive plant near the large hydropower resources of Sweden, which are located far away from the country's main electricity consumption centres, allows the electricity transport system operator to avoid massive grid investments, especially in countries having large resource potential in regions with low demand.

Steel is a globally traded good requiring large volumes of iron ore and generating large volumes of final product. Thus, access to deep-sea harbours and inbound and outbound logistics infrastructure (such as railways) will also be a decisive factor for future plants. The Boden site will be built on undeveloped land meant for industry use, yet slightly far from the main existing infrastructure. This requires ensuring the timely connection to water, energy, rail and road infrastructure besides the construction of the steel plant.

Tens of permits and licences are usually required to develop vertically integrated projects. A lean permitting and regulatory process will be a critical factor in the country selection for future projects. Moreover, a stable economic environment and the engagement of local communities will be crucial for projects in emerging economies. As such projects are highly capital intensive, this is key to reduce country risk for domestic and international lenders. In the case of Sweden, banks and financial institutions have indicated that positive perception of the project by the local municipality and citizens is a factor in their investment decision.

Financing

H2 Green Steel is financing its first project through a combination of equity at the holding level and debt at the Boden project company level. The total investment aims for a similar gearing ratio as in typical capital-intensive industry and infrastructure projects.

H2 Green Steel equity investors are primarily interested in the holistic decarbonisation of heavy industries rather than in a single project. As the company is still young, investments will be staggered as the project progresses. In 2021, H2 Green Steel raised USD 105 million in Series A equity from various investors, including potential customers from the automotive industry. In July 2022, Hitachi Energy made an equity investment in H2 Green Steel, along with commitments to support electrical infrastructure development and to offtake the green steel product for its own manufacturing. In August 2022, the company announced a further USD 190 million in Series B equity financing.

On the debt side, H2 Green Steel is discussing possibilities with various public and private financial institutions. A combination of debt instruments with various seniorities and guarantees will be required to finance the project.

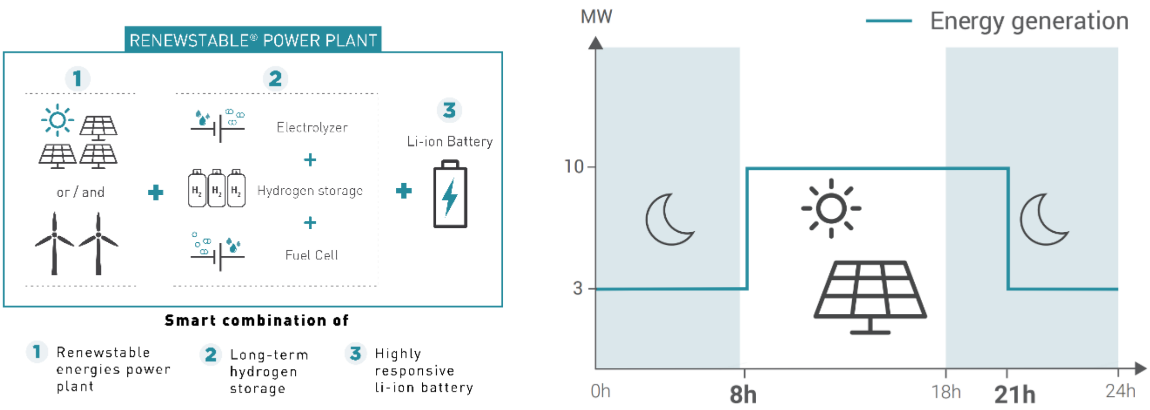
HDF Energy, French Guiana and Indonesia, dispatchable power

Basic description

Renewable electricity is the cheapest source of power supply today, but the variability of wind and solar energy impedes the integration of higher shares into the power mix. To overcome this issue, HDF Energy has developed the Renewstable concept combining variable renewable energy, batteries, hydrogen storage and fuel cells to provide stable electricity supply.

Two of the first Renewstable projects are CEOG in French Guiana and Sumba in Indonesia. These projects are expected to be commissioned in 2024 and 2025 respectively, following a staggered approach to gradually increase capacity. The CEOG project is located at Saint-Laurent du Maroni in French Guiana, where land preparation and construction started in September 2021. Although French Guiana is a continental country, its grid is similar to an isolated island grid, as it is not connected to neighbouring areas and has a limited total capacity of 450 megawatts (MW). The CEOG project aims to deliver 10 MW during daytime and 3 MW at night with an installed capacity of 55 MW of solar photovoltaic (PV), complemented by 130 megawatt-hour (MWh) energy storage capacity comprising 16 MW alkaline electrolysers and 3 MW of fuel cells. Around 600 tonnes of green hydrogen will be produced every year for this project, enabling long-term (more than 5 hours) energy storage. The Sumba project follows a similar approach for a pipeline of projects to achieve more than 10 MW firm power supply.

Figure 3.3. Renewstable concept and electricity load curve



Source: Company's communication document.

Project rationale

The CEOG project contributes to French Guiana's target of reaching 100% locally-produced renewables in the electricity mix by 2030, with wind and solar energy playing significant roles. However, the variability of these resources can cause disruptions in small electricity grids like French Guiana's, and flexibility measures are required to integrate wind and solar energy shares greater than 10%-20%. One such flexibility measure is short- to long-term electricity storage using green hydrogen.

The Sumba Island in Indonesia was selected both due to its island grid nature as well as the existence of the Sumba Iconic Island programme targeting renewables development. Expanding solar photovoltaic capacity under this programme, however, resulted in the installation of a new diesel plant in order to maintain grid stability. To reduce the fossil fuel dependency of the grid, the national government, supported by the local government, expressed interest in a Renewstable solution to achieve at least 80% grid penetration of renewables.

Business model

The main potential markets for Renewstable are located in island grids, i.e. grids with low capacity (typically, below 1 GW) and limited or no interconnections with other grids. To avoid relying on subsidies, HDF Energy targets grids where current electricity prices are high, especially when electricity generation assets are not diversified and are dependent on imported fuels, as it is the case for diesel generators.

In the case of French Guiana, the average cost of electricity generation is fairly high at around EUR 243 per MWh. Slightly more than half of the electricity production comes from hydropower, more than one-third from fossil fuels, and less than one-tenth from biomass and solar.

A well-priced, long-term PPA with a creditworthy off-taker is an important element of the business model. The CEOG project's business model is based on a 25-year PPA. Although there are no standard PPA models in Indonesia, the Sumba project will rely on long-term agreements commonly used by local small-scale projects. HDF Energy promotes the use of PPAs including capacity payments[5] to implement an economically viable contracting scheme for sustainable, pilotable power production.

Governance

HDF Energy is the main project leader and independent power producer (IPP) in the CEOG project. It has signed a power purchase agreement (PPA) with EDF SEI (Electricité de France, Systèmes énergétiques insulaires), a subsidiary of the French power company EDF, specialised in overseas grids.

While HDF Energy started the project as a standalone developer, it subsequently partnered with two other firms – Meridiam, a French benefit corporation, and Rubis, an international chemical storage, distribution, and sales company with a strong local footprint in French Guiana. At financial close, ownership of the CEOG project was split between Meridian (60%), Rubis (30%), and HDF (10%). While Meridian now has a majority share, several matters still require strategic alignment and shared decision-making among the three entities. For technical development, HDF Energy further partnered with companies such as McPhy for electrolysers and Siemens Energy for engineering, procurement and construction as well as operations and maintenance.

Now, the role of HDF Energy is primarily to lead project development, although the company intends to remain a long-term investor over project lifetimes.

Enabling market conditions and investment de-risking

As the Renewstable concept is still nascent, the primary criteria for HDF to engage in a project is that the solution addresses specific issues faced in the country or region. Archipelagic countries like Indonesia and the Philippines were identified as particularly suitable candidates. Political stability of a country is also a key consideration, as is its renewable electricity production potential and local capacity to develop and operate wind and solar photovoltaic plants.

