DECARBONISING END-USE SECTORS:

PRACTICAL INSIGHTS ON GREEN HYDROGEN

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About the Coalition

The IRENA Coalition for Action brings together leading renewable energy players from around the world with the common goal of advancing the uptake of renewable energy. The Coalition facilitates global dialogues between public and private sectors to develop actions to increase the share of renewables in the global energy mix and accelerate energy transitions.

About this paper

This white paper has been developed jointly by members of the Coalition's Working Group on Decarbonising End-Use Sectors. Featuring several case studies on pioneering green hydrogen projects and first-hand interviews, the paper provides insights from a renewable energy industry perspective on the growth opportunities of green hydrogen and what is needed from policy makers to accelerate its adoption worldwide.

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CONTENTS

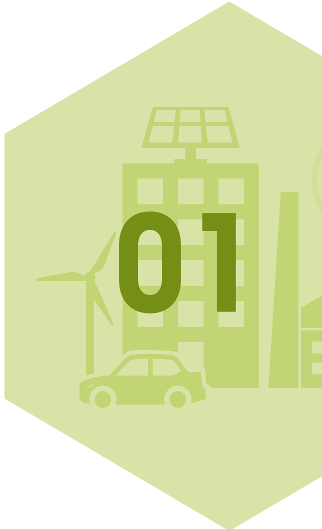
FIGURES AND BOXES

ABBREVIATIONS

ARENA Australian Renewable Energy Agency
AUD Australian dollar
CCS Carbon capture and storage
CO_2 Carbon dioxide
DRI Direct reduced iron
EAF Electric arc furnace
EJ Exajoule
ESG Environmental, social and governance
EU European Union
EUR Euro
FCH JU Fuel Cells and Hydrogen Joint Undertaking
FH2R Fukushima Hydrogen Energy Research Field
GDP Gross domestic product
GHG Greenhouse gas
GW Gigawatt
GWh Gigawatt-hour
H_2 Hydrogen
IDAE Instituto para la Diversificación y Ahorro de la Energía
JPY Japanese yen
kW Kilowatt
LRC Lined Rock Cavern
Mt Million metric tonne
MW Megawatt
MWp Megawatt-peak
NDC Nationally determined contribution
NEDO New Energy and Industrial Technology Development Organization
Nm^3 Normal cubic metre
NOx Nitrogen oxide
O_2 Oxygen
PEM Polymer electrolyte membrane
PPA Power purchase agreement
PPP Public-private partnership
PV Photovoltaic
QNP Queensland Nitrates
R&D Research and development
RED-II Renewable Energy Directive II (European Union)
SCADA Supervisory control and data acquisition
SMR Steam methane reforming
tCO_2 Tonne of carbon dioxide
tH_2 Tonne of hydrogen
TWh Terawatt-hour
USD United States dollar


H2

INTRODUCTION



The ongoing climate crisis, coupled with the COVID-19 pandemic, has spurred many countries to adopt green recovery measures and policies that have the potential to drive a lasting shift in the global energy mix. As of December 2020, over 120 countries – responsible for nearly two-thirds of the world's greenhouse gas (GHG) emissions – have announced commitments to reach net-zero emissions (Energy and Climate Intelligence Unit, 2021).

To meet these commitments, countries will need to pivot from fossil fuels to renewable energy sources and pursue widespread decarbonisation of all end-use sectors. While renewable electricity generation capacity has been outpacing new installed capacity in fossil fuels for the past decade (IRENA, 2020a), not all sectors can be easily electrified.

Green hydrogen – hydrogen produced from renewable energy – can provide the critical link between renewable electricity generation and hard-to-abate sectors such as industry and heavy transport (IRENA, 2018). It has become a versatile energy carrier suitable for decarbonising applications without electricity grid access or as a carbon dioxide (CO_2)-neutral feedstock for chemical processes. Green hydrogen can also be leveraged to provide grid balancing services in systems built on very high shares of renewable energy (IRENA, 2019).

Today, green hydrogen makes up less than 1% of global hydrogen produced (IRENA, 2021c). However, with the production cost of green hydrogen reducing rapidly due to falling technology costs and the availability of cost-competitive renewable power, countries are increasingly seeing green hydrogen as a smart long-term investment.

Over the last two years, at least 11 countries and the European Union (EU) have launched national hydrogen strategies, with many more countries set to follow suit. A number of national post-COVID recovery packages have also included support measures for green hydrogen.

According to IRENA's 1.5°C Scenario, by 2050 hydrogen and its derivatives will account for 12% of final energy use worldwide. Two-thirds of this demand will be met by green hydrogen (IRENA, 2021c). In anticipation, investors and the private sector are making strategic investments in green hydrogen and forming cross-sectoral partnerships to drive down cost curves and create greater economies of scale for this emerging technology. In addition to investments in electrolysers, the production of green hydrogen in high quantities will require significant additions of dedicated renewable generation capacity.

While the global market for green hydrogen is just beginning to develop, both public and private sectors are proceeding with demonstration and at-scale deployment of projects to build technical capacity and showcase the potential to scale up green hydrogen uptake in energy-intensive, hard-to-abate sectors. This white paper developed by the IRENA Coalition for Action showcases projects across different end-uses and offers recommendations to policy makers on how to accelerate green hydrogen development.

The following chapter provides an overview of the potential of green hydrogen across different end-uses and the investments required to unlock this potential. Chapter 3 elaborates on the main actions needed to create national, regional and global markets for green hydrogen. Chapter 4 summarises key takeaways on accelerating the implementation and uptake of green hydrogen. Finally, Chapter 5 presents case studies on green hydrogen projects from around the world based on first-hand data and interviews with key project stakeholders.

Box 1 Definition of green hydrogen

The IRENA Coalition for Action has agreed on the following definition for green hydrogen:

Green hydrogen is hydrogen produced from the electrolysis of water*, powered by 100% renewable energy sources. To verify that the origin of the energy used throughout the production process is renewable, a green hydrogen producer may:

- » Source energy from a renewable generation facility physically linked to the electrolyser (e.g., on-site production for self-consumption); or
- » Source energy from the grid through models that guarantee the renewable origin of the energy. Examples include procuring renewable energy through power purchase agreements (PPAs) and purchasing attribute certificates (e.g., guarantees of origin, renewable energy certificates), ensuring that delivery of the energy is physically feasible. The transparency of renewable attribute certificates is essential and may be verified through the use of robust tracking technologies that physically match supply and demand.

Additionality requirements should be imposed in principle but may present implementation challenges for the nascent green hydrogen sector. Therefore, some flexibility may need to be factored into additionality criteria in the short term.

Moving forward, to provide transparency to consumers and foster market demand, the development of specific mechanisms to label and track the origin of hydrogen will also be essential. Such mechanisms should avoid the double counting of renewable energy attributes.

*Other renewables-based solutions to produce hydrogen exist based on thermochemical, photo-catalytical and biochemical processes (IRENA, 2018). Hydrogen production from the electrolysis of water is the focus of this report due to its potential to link low-cost renewable electricity generation with hard-to-abate sectors.

02

GREEN HYDROGEN: AN ENABLER FOR REACHING NET-ZERO

Hydrogen can be produced with multiple processes and energy sources. Natural gas and coal presently account for approximately 95% of global hydrogen production (IRENA, 2020b).

As energy transitions progress, green hydrogen produced from low-cost renewable electricity will play a growing role.

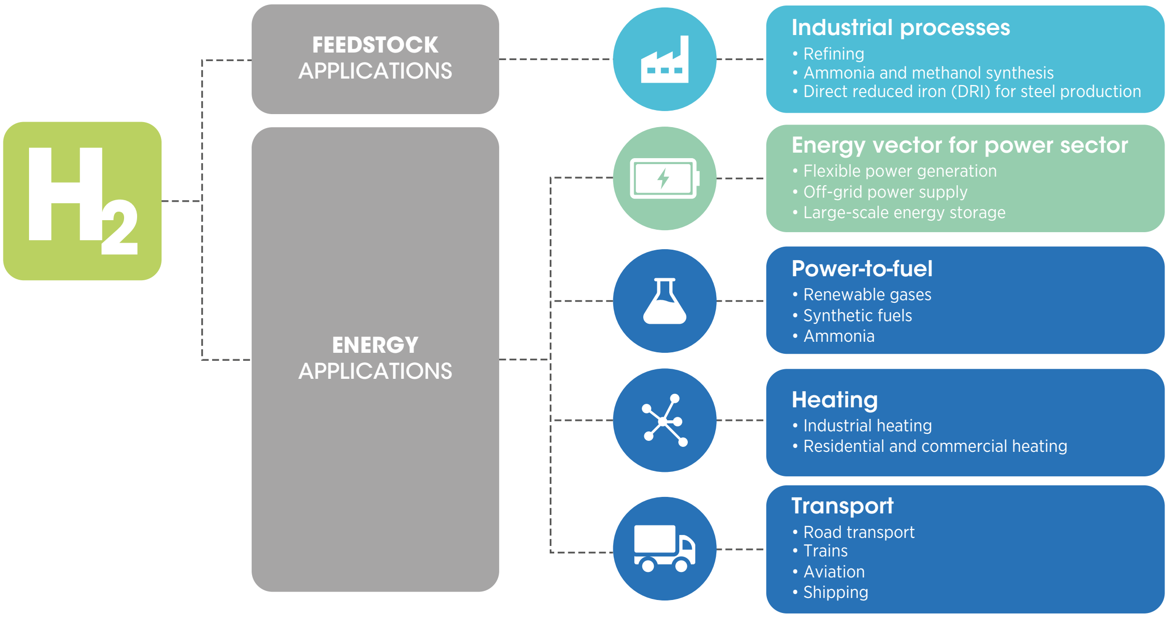
2.1 End-uses for green hydrogen

Green hydrogen offers a diversity of potential uses. While direct electrification via renewable energy and energy efficiency is the most efficient path to reducing emissions in **easier-to-abate** sectors such as buildings, low-temperature industry (e.g., agriculture, pulp and paper) as well as some transport (mainly light and short-haul freight vehicle, but also long-haul transport in cases where charging infrastructure can be deployed), green hydrogen can play a crucial role in supporting the decarbonisation of **harder-to-abate** sectors where direct renewable electrification is not technically feasible or would take too long.

According to IRENA's World Energy Transitions Outlook, green hydrogen can contribute to significant CO_2 emissions abatement as part of a 1.5°C pathway — particularly in the industrial sector as well as long-haul transport, shipping and aviation (IRENA, 2021c).

In the short to medium term, green hydrogen is expected to make its most substantial impact in the **industrial sector.** Energy use in the sector is dominated by a few industries: iron and steel, non-ferrous metals (e.g., aluminium), chemicals and petrochemicals (e.g., refineries, ammonia production), and non-metallic minerals (e.g., cement) (IRENA, 2020a; IRENA Coalition for Action, 2021). For some energy uses in these industries, green hydrogen represents the only low-carbon alternative (Hydrogen Council, 2020). Moreover, green hydrogen can replace existing fossil fuel-based hydrogen feedstocks in a number of industrial processes, including refining of petrochemicals, ammonia production for fertiliser, methanol production for a wide variety of chemical products, and even the production of zero-emission steel via direct reduction of iron.

Figure 1: Potential market opportunities for green hydrogen identified by IRENA Coalition for Action



In addition to feedstock applications, green hydrogen can replace the use of fossil fuels in **high-temperature heating for industrial processes** such as steel and cement production (IRENA, IEA, REN21, 2020). In the **buildings sector**, green hydrogen also has the potential to contribute to energy transitions through direct use for **heat production.**

Green hydrogen can also facilitate the decarbonising of key segments of the **transport sector** through its direct use in fuel cell electric vehicles, mostly for long-haul road freight transport where charging infrastructure cannot be deployed, or potentially combined with nitrogen or sustainably sourced carbon to produce ammonia, methanol and other synthetic fuels for shipping and aviation.

Finally, green hydrogen can potentially play an important role in the **power sector.** Technologies such as hydrogen-fired gas turbines and large-scale stationary fuel cells can complement other renewable sources of electricity and replace demand currently met by fossil fuels. Green hydrogen can also serve as a **seasonal storage** medium in energy systems with high shares of variable renewable generation and low demand response providing **system reliability and flexibility** as an additional form of dispatchable electricity.

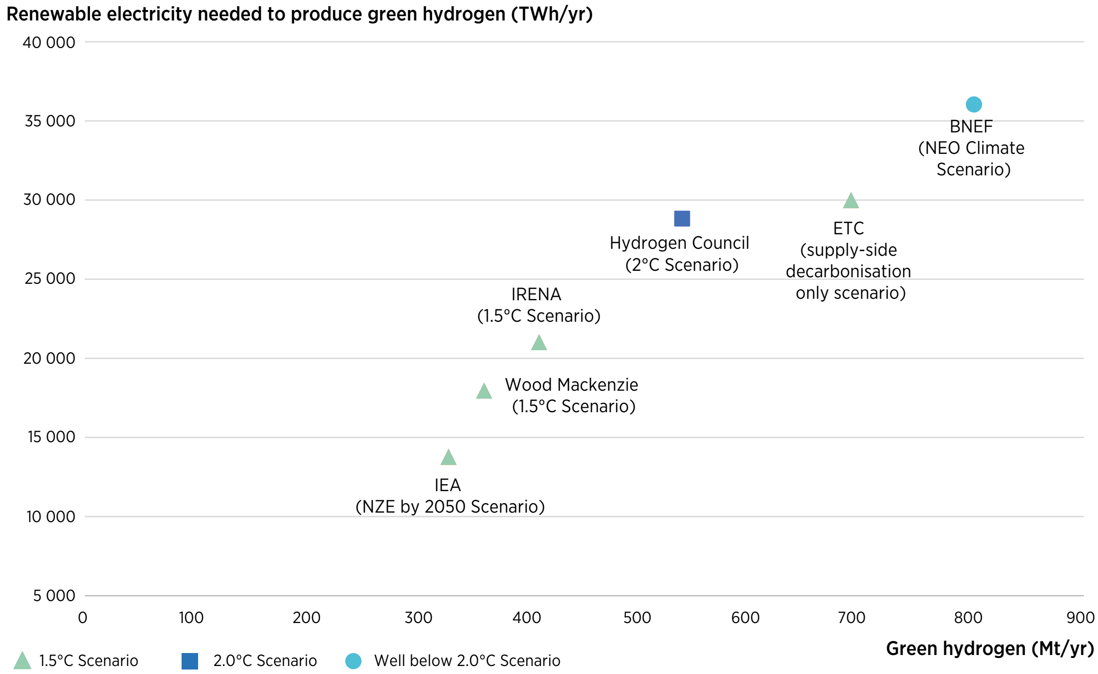
Green hydrogen offers great potential for replacing fossil fuel use in sectors where direct electrification is difficult, making net-zero attainable (see Figure 1). With nearly 6% of global natural gas and 2% of global coal currently going to the production of hydrogen (IEA, 2019), switching to the use of renewables to produce green hydrogen will also create additional emission savings.

2.2. Looking ahead: Market projections for green hydrogen

To achieve climate objectives, the scale of investment needed in green hydrogen is immense. As of 2021, green hydrogen projects totalling approximately 0.3 gigawatts (GW) of electrolysing capacity are in operation. IRENA's 1.5°C Scenario forecasts nearly 5 000 GW of electrolysing capacity will be needed by 2050 to produce approximately 400 million metric tonnes (Mt) of green hydrogen per year. To reach this target, annual average investments in electrolysing capacity and associated green hydrogen transport infrastructure (which averaged less than USD 1 billion [United States dollars]/year from 2017-19) will need to increase to an estimated USD 78 billion between now and 2050 (IRENA, 2021c).

Widespread availability of abundant, low-cost renewable electricity will be crucial to realising green hydrogen's market potential (see Figure 2). Under IRENA's 1.5°C Scenario, 30% of the world's electricity use will be dedicated to the production of green hydrogen and its derivatives by 2050. Meeting global demand for green hydrogen will require nearly 21 000 terawatt-hours (TWh) of renewable electricity annually to meet the needs for both the electrification of end-uses and the development of a global green hydrogen supply chain (IRENA, 2021c).[1]

Figure 2: Global demand for renewable electricity to produce green hydrogen by 2050



Sources: Energy Transitions Commission (ETC) supply-side decarbonisation only scenario (Energy Transitions Commission, 2021), IEA's Net-Zero Emissions by 2050 Scenario (IEA, 2021), IRENA's 1.5°C Scenario (IRENA, 2021c), BloombergNEF's New Energy Outlook Climate Scenario (BNEF, 2020), Hydrogen Council's 2°C Scenario (Hydrogen Council 2017, 2021b), Wood Mackenzie Energy Transition Service.