The generation of electricity from green hydrogen is still expensive compared to natural gas-fired power plants production costs, and most countries have not yet defined full-fledged hydrogen strategies or bespoke regulations. While HDF Energy's strategy is to remain independent from specific policy support, the existence of a long-term green hydrogen vision is a major enabler, as it helps validate the contribution of Renewstable projects in building a country's green hydrogen capacity and eventually creating a domestic market.

Another key policy enabler is the existence of high fossil fuel taxes, as this helps create a level-playing field and increase the competitiveness of HDF Energy's solutions.

Standardising the documentation required for loan approvals is also crucial to avoid delays and additional costs in the development phase. Some banks may ask for additional documents to sanction project loans than those normally required by the official permitting and licensing process, thus obliging project developers to carry out multiple studies to meet specific lender expectations. Developing a country platform and a mainstreamed permitting process can help clarify lender requirements. Further, a strong track record of renewable energy projects in the country will boost investor confidence, limit additional documentation requirements and thus reduce transaction costs.

Financing

The financing structure of the CEOG project included debt instruments from commercial banks (Sumimoto Mitsui Banking Corporation, BNP Paribas, Crédit Industriel et Commercial), public investment banks

[5] A capacity payment is a fixed revenue mechanism for electricity producers guaranteeing the availability of a given generation capacity over a given time period in the future.

(French Public Investment Bank) and the French Development Agency (AFD). Many private banks have also shown interest in the project, although the proposed average debt amount was rather low, highlighting the need for diversifying funding sources and sharing risks. The CEOG financing structure was typical of infrastructure projects, with 20% equity and 80% debt financing, for a total amount of around EUR 180 million.

The Sumba project financing will use blended finance.[6] Different development agencies and international organisations, such as the German Corporation for International Cooperation (GIZ), the United Kingdom's Foreign, Commonwealth & Development Office MENTARI Programme, the Asian Development Bank (ADB) and the United Nations Development Programme (UNDP), are already involved in the financing of the environmental and social assessments, pre-feasibility studies, and other related studies. Letters of intent from development banks (United States International Development Finance Corporation, ADB) and commercial banks (BNP Paribas) highlight interest from various actors. Additionally, the project aims to secure funds from the Green Climate Fund. Financing instruments from all actors will cumulatively result in a combination of equity, loans, mezzanine debt and credit enhancement.

Hychico, Argentina, power

Basic description

Hychico's operations in renewable energy started in December 2008 with the Diadema demonstration project.

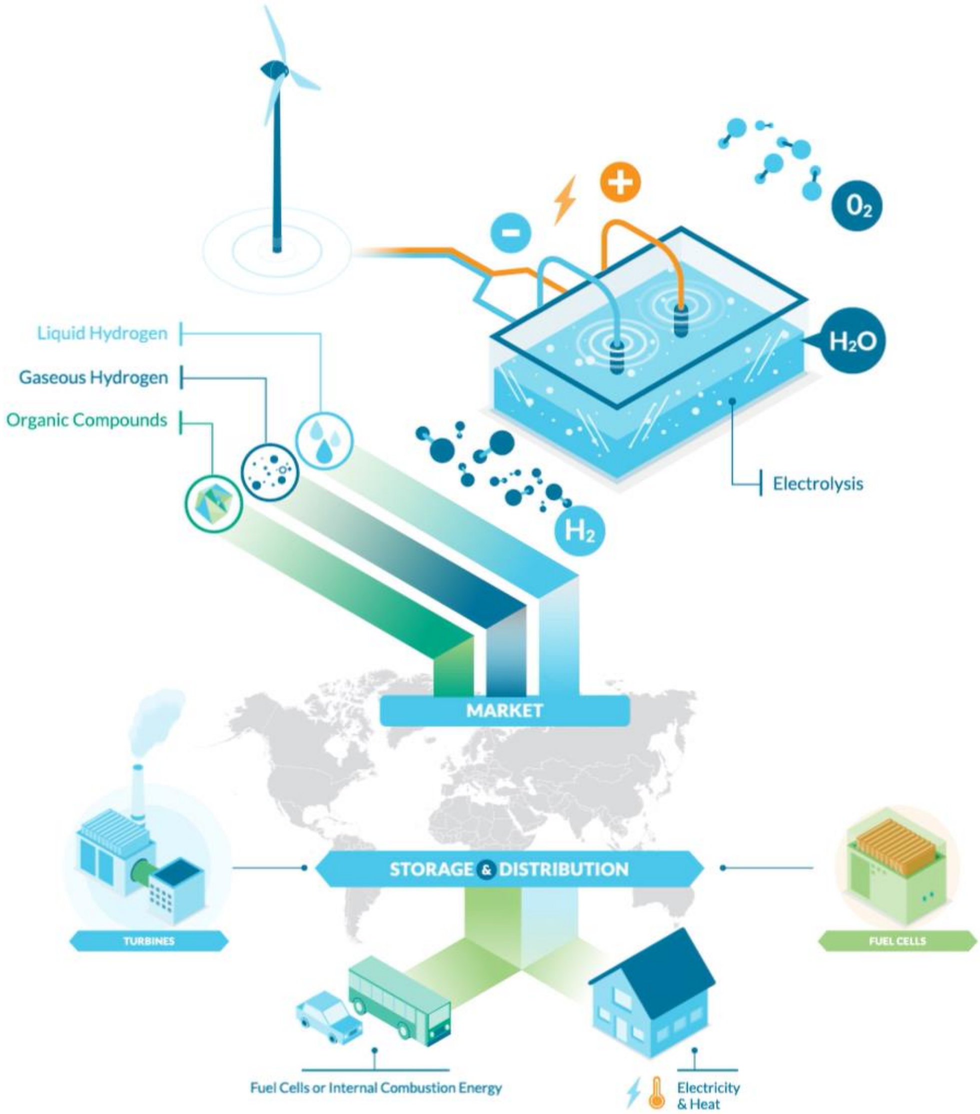
The green hydrogen project benefits from the experience of a decade of operations. The project located in Rivadavia City, Patagonia, includes 6.3-megawatts (MW) wind power capacity comprising seven 0.9-MW turbines and a 1.4 MW electrolysis capacity of two alkaline electrolysers. The project's production capacity is 120 normal cubic meters (Nm3) of hydrogen per hour (h) (equivalent to 10 kilograms per hour) and 60 Nm3/h of oxygen.

The high purity hydrogen (99.998%) is mixed with natural gas to feed a 1.4 MW gas turbine producing electricity. Hychico tested up to 42% concentration of hydrogen in the mix, showing good performance and efficiency in reducing emissions of carbon dioxide and air pollutants, namely carbon monoxide and nitrogen oxide.

Hychico aims to develop activities in the green hydrogen value chain including the production of renewable power. The company has been working on an underground hydrogen storage pilot project since 2010, including a 2.3-kilometre (km) hydrogen pipeline. The company is now investigating options to develop large-scale projects in South America.

[6] OECD defines blended finance as the strategic use of development finance for the mobilisation of additional finance towards sustainable development in developing countries. Further information can be found on https://www.oecd.org/dac/financing-sustainable-development/blended-finance-principles/.

Figure 3.4. Hychico's production and distribution concept



Source: Company's communication document.

Project rationale

Diadema is a small-scale demonstration project with the objective to acquire operational capacity well ahead of market development. Hychico's many years of operational experience from electrolysis, storage, transport and distribution of hydrogen will be a key success factor to overcome the challenges to develop GW-scale projects.

Business Model

The large-scale projects in the Latin America region will benefit from high wind and solar availability. Hychico has reached an annual capacity factor of 50% in its demonstration project in Patagonia.

Then, green hydrogen could be used for applications with the most advanced commercial maturity, such as ammonia, whose production process already uses (fossil fuels based) hydrogen today, and for which production and transport infrastructures already exist.

As the economic viability of projects in the short term remain challenging, Hychico explores the options to valorise the surplus wind electricity generated in the power market. Additionally, by-products from the electrolysis process can be used in an industrial area to bring down the cost of hydrogen production. Thus, the presence of industry to consume heat and oxygen and the access to electricity transport infrastructures to offtake the surplus will be important factors in the location selection.