Notes:

1. The information in this figure was compiled by IRENA with the support of Coalition for Action members with a focus on the renewable electricity needed for green hydrogen production by 2050. The role given to green hydrogen in existing regional and global energy transition scenarios can differ greatly due to a number of factors, which include GHG reduction targets, assumed set of enabling policies, assumed technology options available between scenarios, end-uses considered and cost assumptions (IRENA, 2020b). For all these reasons, the role of green hydrogen varies widely among scenarios. However, as more scenarios are developed to reach zero or net-zero emissions, green hydrogen's presence will be more prominent in scenarios and public discourse.
2. The ETC supply-side decarbonisation only scenario is an illustrative scenario considering 2050 final energy demand without application of energy productivity levers. This scenario assumes green hydrogen will make up 85% of total hydrogen production in 2050.
3. Numbers for BNEF's New Energy Outlook Climate Scenario denote a well below 2°C pathway based on clean electricity and green hydrogen.
4. Numbers for Hydrogen Council's 2°C Scenario denote the case where green hydrogen meets all projected hydrogen demand.

1 By way of comparison, the world's total electricity final consumption in 2018 reached 22 315 TWh (IEA, 2020).

The private sector also sees large market potential in green hydrogen (see Box 2). Based on a survey of over 200 green hydrogen projects, the Hydrogen Council estimates that total investments in spending on green hydrogen will exceed USD 300 billion by 2030 (Hydrogen Council, 2021a).

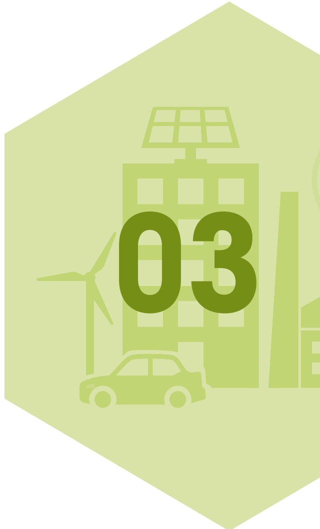
Over the longer term, PwC estimates the green hydrogen export market could be worth USD 300 billion yearly by 2050 (Strategy&, 2020), and Goldman Sachs projects green hydrogen could become a USD 10 trillion addressable market that same year (Goldman Sachs Research, 2020).

Box 2 **Green hydrogen market potential identified by IRENA Coalition for Action**

IRENA Coalition for Action members active in the green hydrogen space expect to collectively develop at least 5 GW of electrolysing capacity and 250 GW of renewable generation capacity by 2030. To compare, this forecasted renewable generation capacity almost equals the 261 GW net increase in global renewable generation capacity in 2020 (IRENA, 2021b).

Key value drivers for Coalition members include the sale of green hydrogen to industrial off-takers, cost savings realised through the optimisation of electrolyser-renewable energy hybrid solutions, and revenues earned from providing grid ancillary services. Business opportunities along the supply chain include investment in electrolyser production to meet projected market demand and enable technology cost reductions to accelerate competitiveness.

Electrolysers installed by Enel Green Power in 2017 in the geothermal Cerro Pabellón plant. The electrolysers are part of a micro-grid solar PV facility combined with two energy storage systems, one based on green hydrogen.



ACCELERATING GREEN HYDROGEN UPTAKE

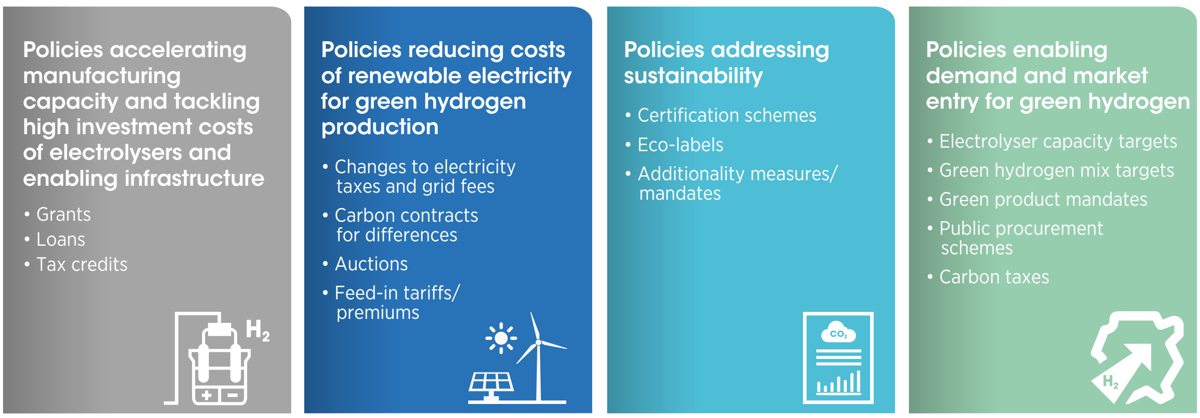
Government commitments and private sector participation are key to scaling up investments in green hydrogen, accelerating its market uptake and driving its integration into the global energy system. In addition to the production costs of green hydrogen, massive investments in hydrogen transport and storage infrastructure, as well as power grid infrastructure to transmit electricity to electrolysers, will be needed.

As with renewables, production costs for green hydrogen will continue to fall as large-scale projects emerge. Along with the declining costs of renewable electricity, further cost reductions in electrolysers are expected to be achieved through improved economies of scale, increased availability of components from original equipment manufacturers, and growth in market demand (IRENA, 2020c). While green hydrogen can already be produced more cheaply than other forms of hydrogen in some regions, on a global scale green hydrogen is projected to be cost-competitive with hydrogen produced from fossil fuels with carbon capture and storage (CCS) by 2030 (IRENA, 2020c; BNEF, 2021).

3.1 Government buy-in and support

Governments can put in place various policies to accelerate green hydrogen production and implement national hydrogen strategies (see Figure 3). Policies enabling green hydrogen must be tailored to the context of a given jurisdiction. They must also factor in priorities beyond the energy system such as sustainable economic development. Only by adopting a mix of policies can a country most effectively drive green hydrogen growth (IRENA, 2021a).

Figure 3: Policy measures to accelerate green hydrogen production



Interest in green hydrogen from governments has accelerated in the last two years. Various countries have progressed beyond research and development (R&D) programmes and the development of vision documents to develop comprehensive hydrogen strategies and enabling policies reflecting their energy needs, environmental goals and economic objectives (IRENA, 2020b).

In its hydrogen strategy, the **EU** has identified green hydrogen as a key enabler in its goal to reach net-zero emissions. The strategy establishes a 40 GW by 2030 electrolyser capacity target and expects investments amounting up to USD 567 billion (EUR 470 billion) in green hydrogen by 2050 (European Commission, 2020). The EU has also committed to continue funding research and innovation on green hydrogen through the next framework programme, Horizon Europe (2021-2027). Several EU member states have identified dedicated 2030 targets for installed electrolyser capacity in their national strategies, road maps and vision documents, including France (6.5 GW), Germany (5 GW), Italy (5 GW), Spain (4 GW), Netherlands (3-4 GW) and Portugal (2-2.5 GW) (IRENA, 2021a).

Some countries with net-zero emissions targets have placed less emphasis on green hydrogen production and have instead focused on industrial competitiveness, including developing specific sectors that make use of hydrogen. **China**, the world's largest hydrogen producer, has not released a national hydrogen strategy; however, it has implemented policies targeting the transport sector including the implementation of dedicated subsidies for fuel cell vehicles (Meng et al., 2020). **Japan**, which has a long history of R&D in hydrogen and fuel cell technologies, released a Basic Hydrogen Strategy in 2017 outlining its vision for an integrated hydrogen economy; in the near term, the country's strategy focuses on lowering the production cost of hydrogen and developing international hydrogen supply chains (Ministry of Economy, Trade and Industry, 2017). The country subsequently updated its Strategic Roadmap for Hydrogen and Fuel Cells in 2019 (Hydrogen and Fuel Cell Strategy Council, 2019). That same year, the **Republic of Korea** launched a Hydrogen Economy Roadmap prioritising the development of fuel cells for vehicles and large-scale stationary fuel cells for power generation (Kao, 2020).

An increasing number of countries seek to leverage their high renewable energy resource potential to become global exporters of green hydrogen. Through the NEOM project, **Saudi Arabia** plans to install 2 GW of electrolyser capacity by 2025 to produce green hydrogen for export (Air Products, 2020). **Morocco** has signed declarations of co operation with Germany and Portugal for the development of green hydrogen in Morocco (Takouleu, 2021). Of those countries with national hydrogen strategies, **Australia** proposes to leverage the country's expertise in renewable energy deployment to build a substantial clean hydrogen export industry (Commonwealth of Australia, 2019), and **Chile** plans to develop an export industry for green hydrogen and its derivatives, including 5 GW by 2025 and 25 GW by 2030 electrolysis targets (Ministry of Energy, Government of Chile, 2020).

The emergence of national hydrogen strategies targeting multiple end-use sectors for green hydrogen, apart from electrolyser capacity targets, is an encouraging development, reflecting the growing recognition of green hydrogen's economic potential. For example, Spain's hydrogen strategy includes a 25% green hydrogen target for hydrogen used in industry by 2030. Many national hydrogen strategies include concrete electrolyser capacity targets, which will be key to boosting private sector confidence and providing the long-term signals needed to attract investment. Some countries have also established other measures to close the price gap between green hydrogen and fossil fuel-based alternatives. For example, in France hydrogen produced from fossil gas and coal is subject to the carbon tax ("Contribution Climat-Énergie"), and the Netherlands has instituted an auction scheme for a feed-in premium for green hydrogen ("SDE++") (IRENA, 2021a).

However, a majority of countries have not yet released strategies targeting green hydrogen, and of the countries that have, most are concentrated in Europe.

Furthermore, the hydrogen strategies released to date have several shortfalls:

1. Targets must be backed with **sufficient R&D funding and other forms of financial support** to develop technical capacity and de-risk green hydrogen production, distribution and use. Many strategies rely on sources of funding beyond national budgets to deliver the subsidies needed to meet national hydrogen goals (e.g., private investments, EU-level funds in the case of Europe) (BNEF, 2021).

2. Some strategies focus mainly on building green hydrogen supply through large-scale projects. This risks excluding smaller projects, which must also be supported to fully integrate green hydrogen into the energy system. In this respect, **regulatory policies that enable demand and green hydrogen uptake at all scales** (e.g., permitting processes that differentiate green hydrogen from other hydrogen projects) are needed.

3. The **energy system implications** of scaling up green hydrogen are not fully considered. Strategies must address the need for the massive scale up of renewable electricity generation capacity, build out of associated power system infrastructure to supply electrolysers, and dedicated transport infrastructure for green hydrogen, while avoiding carbon lock-in and stranded assets.

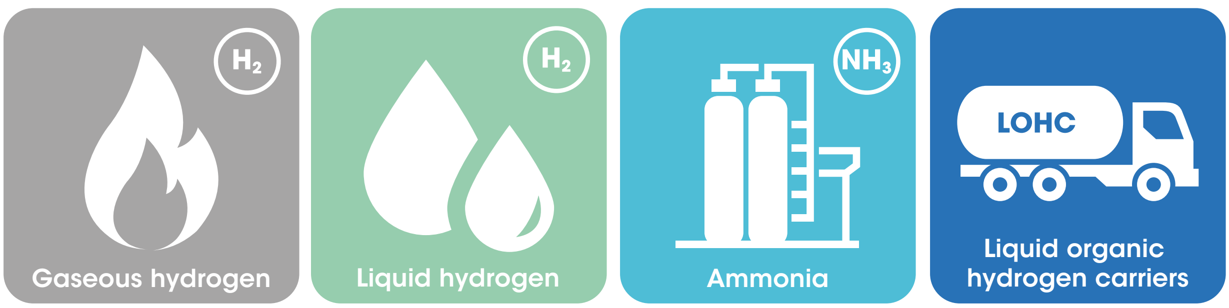
4. Many strategies recognise the need for **robust certification schemes for hydrogen** but have not put forward supportive enabling frameworks to encourage their development. Certification schemes will be central to creating national, regional and global markets for green hydrogen.

3.2 Moving towards a global green hydrogen market

Each country's hydrogen strategy is driven by its domestic energy demand and renewable energy potential. Through the export of green hydrogen, countries rich in renewable resources but low in national electricity demand are well-positioned to support the deployment of additional renewable energy for green hydrogen production. Other countries can reduce pressures on limited domestic resources and make further progress on climate objectives through green hydrogen imports.

Initial efforts to develop global trading of green hydrogen are beginning to emerge. Countries with high production potential and countries with high demand for green hydrogen are entering into bilateral agreements to explore new trade routes (IRENA, 2021a).

Figure 4: Hydrogen energy vectors for trade



Moving forward, the path towards a global green hydrogen market will not only require overcoming technical and economic barriers, but also the removal of market and regulatory obstacles. For green hydrogen to become a tradeable commodity, producers must be able to get their product to international markets. Off-takers of green hydrogen must also have assurance the hydrogen product they are receiving is produced from 100% renewable energy.

Governments must **create or adapt existing regulatory frameworks** to enable producers to generate, transport and store green hydrogen when and where efficient. This includes adapting: 1) rules for permitting of hydrogen projects in jurisdictions where green hydrogen follows the same permitting processes as hydrocarbons; 2) rules governing hydrogen injection into natural gas networks; 3) rules establishing fair access to different types of energy markets; and 4) regulations related to hydrogen safety. Entirely new regulatory frameworks may also be needed for the exclusive sale of green hydrogen.

Governments also must further work together to create an **international taxonomy for hydrogen**. This includes a transparent classification system for green hydrogen and its derivatives (e.g., green ammonia, synthetic fuels). The system should be based on emissions thresholds and clear sustainability criteria, ensuring green hydrogen is distinguished from other forms of hydrogen (e.g., hydrogen produced from fossil fuels using CCS).

Promoting an international taxonomy for green hydrogen – in which hydrogen produced from 100% renewable energy sources becomes the status quo – should make it easier to finance projects in coming years as banks and other financial institutions are increasingly turning to investing in activities compliant with environmental, social and governance (ESG) criteria. Such a taxonomy can also inform the development of international codes and standards for green hydrogen, which will encourage the application of best practices and the development of cross-border projects.

Finally, **certification schemes based on internationally accepted standards** must be established to foster a global market for green hydrogen. **Tracking instruments (e.g., certificates)** create the necessary transparency, foster transferability and stimulate demand by final consumers.

To preserve value and to avoid double-counting, a clear distinction must be made between certificates for renewable electricity and certificates for green hydrogen produced from renewable electricity. This is a prerequisite for an effective regulatory framework and to provide the correct market signals on the “greenness” and the sustainability of gases. Efforts are underway in several countries and regions such as the EU to create a certification scheme for green hydrogen.

KEY TAKEAWAYS AND RECOMMENDATIONS

The following key findings may serve as guidance and inspiration for governments on how to ensure green hydrogen is produced from renewables, scale up its production and facilitate its uptake in new end-use applications in support of global climate objectives.

Act now to develop national strategies and plans for green hydrogen. To date, fewer than one-fifth of countries have put forward national hydrogen strategies. Furthermore, some of these strategies do not prioritise green hydrogen over other forms of hydrogen. Now is the time for governments to develop comprehensive action plans and detailed roadmaps for green hydrogen based on concrete targets, leveraging post-COVID stimulus and recovery packages to kick-start production and energy transition-related infrastructure development. Action plans and road maps should take into consideration projected future demand and promote the long-term development of a sustainable green hydrogen sector, drawing on lessons learned from renewables. Countries can formalise their commitments by including green hydrogen in the revision of their nationally determined contributions (NDCs).

Increase ambitions in renewable energy deployment. Action plans for accelerating the uptake of low-cost renewables and grid infrastructure to a pace that can sustain both electrification of end-uses and green hydrogen production are key. This will also ensure additional renewable energy is used for green hydrogen production and that it is not diverted away from more cost-effective ways to further decarbonise end-use sectors (i.e., electrification).

Develop globally recognised standards and supporting certification schemes for green hydrogen. Green hydrogen uptake will rely on the widespread acceptance of tracking instruments certifying the origin of green hydrogen, ensuring that its production is backed by 100% renewable electricity generation. This requires the development of an internationally accepted taxonomy for green hydrogen and its derivatives. In parallel, governments must work on removing existing market and regulatory barriers surrounding green hydrogen including, but not limited to, clarifying rules around green hydrogen's access to different types of energy markets.

Prioritise use of green hydrogen in hard-to-abate sectors where no cheaper decarbonisation options exist and avoid applications leading to carbon lock-in. Governments should place initial focus on replacing fossil fuel-based hydrogen with green hydrogen feedstocks for industry, as demand in this area – currently met by hydrogen produced from fossil gas and coal – already exists and is difficult to substitute. Moreover, national strategies and action plans should avoid carbon lock-in and stranded assets. In this respect, the blending of green hydrogen into existing natural gas networks should not be prioritised as it prolongs the use of high-carbon assets and displaces more efficient decarbonisation options for some applications.

Implement financial policies and incentives to accelerate early-stage innovation and deployment of green hydrogen technologies. Financial support for green hydrogen is needed until this energy carrier becomes cost-competitive with other forms of hydrogen. Support mechanisms can come, for instance, in the form of grants and loans to drive down the cost of financing projects or tax credits to incentivise adoption. Access to funding is also key to accelerate innovation and R&D for early-stage green hydrogen technologies such as steel production through DRI, synthetic fuels or ammonia use in ships. In the near term, targeted financial supports should be provided to the industrial sector for the purpose of converting existing industrial processes to use green hydrogen produced from variable sources of renewable electricity.