Governance

The Diadema project is fully owned and developed by Hychico. In the future, a different ownership model can be put in place for large-scale projects that can help to bring in new sources of finance and experiences of other companies.

Enabling market conditions and investment de-risking

A new National Hydrogen Law and a regulatory framework could help to update and expand the 2006 published first National Hydrogen Law of Argentina. This renewed regulatory frame should allow the development of a National Hydrogen Strategy and increase the exposure of Argentina as a potential supplier of green hydrogen for international markets.

Financing

The whole value chain for green hydrogen production is capital intensive, thus improving the cost of finance will play a prominent role to achieve green hydrogen production costs at a competitive price.

Industrial consortiums and a pool of finance institutions will be required to share risks and ensure the viability of the first-of-a-kind large-scale projects. Hychico already has experience in working with industrial consortiums, multilateral and commercial banks.

HIF Global, Chile, e-fuels

Basic description

Haru Oni is an e-fuels[7] production project developed by HIF Global and located in southern Chile's Magallanes region. A demonstration plant reached the final investment decision in 2021, with construction set to begin in September 2022 and the plant expected to be commissioned by October 2022. Under this project, renewable electricity produced by an on-site 3.4 megawatt (MW) onshore wind turbine will power a 1.2 MW electrolyser to produce 143 tonnes of green hydrogen annually. Hydrogen will then be synthesised with carbon dioxide (CO_2) captured from the atmosphere with a Direct Air Capture (DAC) system to produce carbon neutral or low-carbon e-fuels. These e-fuels will have physicochemical characteristics similar to fossil fuel-based gasoline and liquefied petroleum gas (LPG).

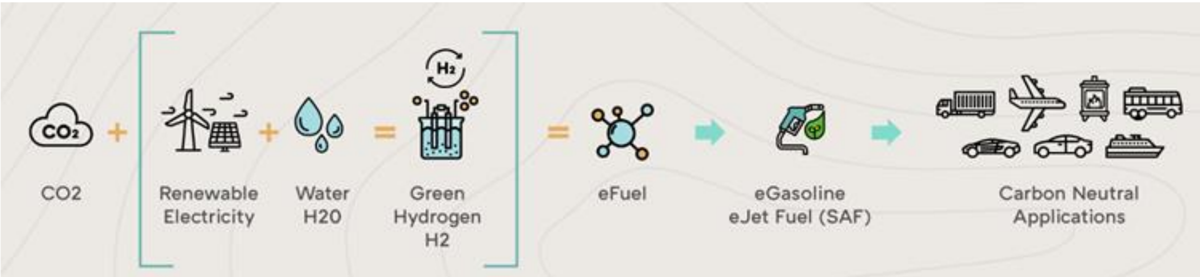
While the demonstration plant has an annual production capacity of 130 thousand litres of e-gasoline, the project is expected to ramp up production to 66 million litres annually by 2025 in its next phase ("HIF Cabo Negro") set to begin construction by end of 2023. The scaled-up production of HIF Cabo Negro will correspond to the annual fuel consumption of 50 000 cars, and the project will be supplied by a total wind

[7] E-fuels (also called synthetic fuels or electrofuels) are liquid fuels manufactured by combining captured CO_2 with green hydrogen. When an e-fuel is burned, it releases an amount of CO_2 equivalent to the amount captured during the production process. Thus, e-fuels are considered carbon-neutral, or having an overall low carbon footprint.

power capacity of 325 MW and electrolyser capacity of 240 MW. In the longer term, HIF Global aims to further scale up capacity expansion by more than 10 times to reach 700 million litres, a quantity equivalent to the annual fuel demand of around half a million passenger vehicles.

HIF Global is also expanding beyond Chile with similar projects. An industrial site and potential partners have been identified in the United States for a large-scale e-fuels facility with 2 gigawatts (GW) of electrolyser capacity and expected annual production of 700 million of litres of e-fuels. Construction is expected to begin by 2023 and operations are expected to start by the end of 2026.

Figure 3.5. The e-fuel production process



Source: Company's communication document.

Project rationale

HIF Global aims to leverage the market opportunity for decarbonising the transport sector with green hydrogen derivatives and end products such as e-methanol and e-gasoline. Given that there is already a premium market for e-fuels, with existing indices on energy exchange markets as well as infrastructure for storage and transport of these fuels, the time-to-market for their products would be short. Further, market maturity will enable consumers to switch more rapidly from convention fuels to e-fuels, thereby realising short-term lifecycle carbon emissions abatement.

Additionally, the Haru Oni project benefits from one of the best wind locations in the world, providing HIF Global access to cheap renewable electricity for green hydrogen production. This enables the company to leverage business opportunities along the full value chain, from generating renewable power to manufacturing green hydrogen derived end products.

Business model

HIF Global will focus on several activities along the value chain, including electrolysis, carbon capture and e-fuels production. The demonstration plant aims to demonstrate the end-to-end process, raise market interest in the technology and bring new investors or partners on board. While the project does not prioritise profits at this stage, it is still expected to generate revenues, thanks to guaranteed e-gasoline exports to Porsche in Germany.

The cost of e-fuels production should decrease significantly in the HIF Cabo Negro commercial facility, thanks to economies of scale along the value chain. For instance, current momentum in the green hydrogen market enables electrolyser manufacturers to build gigafactories, which will reduce the capital costs of electrolysers and, in turn, the production costs of e-fuels.

Moreover, given the favourable location of the project, it has access to cheap green electricity below USD 20 per megawatt-hour (MWh). In the Magallanes region, the capacity factor for wind power plants can be as high as 70% throughout the year (close to a baseload equivalent), thus supplying the continuous electricity needs of green hydrogen electrolysers. For most of the large-scale projects, green electricity will be purchased either through power purchase agreements (PPAs) or directly from the grid, depending on location.

Given its long-term commercialisation potential, DAC was selected as the carbon capture technology for the pilot in HIF Haru Oni. This breakthrough technology does not require capturing carbon from existing industrial plants, thus providing flexibility in location choice. For the next projects, CO_2 is expected to be sourced from industrial processes or biogenic sources to lower e-fuels production costs.

For HIF Cabo Negro, HIF Global aims to secure the sales of 55 million litres of e-gasoline, with more than 70% of the total sale already secured. Synthetic fuels can be sold at a premium. Given the large amounts produced and the need to de-risk investments, HIF Global will favour long-term purchase agreements rather than spot markets for most of its production.

The business case for large-scale projects developed by HIF Global does not depend on subsidies; instead, the location choice provides an opportunity to be competitive with fossil fuels at carbon rates currently in place. Additional revenue streams, such as from the sale of heat or oxygen as by-products from electrolysis, are excluded from the current financial model.

Governance

HIF Global is the sole owner, lead developer and engineering integrator of the demonstration plant in Haru Oni. However, the project relies on a strong network of partners all along the value chain. Siemens Energy designed the power-to-methanol supply chain. Enel Green Power partnered with HIF Global for wind power and hydrogen production for Haru Oni and HIF Cabo Negro. Global Thermostat provided the DAC system solution. Exxon Mobil licensed the methanol-to-gasoline (MtG) process while the MtG technology was built by Sinopec. Purchase of output from the demonstration plant is guaranteed by Porsche.

HIF Global is structured as a US holding company originat**ing** in Chile with local subsidiaries, namely HIF Chile, HIF Australia, HIF USA and HIF EMEA[8] (based in Germany). This structure centralises the management and equity financing, while enabling local entities to develop projects and raise project finance from the market themselves. Following the capital increase of HIF Global in April 2022, Porsche and EIG have joined the HIF board.

Enabling market conditions and de-risking investment

Offtake risk is the most relevant financial risk for HIF Global. The choice to produce e-fuels, starting with e-gasoline but potentially expanding to sustainable aviation fuels or LPG in the future, anticipates the emergence of clean fuel markets supported by green mandates or blending obligations. Certification of e-fuels and associated carbon tax relief are crucial factors for uptake by consumers. The ability to secure the power price in USD through PPAs or on the market (or to hedge the currency risk) is also a major enabler, as most of the investment costs and revenues for large-scale projects are in USD.