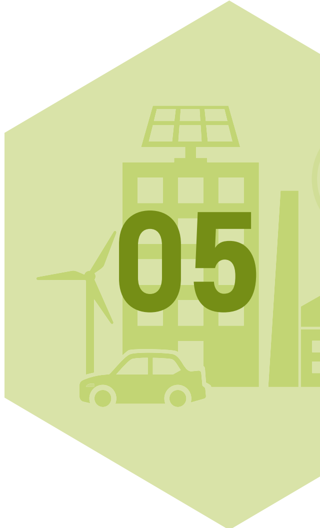
Stimulate demand for green hydrogen through carbon pricing and other regulatory measures. Subsidies for fossil fuels continue to distort energy markets and limit the potential growth of green hydrogen. Carbon pricing signals should be strengthened to account for environmental externalities (GHG emissions), creating a level playing field between the different energy vectors and encouraging efficient consumption. Carbon pricing mechanisms must also be accompanied by border adjustments or robust certification schemes for hydrogen imports to avoid competitiveness issues. Other mechanisms, such as green product mandates (e.g., for steel, cement, fertilisers), public procurement schemes and sectoral targets, can also stimulate demand for green hydrogen.

Consider how existing regulation of electricity grid fees and taxation affect opportunities for green hydrogen production. The ability of producers to optimise green hydrogen production to periods when renewable electricity is in excess supply and available at lower costs can be hindered by electricity consumption taxes or grid fees. To encourage green hydrogen production and realise its potential to provide grid balancing services, governments should consider how to implement more efficient electricity taxes and grid fees as well as congestion-based tariffs.

Promote development of green hydrogen hubs and valleys. In the near term, governments should work with partners to develop integrated green hydrogen "hubs" or "valleys" co-locating green hydrogen production, storage, distribution and consumption in one geographic area. By involving both producers and consumers in partnerships, off-takers for green hydrogen production can also be identified upfront, thereby diminishing project risks. Co-location also reduces the immediate need for long-haul transport infrastructure while guaranteeing the renewable origin of any hydrogen produced. Beyond domestic production, hubs could be located strategically to take advantage of existing infrastructure for potential transport and export of green hydrogen (i.e., pipelines and shipping).

Strengthen international co-operation and partnerships to accelerate green hydrogen uptake. Greater collaboration is still needed among governments, industry and academia to pioneer green hydrogen solutions for rapid decarbonisation. This could include joint collaboration on R&D, common agreements on standards and certification principles, and identification of supply chain and trading opportunities.

CASE STUDIES



To better understand the technical, economic and policy opportunities and challenges of green hydrogen and its role in energy transitions, this white paper profiles a selection of green hydrogen projects covering different geographies and end-uses.

The case studies were selected by members of the Coalition for Action based on first-hand experience with the projects and build on insights obtained through interviews with key stakeholders. Figure 5 below provides an overview of the selected case studies.

Figure 5: Overview of case studies

PROJECT NAME	PRODUCTION	END-USE
Queensland Nitrates (QNP)	Alkaline electrolyser	Green ammonia → Ammonium nitrate for explosives
Fukushima Hydrogen Energy Research Field (FH2R)	Alkaline electrolyser	Road transport; Power generation
HYdrogen BReakthrough Ironmaking Technology (HYBRIT)	Alkaline electrolyser	Steel industry
Green H2F Puertollano I	PEM electrolyser	Green ammonia → Fertiliser industry
Power-2-Green Hydrogen	PEM electrolyser	Road transport; Industry
Westküste 100	Electrolyser (TBD)	Green methanol → Road transport; Aviation

QUEENSLAND NITRATES: GREEN AMMONIA PRODUCTION FEASIBILITY IN AUSTRALIA

Queensland Nitrates (QNP) is an ammonium nitrate facility located near Moura in central Queensland, Australia. A joint venture by Dyno Nobel (acquired by Incitec Pivot Limited in 2008) and CSBP (Wesfarmers), QNP has a production capacity of 235 000 tonnes per year of ammonium nitrate, which it supplies to the Queensland mining industry (Incitec Pivot Limited, 2020).

In September 2019, QNP conducted a feasibility study for a green hydrogen and ammonia project that aims to use green hydrogen to produce ammonia at QNP's existing manufacturing plant. With an estimated project cost of USD 115 million to USD 154 million (AUD 150 million to AUD 200 million), the proposed facilities investigated in the study include a 30 MW alkaline electrolyser and a small-scale ammonia synthesis plant using the Haber-Bosch process. The facilities would consume 208 gigawatt-hours (GWh) of electricity per year to produce 3 500 tonnes of green hydrogen to make 20 000 tonnes of green ammonia, displacing approximately 20% of the ammonia currently used by QNP (natural gas-based ammonia purchased from third parties) and associated GHG emissions (QNP, 2020).

The feasibility study, undertaken in collaboration with Neoen Australia and Advisian (part of Worley Group) was completed in April 2020 at a total cost of USD 3 million (AUD 3.89 million). The Australian Renewable Energy Agency (ARENA) provided USD 1.47 million (AUD 1.91 million) in grant funding to support the study as part of ARENA's Advancing Renewables Program (ARENA, 2019). Neoen examined renewable-based electrical supply options for the proposed new facilities, while Advisian completed the overall modelling and engineering feasibility work.

Off-site wind and solar generation supplied by Neoen through a PPA was found to be the best option to power the facilities. This was because the QNP site was not suitable for wind power generation and the solar field needed to generate the electricity required was too large to be located behind the meter. The feasibility study also found the project to be economically viable with funding support in the form of grants and concessional loans. However, without subsidies a potentially viable business case was found to be achieved when producing 1 Mt of green ammonia per year (QNP, 2020).

Interview with David Armstrong, General Manager, Queensland Nitrates Pty Ltd (QNP) and Paul Ebert, Group Director, Energy Transition, Worley

Why did your organisation decide to pursue hydrogen? How did your organisation first get involved in the project?

Mr Armstrong: Hydrogen is needed to make ammonia, and we wanted to replace the 20% of our ammonia requirement currently purchased from others. Worley was seeking potential projects with a market for hydrogen from renewables. QNP had the ideal project size and an existing market for the hydrogen, via ammonia.

Our project was the right scale to take the next step up in size with the production of hydrogen from electrolysis. In addition, it could potentially achieve funding support by playing a part in the development of a renewables-based energy export industry, along with decarbonisation of existing supply chains with our customers.

Dr Ebert: We see low-carbon hydrogen as a foundation of a future energy system capable of meeting global decarbonisation and broader sustainability objectives. Its versatility, particularly the linking of electricity and gas markets that it offers (helping to integrate variable renewables in particular and through inherent energy storage), its ability to displace higher emissions fuels in difficult-to-shift sectors, and its sustainable circularity are all reasons to drive it to become business as usual. We are agnostic as to how low-carbon hydrogen is produced – blue[2] or green – as both are needed.

To kick off green hydrogen as a new industry, exemplars are needed to pave the development cycle, de-risk investment and build capability. Initial projects make more sense in the more valuable hydrogen uses, such as heavy transport and chemicals, and QNP had almost the perfect circumstance. We took the project to them as a concept and it resonated.

Have any commercial pressures (for example, climate change risk) led to the exploration of green hydrogen?

Mr Armstrong: Commercial pressures include a publicly stated (and growing) desire by our customers to decarbonise, as well as some strategic risk mitigation by us as a business.

Dr Ebert: We certainly see this pressure on our customers, some of whom have very difficult decarbonisation challenges in which low-carbon hydrogen is a solution among a sometimes small portfolio of options, while their markets are placing more attention on cleaner products.

What have been some of the major challenges of developing and operating the project? How were these challenges overcome?

Mr Armstrong: There were several key things we did not bring to the project: 1) a detailed knowledge of the electricity market; 2) access to potential global technology providers; 3) resource and specific technical knowledge; and 4) a potential funding pathway for the project. Project partners allowed the first three of these to be overcome.

Dr Ebert: Potential developers and users of low-carbon hydrogen face difficult economics and a lack of experience in assessing, developing and reaching final investment decisions for green hydrogen assets. The way the PPA is structured, how the operation of the electrolyser is integrated and optimised, and the opportunities that can be provided back to the energy market from this – totally new contract thinking is needed. Project procurement, specification issues, arrangements, process flows, technical optimisations, and plant safety and operability all have to be considered and dealt with. Being a complex process industry, project technical rigour is very important.

2 “Blue hydrogen” is hydrogen produced from fossil fuels with carbon capture and storage (CCS).

What role did local or national authorities play in addressing these challenges?

Mr Armstrong: ARENA provided grant funding to offset the costs of the feasibility study. The Northern Australia Infrastructure Facility has also been supportive in potential funding solutions.