Technology risk is also critical. While there is global confidence that technical parameters and costs will improve, project developers must choose the right technologies for the first projects to make end products cost competitive in the long run, acknowledging the potential steep learning curves of nascent technologies. For instance, technology risk is a major concern for DAC in the HIF business model, as its costs are estimated to range widely from USD 100 to USD 1 000 per tonne of CO2. In the short term, use of carbon captured from industrial sources could be a more technically and economically viable alternative, as this would also enable the use of unavoidable CO_2 for e-fuels production.

[8] Europe, Middle East and Africa.

Country risk also plays a crucial role in reaching final investment decision. Beyond the availability of low-cost renewable power, other major enablers include ease of doing business, rapid permitting processes, and depth of domestic financial markets.

Financing

The demonstration project HIF Haru Oni has raised over USD 60 million in total, split between a USD 10 million grant from the German government and USD 50 million of equity. The holding company HIF Global has further secured USD 260 million through a capital increase in April 2022, corresponding to 25% of company shares. Various actors including Porsche, EIG, Baker Hughes, and private investors based in the United States, will develop projects in Chile, the United States and Australia. Future projects will be developed by different subsidiaries for different geographical zones, replicating a conventional project finance model for large infrastructure (20%-30% equity and 70%-80% debt).

Hyphen Hydrogen Energy, Namibia, ammonia

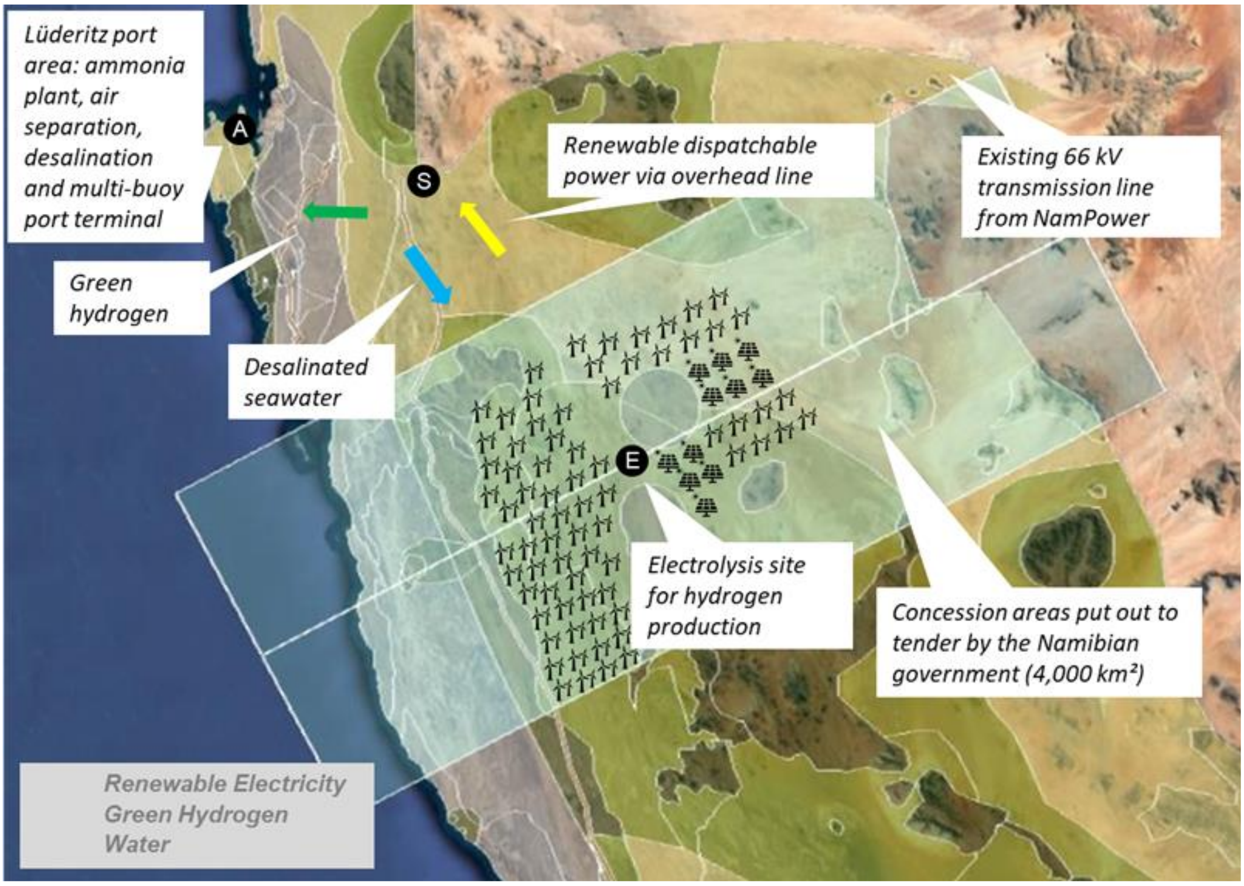
Basic description

Hyphen Hydrogen Energy is a Namibian company established with the objective of developing, constructing and operating green hydrogen production facilities in Namibia for international, regional and domestic markets. The company was selected in November 2021 by the Namibian government to develop a large-scale vertically integrated greenfield green hydrogen project in the Tsau//Khaeb national park. The allocated area is owned by the government and co-located with the deep-water port of Lüderitz.

The project consists of around 5 gigawatts (GW) wind and solar energy capacity vertically integrated with 3 GW electrolyser capacity, capable of producing around 300 kilotonnes of green hydrogen. This is to be used as an input to produce around 1.7 million tonnes of ammonia per year, representing over 1% of the current worldwide ammonia production. Hyphen estimates the total project cost to be around USD 10 billion.

The project will follow a two-stage process. Phase one will require a total investment of around USD 4.5 billion to produce around 0.7 million tonnes of ammonia. An implementation agreement with the government on the detailed engineering is expected by end 2022, targeting financial close in 2024 and commercial production starting in 2026. Phase two is expected to be commissioned by end 2028, with production reaching around 300 kilotonnes per year of green hydrogen from 2029 onwards.

Figure 3.6. Overview of Hyphen Hydrogen Project in Namibia



Source: Company's communication document.

Project rationale

In August 2021, the Government of Namibia issued a request for proposal to develop green hydrogen production facilities in two areas of land in the Kharas region. This was part of the Southern Corridor Development Initiative (SCDI), the umbrella programme for the development of a green hydrogen industry in southern Namibia. The selected location benefits from one of the highest resource potentials worldwide for the combined production of wind and solar-based electricity.

Namibia's ambition to develop green hydrogen offers a double opportunity to deploy renewable energy at scale, facilitating both energy independence and green industrialisation-led economic growth in the country. The project's estimated capital cost is almost equivalent to Namibia's gross domestic product, underscoring its strategic importance for the country.

Hyphen's project is expected to create around 15 000 construction jobs over the construction period of 4 to 5 years. Once fully developed, it will employ approximately 3 000 people. At least 90% of these jobs are expected to be taken by Namibian citizens.

As part of the project, Hyphen will develop a common user infrastructure (CUI) encompassing a desalination plant, water pipelines, electricity transmission lines, hydrogen pipelines, and an ammonia storage and export facility. The establishment of the CUI by Hyphen will benefit all subsequent projects, facilitating the scale up of hydrogen production in the SCDI project portfolio and potentially leading to up to 3 million tonnes of green hydrogen production per annum. This represents one-fifth of Namibia's total green hydrogen production potential of 15 million tonnes per year, which is between 5% and 10% of the expected global hydrogen demand in 2030.

Business model

Hyphen's business model in Namibia is market-based, relying on the production of green hydrogen-based chemicals (such as ammonia) and the sale of green electricity. The choice of ammonia is driven by the maturity of its value chain and the consequent viability to produce, store, transport and consume it as a globally traded product.

Given the size of the project and the low domestic needs for green hydrogen and ammonia, Europe and East Asia are likely to be the key drivers for demand. Negotiations with potential off-takers are ongoing. The first projects will be costlier while the green hydrogen industry is at the beginning of the learning curve, but access to low-cost renewable energy sources and the CUI should contribute to its longer-term competitiveness at the international level.

As additional projects in the SCDI are brought online, Namibia could also benefit from further regional integration. For instance, a better-integrated regional grid can help South Africa, the largest electricity consumer in the region, where more than 80% of electricity generation is based on coal, achieve its ambitious decarbonisation targets. Green hydrogen projects in Namibia will lead to surplus electricity generation which cannot be absorbed by the domestic grid. Given that South Africa has a large industrial sector that could potentially use green hydrogen to achieve its decarbonisation goals, Namibian green hydrogen and electricity could be exported there. This would generate additional revenues, improve the profitability of Namibia's green hydrogen industry and foster regional decarbonisation.

In the longer term, access to low-cost renewable electricity and hydrogen in Namibia can be used to develop fossil fuel-free industry and transport sectors, for instance, mining and processing of zinc and other minerals or the conversion of diesel locomotives.

Governance

Hyphen was formed as a partnership between its two shareholders, Nicholas Holdings and Enertrag. The governance of Hyphen's project in Namibia will rely on a public-private partnership, although it is not yet fully defined, as financial closure is expected in 2024. The government, either directly or via its Welwitschia Sovereign Fund, has proposed becoming a strategic equity partner in all green hydrogen projects in Namibia, targeting a 24% equity shareholding in Hyphen's project.

The Government of Namibia was responsible for designing and administering the tendering of the first land parcels in the SCDI. The tender was undertaken in an open and transparent manner, with a request for information having been initiated by the government ahead of the tender process. In evaluating the tender submissions, the government drew on international expertise from two advisors appointed by the European Union Global Technical Assistance Facility on Sustainable Energy and the United States Department of Energy.

The CUI, to be implemented in phases, will be designed to support the long-term production potential of the SCDI of 3 million tonnes per annum of green hydrogen, the equivalent of 10 Hyphen projects. The CUI is intended to be operated on a system ensuring access, transparency and equal treatment for all future projects.

To drive implementation, the government has established the Green Hydrogen Council, comprising key ministers responsible for the development and implementation of Hyphen's project and Namibia's broader green hydrogen strategy.

Enabling market conditions and de-risking investment

Government support has been a critical enabler for the development of Hyphen's large-scale project. The government has defined its ambition, set a clear strategy for the development of its green hydrogen industry, initiated the request for proposal, and is providing the land. A clear master plan fosters confidence in the project development despite it being a complex cross-ministerial project. In addition, the government facilitated an early stakeholder engagement to address the environmental, social and governance issues.

Access to infrastructure is also a major enabler, as the economic viability of Hyphen's project requires the use of desalinated water, power transmission lines to sell electricity, green hydrogen pipelines, storage of green ammonia and a deep-water port. As infrastructure development can potentially delay project development, the CUI design and the vertical integration of the Hyphen project have ensured its attractiveness to investors.

Although the project's business model relies on the existing ammonia market, it is expected that current and future interventions will drive the adoption of green hydrogen products. These measures are likely to include carbon pricing and minimum blending requirements of green hydrogen in the ammonia production process. Contracts for difference could also help ensure competitiveness of the project, independent of the variation of competing fossil fuel markets (such as in Germany's H2Global programme). Carbon credits could also provide an additional revenue source.

Financing

Although SCDI is a government-led process, public financing of such large projects is constrained by the size of the Namibian economy. Thus, sound financial structuring is critical to avoid debt financing obligations for the Namibian government.

Hyphen's project is capital-intensive and will have a substantial balance sheet impact for the project developers and equity investors. The government targets a 24% equity shareholding in Hyphen's project; as there are other requirements for local equity shareholders, this allows new international actors to acquire stakes. Still, the lion's share of the financing needs to come from debt instruments.

The local debt market is not sufficiently developed and there is no possibility to access local currency debt instruments at the scale of Hyphen's project. However, the vertical integration of the project and the sale of ammonia on the international market reduces currency risk. Moreover, there is substantial interest from Development Finance Institutions (DFIs) and commercial lenders in the potential for blended finance solutions to help the project reach financial close.

Port of SOHAR, Oman, hydrogen, ammonia and steel

Basic description

The Port of SOHAR is a deep-sea port located in Oman, handling almost 60 million tonnes (Mt) of ship-to-ship cargo, containers, dry bulk and liquid bulk each year. The economic freezone where the port is located covers a total area of 4,500 hectares which is under development, with close to 500 hectares already leased. It is attracting various projects of renewable electricity, green hydrogen production and industrial goods produced from green hydrogen. The port and the freezone are managed by a joint venture between the Port of Rotterdam and the Sultanate of Oman.

An example of the project is the development of a 35-megawatt (MW) electrolyser capacity combined with a solar power plant by mid-2024. This will be led by a partnership between Hydrogen Rise, Jindal Shadeed Iron & Steel and Sohar Port and Freezone. The produced hydrogen could then be used partially as a substitute for the natural gas used in the 1.8 Mt per year capacity direct reduction iron (DRI) plant located in SOHAR. The parties will then explore further development of a 10 times larger electrolyser capacity of 350 MW.

The development plan of SOHAR Port and Freezone includes a 3.5-gigawatt (GW) capacity solar power plant to supply electricity to the industrial companies operating in the region. The objective is to turn the current port into a hub for low-cost hydrogen, replacing fossil fuel hydrocarbons, and produce green ammonia and green steel.

If the development of all the activities along the value chain at scale requires more land than what is available, another model that may be possible is the renewable electricity generation and green hydrogen in the middle of Oman and this could be transferred to the SOHAR port and Freezone with hydrogen pipelines for producing green ammonia and green steel.

Project rationale

In SOHAR, the main rationale for a green industry transition is to provide a better stability and competitiveness for companies. In the context of the global energy crisis in 2022, green ammonia is becoming cheaper than fossil fuel-based ammonia in many countries, especially considering the high potential for wind and solar electricity production in Oman. Renewable electricity costs have sharply decreased in the last decade by as much as 80% and analysis suggests that electrolysers will follow a similar learning curve in the next decade.

Another reason is that liquefied natural Gas (LNG) will still play a major role in the foreseeable future. As more LNG infrastructure is being considered in the Port of SOHAR, several actors plan to reserve the available natural gas as much as possible for LNG trade, especially as LNG can be sold on the international market with a significant premium compared to the domestic natural gas market. Thus, they rather plan to convert domestic usages of natural gas (such as steelmaking and aluminium plants) to green hydrogen.

The access to low-cost green hydrogen in Oman could justify the development of green ammonia synthesis plants. However, rather than exporting green hydrogen or green ammonia, vertically integrating the downstream part of the value chain, producing, for instance, urea or steel, could enhance the local value added and improve the economic viability of the projects. In this context, the domestic steel industry is well positioned to become a first mover to consume green hydrogen locally. However, some existing industrial plants in Oman, e.g. in the chemical sector, face higher technical challenges to convert their existing process and may continue relying on fossil fuels in the near future.

The development of green hydrogen production could also be used to decarbonise the mobility applications across the zone such as lorries, cranes, terminal tractors or container transporters. The use of green hydrogen in the port would bring additional benefits and externalities, such as the reduction of air pollution, that could justify the higher operating costs compared to diesel.

Overall, the rational for Oman corresponds to its target to diversify its economic revenues and reduce its dependency on the oil-and-gas sector as a main source of income, as outlined in its Vision 2040 document.

Business Model

The business model of the first projects developed in Oman relies on export markets for customers that are ready to pay for a green premium, or for which the green goods are already competitive. Indeed, as Oman has access to large volumes of cheap natural gas, the viability for local consumption remains uncertain beyond the current crisis. For green steel as a first mover, such as Jindal’s project, a global market is emerging, boosted by initiatives such as SteelZero or the Industrial Deep Decarbonisation Initiative, hinting that the company can find customers. In particular, European companies have expressed interest for green steel imports, and East Asian companies for green ammonia imports.