Dr Ebert: Generally, Australian state and federal governments are very supportive of a low-carbon hydrogen industry. It is acknowledged as a potential new industry for the country's future. Australia's natural gas industry, existing access to energy markets and vast renewable energy resources lend it to becoming a major player in the production and use of both blue and green hydrogen.

What are some of the key lessons learned from the project?

Mr Armstrong: One consideration is the choice of electrolyser technology and whether it has the response characteristics required to deliver frequency control and other ancillary services; this is especially important in light of the Post-2025 Market Design[3] and opportunities to generate additional revenue streams. In terms of cost optimisation, there is also a trade-off to be made between capital costs (i.e., electrolyser, hydrogen storage) and operating costs (i.e., electricity). In our context, the feasibility study found that 60% and 80% electrolyser utilisation rates delivered a similar financial outcome.

Our project is sub-scale and while we gained some pleasing movement in capital, significant support is still required to deliver an acceptable business case. Green hydrogen production on a world scale (1 Mt per year) appears to make the project financially feasible.

However, key questions remain around risk. We need time and experience with large electrolysers to confirm their operating efficiencies, characteristics and maintenance regimes.

How do you expect the market for green hydrogen to grow? What do you see as the major drivers?

Mr Armstrong: Major drivers of demand for green hydrogen include a pathway to an export energy industry and the decarbonisation of existing domestic supply chains. The market may grow in a few directions. Green hydrogen can be directly used, or synthesised into ammonia, for use as a transport fuel; fuel cells are a promising alternative for large/commercial vehicle fleets. Hydrogen or ammonia may also emerge as a significant fuel source replacing or augmenting electricity production from traditional sources.

Dr Ebert: We expect the low-carbon hydrogen market to grow relatively quickly once the investor community is confident that business cases can be met and that the value proposition is real. Ultimately this requires risks to be dealt with – technology, pathways, offtakes – and driving down costs incrementally. The value proposition for low-carbon hydrogen is there, but it requires getting to scale.

We are pragmatic enough to know that blue hydrogen will have a role, but once low-carbon hydrogen pathways are established and the decarbonisation focus moves to natural gas, the only option is green hydrogen from low-emission resources – the bulk of which will be renewables based. Hydrogen will ultimately be a critical component of an energy transition jigsaw involving the integration of vast amounts of variable renewable energy into our energy markets.

3 In 2019, Australia's Energy Security Board was tasked with recommending design changes to the country's National Electricity Market, which covers Queensland, New South Wales, Australian Capital Territory, Victoria, Tasmania and South Australia (Energy Ministers, 2021).

FH2R: GREEN HYDROGEN R&D AND PRODUCTION IN JAPAN

The Fukushima Hydrogen Energy Research Field (FH2R) in Namie town, Fukushima Prefecture, Japan became operational in March 2020 after an approximately two-year construction phase. FH2R consists of a 10 MW alkaline electrolyser with a capacity to produce approximately 1 200 normal cubic metres (Nm^3) of hydrogen per hour by primarily utilising 20 MW of on-site solar photovoltaic (PV) generation capacity (New Energy and Industrial Technology Development Organization, 2020). Hydrogen produced at FH2R is delivered by tube trailer and cylinder cradle to several sites in Fukushima Prefecture as fuel for stationary fuel cells. The green hydrogen will also be used for fuel cell vehicles.

The project is run by a consortium led by Japan's New Energy and Industrial Technology Development Organization (NEDO). Toshiba Energy Systems & Solutions Corporation (Toshiba ESS) oversees the project, and Tohoku Electric Power Network Co., Inc. is in charge of supervisory control and data acquisition (SCADA) and grid-related matters.

Iwatani Corporation focuses on hydrogen demand-and-supply forecasting, transportation, and storage, and Asahi Kasei Corporation is responsible for the electrolysis technology used in the project. Approximately USD 180 million (JPY 20 billion) was allocated to the R&D project at FH2R by NEDO through March 2023.

FH2R serves as a research laboratory for future hydrogen projects by assessing how green hydrogen can be used to manage and optimise fluctuations in electrical power. To that end, a management system has been developed that comprehensively controls various devices such as the electrolyser, the solar PV generation facilities, the hydrogen storage unit and hydrogen compression based on their responsiveness. Another project objective is to acquire data for the practical application of power-to-gas by examining the efficiency and response performance of the electrolyser under various operating conditions.

Interview with Eiji Ohira, Director General, Fuel Cell and Hydrogen Group, Japan New Energy and Industrial Technology Development Organization (NEDO)

Why did NEDO decide to pursue the FH2R project?

Currently, renewables account for approximately 20% of the Japanese power sector. To meet our 2050 net-zero pledge, a significant scale up of renewable energy is needed. In addition to energy storage and batteries, hydrogen production through water electrolysis will play a key role in providing the necessary grid balancing services.

NEDO has a long history in hydrogen and fuel cells research and development. Although we started to promote the concept of FH2R in the early 2000s, we soon realised that we were ahead of our time. We re-initiated the project idea after the Japanese government developed a fuel cells road map in 2014 and adopted its Basic Hydrogen Strategy in 2017.

Initially, our focus was on small hydrogen projects (100 kilowatts [kW] and less), but looking at the future demand of the market we decided to develop a 10 MW hydrogen production unit. The decision to locate the project in Fukushima was based on the prefecture's ambitious 100% renewable energy plans and availability of suitable land for a large-scale hydrogen plant. We also wanted to contribute to its recovery after the nuclear disaster and, looking ahead, showcase the future of hydrogen in time for the Olympic Games. Throughout the site selection process up to today, Fukushima Prefecture remains very committed and involved in the project.

We selected partners through a general tendering process for a power-to-gas programme, from which we found suitable private sector companies to work with. Together with an expert panel, we selected Toshiba ESS as one of the main partners.

What have been some of the major challenges of developing and operating the project? How were these challenges overcome?

The main challenges we faced were technical ones followed by system and operational challenges. First, we needed to develop a large-scale 10 MW electrolyser and secure the technology in a market that is still in its infancy. The upfront investment cost was high, particularly given the risk associated with securing a reliable, efficient and durable electrolysis unit of this size.

We found creative ways to reduce upfront costs as well as operational costs. The utilisation of the 20 MW PV plant depends on, among other factors, weather, so forecasting became very important. We also looked at how power-to-gas can participate in the Japanese grid balancing market, which would provide another source of revenue for green hydrogen projects. Currently we cannot participate in the market because the minimum size threshold for offering into the market is 5 MW. However, we expect this situation to change with the Japanese government planning to commercialise power-to-gas in the near future and the ability to scale up further as we gain technical capacity.

We also had to build human expertise. Many experts with specialised competencies were needed for this project, including technicians and operators. The objective was to find ways to maximise system operation in a cost-effective way. For this, you need human capacity and experience that we had to train onsite.

Finally, we faced challenges developing the project's business model. We could not calculate the exact operation and maintenance costs, as data was not available yet in Japan and very difficult to find globally. Demand forecasting for hydrogen was another issue. This is why we turned to partners, such as Tohoku Electric Power and Iwatani, to support us.

What are some of the key lessons learned from the project?

During the entire project life, we followed an iterative approach developing prototypes, coupled with much testing and multiple feedback rounds involving all stakeholders. I believe this approach made this project successful and showed us the potential for power-to-gas technologies to become an important contributor to achieving our net-zero pledge by 2050.

FH2R is one of the largest hydrogen research facilities globally. The experience and data acquired will be invaluable for commercial implementations in the future. NEDO is using this gained knowledge in its other national fuel cell and hydrogen projects.

The project has shown that we need to improve fuel cell technologies and develop new ones, particularly for specific applications such as heavy-duty vehicles, vessels and more. We also need to develop an international hydrogen supply chain. Although we used Japanese technologies for the Fukushima project, we certainly need to have closer collaboration with other countries to increase necessary R&D and scale up the technology. For instance, for stationary fuel cells, Japanese companies already co operate with German companies.

What role will hydrogen play in Japan's energy transition?

While we intend to use hydrogen in gas turbines first, we also plan to invest in further R&D to capture how we can use hydrogen for different industries, particularly energy-intensive ones. The question is how to integrate hydrogen into existing energy systems or design systems that also maximise the utilisation of local energy sources. This will require the development of a masterplan that also considers supporting infrastructure.

Although Japan will invest in hydrogen production for its own needs and national energy security, the extent to which we can decarbonise through hydrogen depends on our ability to import from other countries. We need to develop global hydrogen markets that allow for long-distance transport of hydrogen.

How do you expect the market for green hydrogen to grow? What do you see as the major drivers?