The Port of SOHAR is also collaborating with the Port of Rotterdam to identify cost-competitive solutions for the adoption of hydrogen as an alternative to natural gas, such as deep-sea vessels fuelled by zero-emission green hydrogen or green ammonia.

Governance

At the national level, the government of Oman has taken several initiatives to co-ordinate initiatives on green hydrogen. In 2021, it brought together 13 public sector and private sector institutions to set up a national alliance called Hy-Fly in order to develop a hydrogen supply chain towards the development of clean fuels. In 2022, Oman communicated plans to create a national energy company dedicated to green hydrogen projects, called Hydrogen Development Oman (HDO). It was foreseen that this company would be a subsidiary of Energy Development Oman (EDO), a state-owned company under the control of the Ministry of Energy and Minerals.

At the project level, SOHAR Freezone provides the opportunity for companies to establish renewable energy plants for self-consumption. The Port of SOHAR is involved in most of the hydrogen projects, leasing the land, including access to all utilities and feedstock (e.g. electricity, natural gas, hydrogen and water), and providing access to facilities to store and ship ammonia. Although the Port of SOHAR s exploring the option to become a minority shareholder in the project, the governance for the future projects is expected to mainly rely on the private sector and national companies.

Enabling market conditions and de-risking investment

The special laws regarding taxes in the economic freezone, such as the corporate tax relief for 25 years, can help attract project developers. Yet, beyond the fiscal measures, a major enabler identified with the first projects is the integration of projects in an inclusive approach covering the entire value chain, possibly even bringing together off-takers to build a sufficient demand. This cross-cutting approach can be supported by government measures such as implementing a one-stop shop for licenses as it is well established in Port of SOHAR.

Financing

For the early applications identified in Oman, the financing can be ensured through traditional finance, as long as the green hydrogen and green hydrogen derivatives manage to secure offtake contracts. Institutional investors like pension funds are showing interest, as well as the national public funding agencies. However, limited capital flows of green or sustainable finance have been observed so far in the region.

Establishing environmental, social, and governance (ESG) metrics and developing the disclosure of sustainability reporting could foster the channelling of international sustainable finance into future green hydrogen projects in Oman. Indeed, there is an increasing pressure from finance institutions to prove that their investments meet stringent ESG criteria, while avoiding greenwashing.

The Green Solutions, Viet Nam, ammonia

Basic description

The Green Solutions (TGS) is an energy company founded in 2016 and based in Ho Chi Minh City, Viet Nam. It is undertaking several local projects, including a liquefied natural gas (LNG) terminal, biomass pellet plants, wind and solar power plants, and green hydrogen production plants.

TGS is currently developing two green hydrogen projects in southern Viet Nam, each with 240 megawatts (MW) of electrolyser capacity. The first project in Tra Vinh Province, which begins construction in

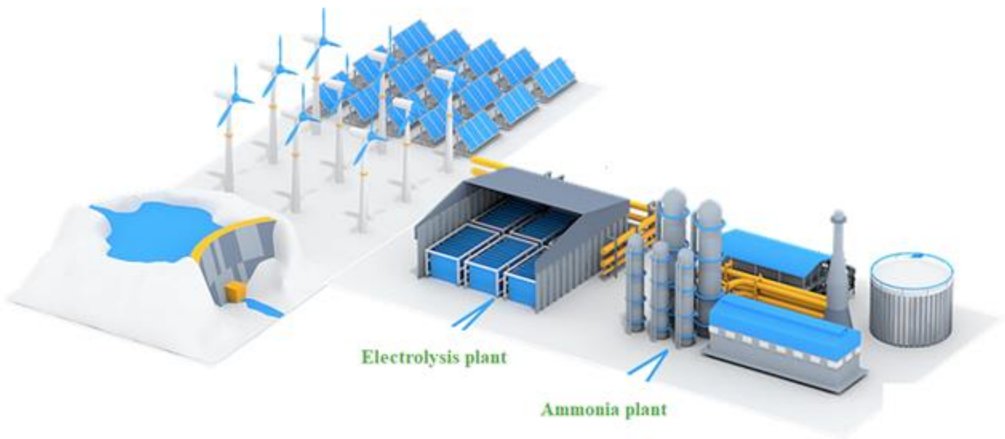
October 2022, will eventually produce 48,000 cubic meters (m3) of hydrogen per hour with surplus renewable electricity from the grid. The corresponding green hydrogen output of 30-36 kilotonnes (kt) will be utilised in the production of 180-216 kt ammonia each year.

The second project located in Ben Tre province will be kicked off at the end of 2022. This project will include 800 MW offshore wind and 50 MW onshore wind power capacity in Ba Tri, near Ben Tre, which will primarily supply renewable electricity for green hydrogen and green ammonia production.

Both projects reached final investment decisions in 2021 and are expected to be commissioned by the end of 2024, with first commercial production planned for the beginning of 2025. They are both strategically located next to deep-sea areas to facilitate exports.

Before 2030, TGS aims to develop six other projects with the same 240 MW electrolyser capacity. Total output from these projects would equal 500 kt green hydrogen and 3 million tonnes (Mt) of ammonia per year. These projects will also produce green hydrogen using surplus renewable electricity from southern Vietnam that cannot be transmitted to the rest of the country due to the lack of transmission capacity.

Figure 3.7. Schematic overview of The Green Solutions facility



Note: For illustrative purposes only.
Source: Company's communication document, picture from ThyssenKrupp AG.

Project rationale

TGS projects are aligned with Viet Nam's COP26 commitment to reach net-zero emissions by 2050. The choice of location is based on availability of renewable energy sources, either from generators with surplus production or from on-site capacity developed by TGS. Both renewable capacity addition and green hydrogen manufacturing plants will contribute to social and economic development of the region by creating jobs.

The decision to vertically integrate projects to produce ammonia is driven by the maturity of this market for exports, for instance to European consumers. While ammonia is expected to be used in fertiliser applications in the short term, TGS expects that future demand will also come from new markets such as electricity generation, shipping fuel and green hydrogen transport.

Business model

Although green ammonia would currently fetch a lower price than fossil fuel-based ammonia due to the ongoing energy crisis, fossil fuel markets are volatile and spot prices could soon return to pre-crisis levels. Thus, it is key to secure medium- to long-term off-take contracts (3-10 years) for green hydrogen and green ammonia, possibly with fixed prices, and/or to identify applications in markets where demand is less sensitive to fossil fuel price variations.

TGS aims to secure export sales for most of its production and has already received Expressions of Interest from potential green ammonia off-takers in Japan, South Korea, Singapore and Europe. In parallel, the company is also exploring local market development.

The business model for green hydrogen in Viet Nam currently focuses on transport applications, especially for fuel cell trucks and hydrogen buses, replicating a model already existing or being developed in other countries. This will require expanding TGS activities in the mobility sector or identifying a key partner to manage the whole value chain, including refuelling stations.

Governance

Each project will be carried out by a unique SPV, with TGS being the parent company and majority shareholder of each. The SPVs will focus on project development, construction and operations, while the financing and commercial discussions with off-takers are done at the TGS group level.

TGS will rely on industrial partnerships in other parts of the value chain. For instance, as the port infrastructure is not yet well developed in southern Vietnam, TGS is collaborating with ECONNECT Energy to develop floating platforms to directly load green ammonia ships.

Enabling market conditions and investment de-risking

Viet Nam's electricity grid does not have the capacity to absorb and transmit all generation from renewable energy sources, thus leading to curtailment. Green hydrogen can be used to store surplus electricity and minimise the financial risk of curtailment for renewable electricity generators. Governments of emerging and developing economies facing similar grid bottlenecks could support the development of green hydrogen in their countries with policies facilitating access to renewable power for green hydrogen producers, which could set up plants in locations where there is a surplus of electricity generation capacity. In particular, a direct power purchase agreement mechanism between renewable electricity generators and green hydrogen manufacturers could accelerate green hydrogen projects. Viet Nam's National Power Development Plan 8 (PDP8) mentions, for the first time, green hydrogen and green ammonia as solutions to replace and move away from fossil fuels.

Financing

For its first projects, TGS is working on project finance solutions with a flexible mix of equity and debt. TGS remains the majority shareholder and aims to raise debt from development banks or development finance institutions at concessional rates. For future projects, it will be exploring flexible co-investment opportunities for renewable electricity production, green hydrogen, and green ammonia plants.

As the green hydrogen and green ammonia markets become more mature, TGS plans to issue green bonds to finance future projects and/or raise capital by undertaking an initial public offering (IPO) in a well-established stock market.

Lessons learnt from case studies

Business model

- A market-based approach not relying on subsidies is critical to engage significant investment. The main challenges faced to reach Final Investment Decision (FID) are the high overall capital requirements and the uncertainty on volumes and revenues. Yet, early business cases exist for green hydrogen, for instance in regions where prices less than USD 2/kg H2 can be achieved in zones with large low-cost renewable production, much below the natural gas prices in the ongoing commodities crisis context. Small-scale projects or niche markets also provide an opportunity to learn by doing, as green hydrogen-based solutions can already be competitive against current solutions.
- For the first large-scale projects, the green hydrogen derivatives or goods must rely on a mature value chain and an existing market. Hence, the first applications of green hydrogen are steel and ammonia. Major enablers to reaching FID include economies of scale to reduce costs as well as mid- to long-term contracts with first-mover customers willing to pay a premium for green hydrogen or green goods (e.g. green steel or e-fuels).
- The targeted business model in emerging and developing economies is often a combination of domestic use to reduce supply chain risks and increased local added value and exports to reach scale. Additional revenue streams can be developed to optimise the LCOH and bring co-benefits, such as the valorisation of heat and oxygen as by-products of electrolysis or the sale of excess renewable electricity.

Governance

- Most of the projects led by private companies replicate a standard governance structure from other industrial sectors. Typically, a holding company acts as an investment vehicle for equity investors, and special purpose vehicles (SPV) are created for each new project. However, several project developers emphasised the role of public-private partnerships, particularly to develop hydrogen hubs and to ensure common user infrastructures.
- A strong network of partners is needed across the value chain as it is challenging for a single actor to cover all aspects. Several project developers rely on vertically integrated partnerships, for instance between a supplier of green electricity, green hydrogen producer and the consumers/off-takers of green hydrogen. In some occurrences, an equity participation of several of these three groups of actors facilitates greatly the FID. One benefit offered by various hydrogen alliances across multiple countries and regions is to find partners for project development.

Enabling market conditions and de-risking investment

- Project developers emphasised that access to low-cost and stable renewable electricity throughout the day and the year, as well as access to land and infrastructure, were pre-requisites for selecting large-scale project locations. In particular, the availability of power transmission lines, inbound and outbound logistics infrastructures and deep-sea harbours, especially for exports of ammonia, steel or e-fuels, have been decisive for some projects.
- An enabling environment in the country, notably identified by indicators on economic stability, ease of doing business and regulatory transparency, is particularly scrutinised by investors. In addition, lean permitting and licensing processes provide additional confidence in the ability to realise projects on time and with limited contingencies.
- Several enabling market conditions were underlined to address offtake risk, such as green mandates or blending obligations, that can provide sufficient visibility on demand. Where no

thresholds are determined by law, the level of taxes on fossil fuels and effective carbon pricing for a given application can help define a level playing field.

Financing

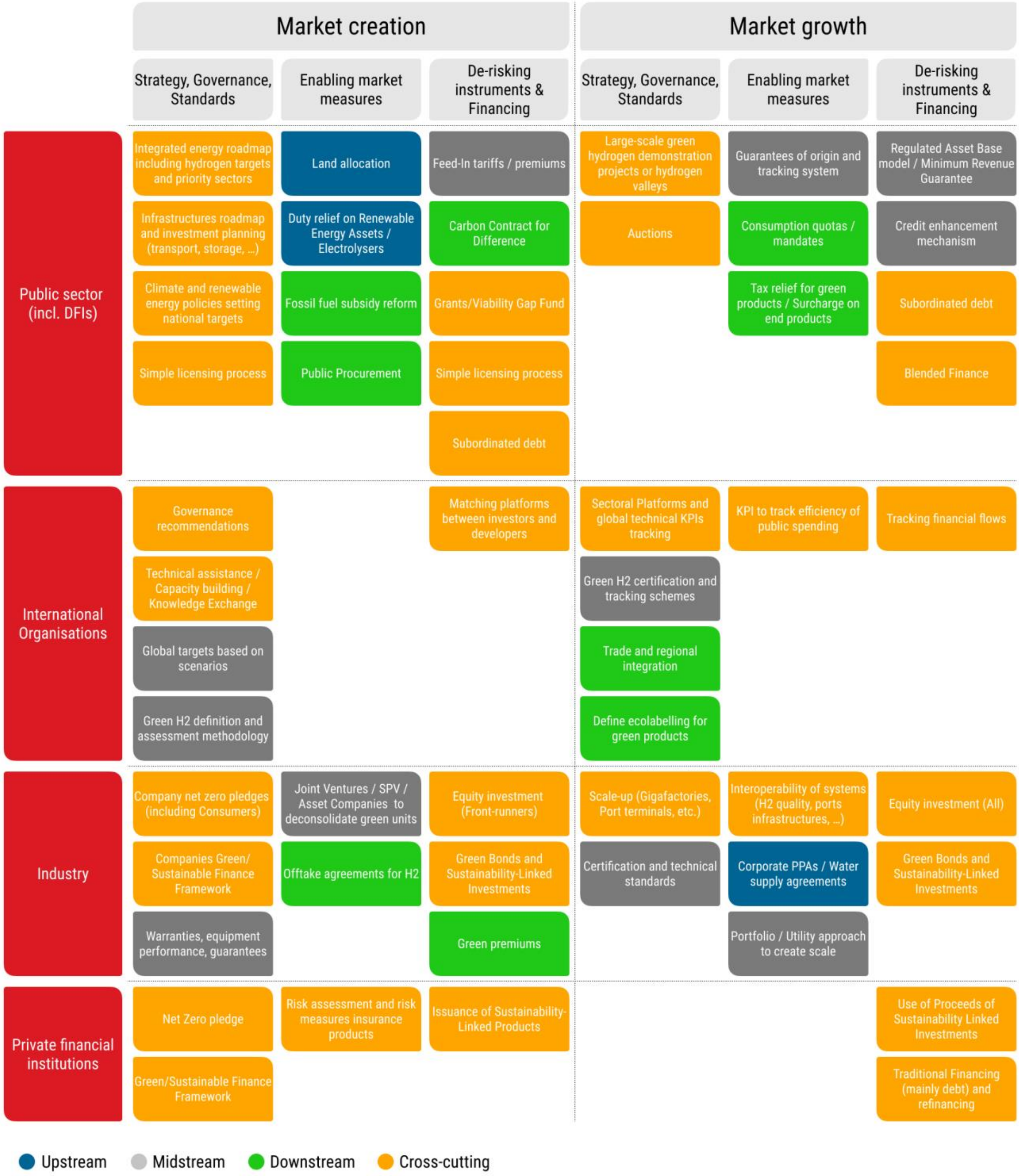
- Governments of emerging and developing economies face constraints in financing large projects. The size of the investment envelope for large-scale projects will require diversifying sources of financing and sharing risks among actors. Both the international and the local financial sector will need to be engaged to reach the announced 2030 and 2050 targets outlined in existing national hydrogen strategies.
- Project finance seems to be the preferred option for developers, replicating for instance the trend observed in the offshore wind industry. Considering green hydrogen is perceived as a risky investment because of high costs, risks related to affordable and reliable output security, market availability etc., first projects will likely require a higher equity share. However, companies target a similar gearing ratio as in typical capital-intensive industry and infrastructures, with 20-30% equity and 70-80% debt. Several companies highlighted the opportunity to recourse to capital increase and green bonds at the holding level.
- The ticket size for large-scale projects and the lower-than-average debt percentage proposed by individual banks adds complexity around financing structures. Developing the green hydrogen market will require specific solutions, notably through public-private partnerships and blended finance, although the latter is still at a nascent stage for green hydrogen. Companies emphasised the key role of Development Finance Institutions (DFIs), Multilateral developments banks (MDBs) and Climate funds to develop projects in emerging and developing economies. Including green hydrogen in taxonomies can also help attract the growing number of private banks and investors that include Environmental, Social, and Governance (ESG) criteria in their investment decision.