Market growth for green hydrogen will likely be different for each country depending on demand, supply and policies. Industry demand for hydrogen will be key to growth. As the cost of hydrogen decreases, more industrial players will seek to decarbonise their operations.

With the EU setting clear targets for hydrogen, a local market is likely to develop rapidly because the industry has clear signals. In Japan, specific hydrogen targets are still under discussion. Japan's policy mandates to reduce GHGs and nitrogen oxide (NO_x), as well as its plans to phase out the sale of gas and diesel-engined cars by 2035 will certainly support green hydrogen development and help remove market risks.

Financing also plays a crucial role in driving hydrogen. With the Japanese government prioritising a green future and putting forward supportive regulation, the Japanese financial sector is not investing in new coal plants anymore and is increasingly investing in energy-transition related technologies, including hydrogen.

To scale-up hydrogen even further, policy and industry will need to work hand in hand to develop a short-, medium- and long-term vision for a hydrogen society. Our Japanese strategy was released three years ago and will be revisited in the near future.

Lastly and most importantly, hydrogen will only kick off if we have public acceptance. This can be done through different means such as information sharing and education. Governments have a key role to play in providing facts and figures to the media and the public showcasing the full potential of hydrogen.

HYBRIT: DECARBONISING STEEL PRODUCTION IN SWEDEN

In 2016, the steel company SSAB invited the mining company LKAB and electricity provider Vattenfall to form the HYdrogen BReakthrough Ironmaking Technology (HYBRIT) initiative with the objective of developing a fossil-free steelmaking process. Following a pre-feasibility study, the three companies formed a joint-venture company and invested in a pilot plant project to develop a fossil-free value chain from iron ore to steel using clean electricity (HYBRIT, 2021).

Fossil-free iron pellet-production trials were started in August 2020 and a direct reduction plant was constructed and inaugurated in the same month. A 4 MW electrolyser plant for green hydrogen production will be put into operation during 2021. Construction on a Lined Rock Cavern (LRC) hydrogen storage pilot facility has also commenced and is to be completed as early as 2022 (Vattenfall, 2021).

An industrial-scale demonstration plant is planned to be built by 2025 with the capacity to produce 1 million tonnes of fossil-free sponge iron, used by SSAB to produce fossil-free steel at a commercial scale. The end goal is to achieve commercial delivery of fossil-free steel products in 2026.

Despite the technology risks involved, steel supply chain actors were willing to invest due to the availability of low-cost renewable electricity and increased confidence in governments and industrial climate policies. Notably, project timelines for the HYBRIT initiative have been accelerated since its 2016 launch in response to competition from other actors in Sweden, European countries and the rest of the world. The HYBRIT project has enjoyed strong financial support from the Swedish Energy Agency and the project was praised during the launch of the Next Generation EU recovery fund.

Interview with Martin Pei, Chief Technology Officer, SSAB

Why did SSAB decide to pursue hydrogen? How did SSAB first get involved in the project?

Industry has tried different options to reduce CO_2 emissions in the steel production process in the past decades. However, incremental improvements in energy efficiency are far from enough to reach the objectives set in the Paris Agreement; on the contrary, breakthrough technology is necessary. As such, two options have been evaluated in the industry: continue with steelmaking using the current dominant fossil coal-based blast furnace ironmaking approach and invest in carbon capture and storage (CCS), or shift to the clean hydrogen-based direct reduced iron-electric arc furnace (DRI-EAF) route for the production of primary steel from iron ore. SSAB decided to take the lead in scaling up the latter and initiated the HYBRIT project.

What are the major challenges of developing and operating the project? How are these challenges overcome?

The ambition of the HYBRIT initiative is to replace coking coal used in ironmaking, an industry with almost 1 000 years of history. Apart from the need to scale up the technology step-by-step – from laboratory through pilot plant to demonstration plant – and solve technical challenges foreseen to emerge during the journey, both policy instruments and public support are necessary to support this transformation. Societal buy-in is important since this shift creates significant change to the industrial landscape and creates a considerable need for more investments in renewable electricity production and transmission infrastructure.

What role did local or national authorities play in addressing these challenges?

In Sweden there is strong support and urgency at the national level regarding climate mitigation. The Swedish Energy Agency provided financial support for the R&D and pilot projects. Such support is extremely important – the steel industry alone will not be able to take all the risk associated with the transformational change. At the local level, understanding of the need for this technology shift is improving. This will be increasingly important as our initiative progresses, and permits and changes in local society become necessary to enable the transition.

What are some of the key lessons learned from the project?

One of the learnings so far is the necessity to create alignment among the most important stakeholders. In the HYBRIT initiative, this includes first the three owner companies, authorities and political parties in Sweden, as well as the academic community (universities and research institutes, both in technical and energy/climate policy areas). Significant effort was made to explain the initiative's goal and the support needed to succeed. Even though there are still skeptical voices, the HYBRIT initiative has gained widespread public support in Sweden and Finland. The European Commission has even designated HYBRIT a "Lighthouse European project", allowing us to receive financial support as part of the COVID-19 green recovery.

How do you expect the market for green hydrogen to grow? What do you see as the major drivers?

The HYBRIT initiative is built on a shift from fossil coal to renewable hydrogen[4]/electricity for iron ore reduction. Since the magnitude of the energy involved is huge, we have focused on the availability of renewable electricity and grid connections to future sites of the HYBRIT DRI facility, meaning that we can produce green hydrogen on-site on an industrial scale using electrolysers. We also plan to develop large-scale hydrogen storage.

Overall we believe the market for renewable hydrogen will develop fast in the future, especially in Europe, driven by the need to rapidly decarbonise our economy. That is why continuing with steam methane reforming (SMR) for hydrogen production and applying CCS (i.e., blue hydrogen) will not be the long-term preferred solution. By the same logic, we do not see the use of blast furnace technology using fossil coal as sustainable. Another driver is the opportunity to store hydrogen at large scales and provide grid balancing services when the intermittent renewable electricity generation capacity increases in the future energy mix.

4 "Renewable hydrogen" refers to green hydrogen.

GREEN H2F PUERTOLLANO I: GREEN AMMONIA AND FERTILISER PRODUCTION IN SPAIN

Green H2F Puertollano I ("Puertollano I") is a green hydrogen and green ammonia pilot project situated in Puertollano, the Spanish province of Ciudad Real. The project is developed in partnership between Iberdrola and fertiliser producer Fertiberia with the technical support of Spain's National Hydrogen Center. Currently under construction with a targeted operational date of 2021, Puertollano I is the first of four green hydrogen projects planned for development under the Fertiberia-Iberdrola partnership. Once completed, the Green H2F Project is expected to account for a combined 800 MW of installed electrolysis capacity by 2027.

Designed as one project with two sites, Puertollano I provides an integrated supply of green hydrogen and oxygen for the production of ammonia and nitric acid.

The first site consists of a 100 MW solar PV plant and a 5 MW/20 MWh lithium-ion battery storage system. The battery storage system and 35 MW of generating capacity will be dedicated to green hydrogen production, with excess electricity production sold to the grid. The second site consists of a 20 MW polymer electrolyte membrane (PEM) electrolyser which will be located within the fertiliser facility premises at the Fertiberia Puertollano plant. The electrolyser is expected to produce 360 kg of hydrogen (H_2)/hour and 2 800 kg of oxygen (O_2)/hour.

Power to the electrolyser will be delivered through a dedicated underground line between the sites, ensuring that all energy used in the electrolysis is renewable and minimising environmental impact. Hydrogen produced will be buffered in pressurised tanks. Oxygen produced as a by-product of electrolysis could be used entirely in a nitric acid unit, which will also undergo a series of modifications to improve its GHG emissions and energy efficiency. Once completed, Puertollano I is expected to reduce natural gas requirements at the Fertiberia Puertollano facility by over 10%. In all, the displacement of a natural gas-based process and the technical modifications in the ammonia and nitric acid production will avoid emissions of almost 40 000 tonnes carbon dioxide (tCO_2)/year (Iberdrola, 2021).

Requiring an investment of USD 180 million (EUR 150 million), Puertollano I will serve as a reference for future developments in the manufacturing of commercial scale electrolyser equipment, the management of power generation from variable renewable sources to deliver a firm hydrogen supply, and the integration of green hydrogen supply within an existing fertiliser production site. It is estimated that Puertollano I could generate up to 700 jobs[5] and provide scale in the region to consolidate its position as a hydrogen hub.

5 Includes direct, indirect and induced employment of investments associated with hydrogen generation (PV plant, energy storage, power line and electrolyser).

Interview with David Herrero, Industrial Director, Fertiberia and Millán García-Tola, Hydrogen Unit Director, Iberdrola

Why did Fertiberia pursue hydrogen? How did Fertiberia first get involved in the project?