Incentives and actions for stakeholders to drive market creation and growth of green hydrogen

The case studies shed light on the opportunities seized by project developers and industrials to build robust business cases. Yet, they also emphasise the need for policymakers and financial institutions to support the industry by defining a long-term strategy and structuring the sector, establishing market measures, and providing de-risking and financing instruments.

The engagement of all stakeholders is critical to build robust business cases and mobilise investments in low carbon solutions. This is particularly true for green hydrogen, considering the high level of investment required and the complexity of the value chain. Rapid scale-up and major investments must occur in the next decade to be consistent with Paris Agreement targets, focusing on short-term barriers to investment decisions. A wide range of actions from different actors can contribute to building an enabling environment (see Figure 3.8).

Figure 3.8. Policies and actions to facilitate the market creation and market growth



Note: PPA stands for Power Purchase Agreement. The three columns under market creation and market growth correspond to the key areas identified in Table 2.1, with the exception of technical development, which is not covered in this chapter. They also correspond to the categories covered in the case studies that can help market actors in developing robust business models.

Source: Authors, based on (IRENA, 2020[14]), (World Economic Forum, 2021[80]), (Hydrogen Council, 2021[81]), (Cammeraat, Dechezleprêtre and Lalanne, 2022[82]), (IRENA, World Economic Forum, 2022[83]), (Agora Energiewende and Guidehouse, 2021[31]), (IRENA, 2022[84]).

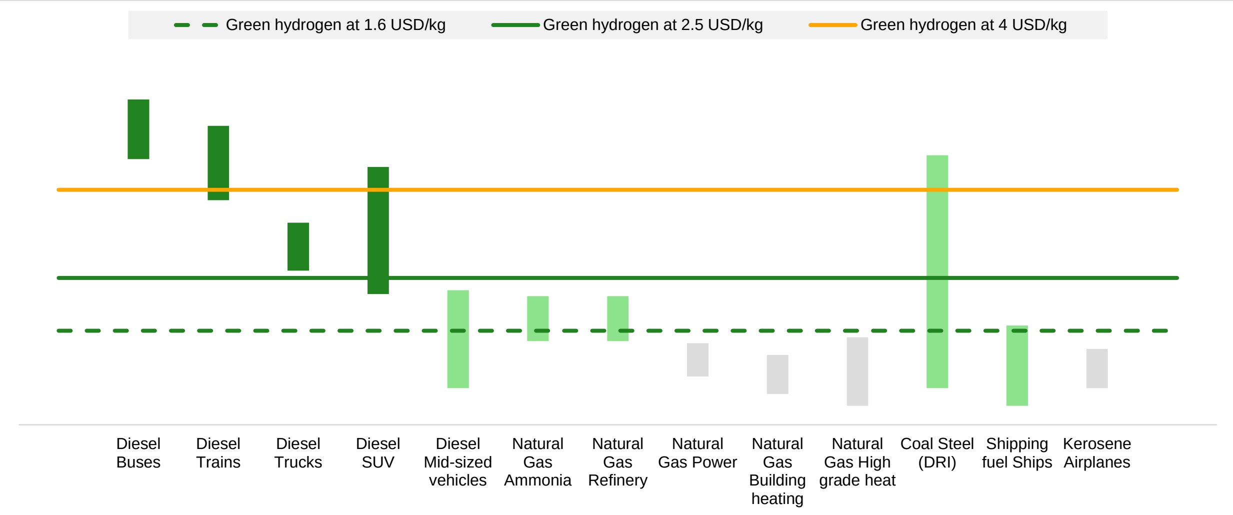
Understanding the different stages of the energy transition is key to implementing efficient decarbonisation measures, depending on the technical and commercial maturity of low-carbon technologies. For instance, financing R&D is particularly critical in the coming years to accelerate market uptake and drive down the costs, as some technical issues around storage, infrastructure and hydrogen handling are not yet fully addressed. Implementing key regulations and de-risking instruments are priorities to create an enabling environment.

At the market creation phase, it is crucial to integrate the hydrogen roadmap within an overall long-term energy and infrastructure development plan, identifying the priority sectors for green hydrogen development. This systemic approach provides certainty to market actors on the future evolution of the green hydrogen sector. For instance, the European Commission proposed that by 2030, 50% of all hydrogen consumption in the industry needs to be produced with renewable electricity, and that 2.6% of all fuels supplied to the transport sector need to be derived from green hydrogen (Hydrogen Europe, 2022[85]). Grants or concessional loans can improve economic viability of projects but building an enabling environment should be prioritised. As public money is limited, especially in emerging and developing economies, indirect support (such as carbon pricing) should be considered to bring in project developers (see Box 3.1). For instance, guaranteeing the availability or fast-track construction of infrastructure or setting up a one-stop-shop for all permitting processes can shorten the project development time. Demand-side measures such as public procurement targets can provide additional confidence in the future marketable hydrogen volume and address offtake risk, thus improving the business model for green hydrogen projects.

Box 3.1. Potential impact of carbon tax on the competitiveness of green hydrogen and its derivatives

Carbon pricing, for instance through a carbon tax, internalises the negative climate externality and can incentivise choosing low carbon alternatives over conventional fuels and products (Nachtigall, Ellis and Errendal, 2022[86]). Thus, it is considered one of the potential measures that can be implemented to promote the development of low-carbon technologies, notably green hydrogen. Implementing a carbon tax would make green hydrogen competitive with polluting fuels currently used for a wide range of applications. For instance, applying a carbon tax of USD 100 per tonne of CO_2 in a country where green hydrogen can be produced at USD 2.5 per kilogramme could provide a price signal to consumers and incentivise them to switch from diesel to green hydrogen for various mobility applications (see Figure 3.9).

Figure 3.9. Minimum required green hydrogen production cost for breakeven with conventional solutions, without carbon tax (higher bound) and with USD 100 /t_CO_2 carbon tax (lower bound)



Source: Authors, based on (Hydrogen Council and McKinsey & Company, 2021[18])

However, assessing the impact on end-consumers is essential to minimise the adverse economic and social consequences of a carbon tax or another carbon pricing instrument on vulnerable households and consumers. Thus, integrating carbon pricing into wider policy packages is crucial to increase the political acceptability of carbon prices (Nachtigall, Ellis and Errendal, 2022[86]).

Moreover, alignment of environmental regulations, industrial policies, trade rules and carbon prices is required such as in the case of the carbon border adjustment mechanism of the EU to avoid carbon leakage, such that companies could relocate to countries with less stringent environmental policies. Carbon leakage could also lead to loss of competitiveness for producers that remain in jurisdictions where green fuels and green products are enforced, compared to those manufacturing in countries with less stringent policies.

Undertaking large-scale projects may still require support from the public sector as the market grows, either through direct participation in projects or through policy measures to boost competitiveness of green hydrogen and its derivatives. Hydrogen valleys and vertical integration along the value chain will provide strong opportunities to scale up the market and increase the share of added value in emerging economies. Identifying off-takers ready to pay for a market premium will help create a sustainably growing demand. This demand growth can be supported by additional measures, such as tax relief for green products, or applying a surcharge on fossil-fuels based alternatives. The size of investment for large-scale projects will require diversifying the sources of financing and sharing the risks among actors. Complexities around financing will require developing specific solutions, notably through public-private partnerships and blended finance.

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