Mr Herrero: Hydrogen is the main feedstock in ammonia production and to date it is predominantly produced by the fertiliser industry using steam methane reforming technology, based on natural gas. Currently, the fertiliser sector accounts for over a third of the total hydrogen consumed in Europe. If we are to meet decarbonisation targets and reach net-zero emissions by 2050, all sectors need to design and implement decarbonisation road maps for the coming years.

The fertiliser sector can and should take a leading role in this transition. Policy makers already recognise the importance of the fertiliser industry as an early adopter of carbon-neutral hydrogen as feedstock and have set up national and European strategies to support the sector.

The Green H2F Puertollano I project aims to offer a zero-emission alternative to ammonia production which will also enable decarbonised fertiliser production. It is the first of its kind in terms of the volume of hydrogen produced and electrolysing capacity, as well as offering an end-to-end solution for the decarbonisation of the fertiliser value chain.

Why did Iberdrola decide to pursue hydrogen? How did Iberdrola first get involved in the project?

Mr García-Tola: For the last 20 years, Iberdrola has been engaged in the transition to a decarbonised energy model, through investments in renewable electricity, smart grids, large-scale energy storage and digital transformation.

Technological development over these past years has made electricity the backbone of a decarbonised energy model with the combination of renewable power generation and direct electrification. However, some industrial uses as well as hard-to-abate sectors will need other technological developments, and this is where we see green hydrogen playing a key role.

Green hydrogen will enable progress on two fronts: emissions reduction in sectors that currently consume hydrogen, produced by processes that emit CO_2, and the adoption of hydrogen in sectors that are difficult to electrify (such as heavy transport and air and sea transport).

Green H2F Puertollano I brings together the expertise of Iberdrola and Fertiberia and will hopefully help move the learning curve forward, speeding up the maturity of technologies for green hydrogen production and showcasing it as a solution for efficient decarbonisation.

What have been some of the major challenges of developing the project? How were these challenges overcome?

Mr Herrero: One of the aims of this pilot project was to demonstrate an end-to-end solution with significant scale at the ammonia production level. Some of the challenges were overcome at the concept-design phase, for instance by siting the PV plant in the vicinity of the Fertiberia plant with battery storage capacity and a dedicated power line.

Producing green hydrogen from renewable electricity sources is challenging in itself, as daily and seasonal fluctuations need to be taken into account. Incorporating the green hydrogen and oxygen into the conventional ammonia production line adds another level of operational complexity. Coupling variable generation with continuous demand requires adjustments to maintain process stability.

To overcome these challenges, we decided to upgrade the control systems of the ammonia plant and install green hydrogen daily buffers. This allows us to maintain a certain level of stability of the hydrogen flow to the ammonia plant, enabling optimised operation despite the generation curve of the renewable source.

What role did local or national authorities play in addressing these challenges?

Mr Herrero: Local, regional and national authorities have been very supportive of the project. The National Hydrogen Center, which is headquartered in the vicinity of the plant, has been a key stakeholder since the beginning, providing technical advice and support. To reach a level of development needed to be competitive, this public support is a must as we progress along the learning curve and achieve economies of scale. First-of-a-kind projects like this need support and funding mechanisms.

Going forward as projects develop, government and authorities should also facilitate access to affordable and abundant renewable electricity. The electricity moving through our networks will be more and more renewable as the power system becomes increasingly decarbonised. Creating a level playing field requires robust certification mechanisms ensuring the renewable origin of electricity.

What are some of the key lessons learned from the project?

Mr Herrero: There are still many lessons to learn from the project as it advances in construction and once it becomes operational. But one of the obvious lessons is that it is not straightforward to connect green hydrogen to an existing conventional ammonia plant. This is a pilot study and many adaptations to the ammonia production process were required. In the future, with increasing ratios of green to grey hydrogen[6] being incorporated, more modifications, automatisations and new equipment will probably be needed.

We have the technical ability now to implement and take further steps in scaling up green hydrogen. In fact, building on this first experience, we have announced a global plan for a total of 800 MW of green hydrogen capacity across four projects to be operational by 2027.

This global plan is 40 times the size of Green H2F Puertollano I and has the potential to set Spain on a transformational pathway to green hydrogen.

How do you see green hydrogen evolving from a technological point of view? How competitive can it get?

Mr García-Tola: Hydrogen production with electrolysis is a mature and known technology, but it has been outpaced by grey hydrogen, given its much lower costs.

Three components have the largest impact on competitiveness. These are the cost of the electrolyser, the cost of the electricity and the plant capacity factor. We see large improvement potential in electricity costs as generation costs in renewables keep on decreasing.

Electrolyser investment costs will show a typical learning curve evolution with large cost reductions as volumes increase. Given the size and number of projects announced, progressing along the learning curve can happen very quickly. Capacity factors will also increase, driven by technological evolution.

In all, and considering uncertainty associated with future developments, we see a potential cost reduction between 35% and 60%, which could make green hydrogen competitive by 2030.

What is needed to accelerate the contribution of green hydrogen to decarbonisation efforts?

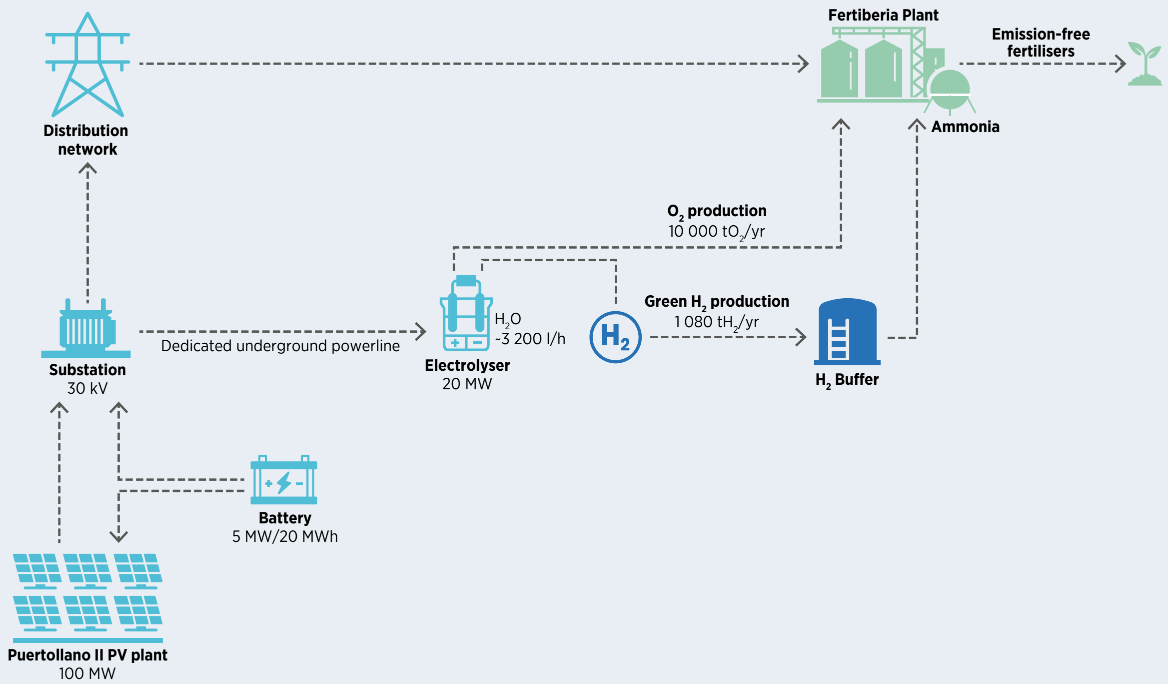
Mr García-Tola: To meet the green hydrogen plans established in many jurisdictions, in addition to cost reductions, production capacity will need to be substantially increased. There are already consolidated manufacturers of electrolysers, but there are needs in the value chain to upscale volume, increase the size of manufactured electrolysers and develop the associated industrial networks.

6 "Grey hydrogen" is hydrogen produced from fossil fuels.

In this sense, we are also pursuing actions to develop the supply chain. Together with the Basque enterprise Ingeteam, Iberdrola has also founded Iberlyzer, which will become the first large-scale manufacturer of electrolysers in Spain.

How do you expect the market for green hydrogen to grow? What do you see as the major drivers?

Mr Herrero: As mentioned before, hydrogen is currently used as feedstock in a number of industrial sectors and currently its production is mostly based on fossil fuel-based processes. The demand for hydrogen – including for the fertiliser sector – is expected to continue to grow. Given the existing demand for hydrogen in the sector, green hydrogen is already a valuable product. The good news is that the technology to produce hydrogen with renewable electricity is known and although the technology lacks scale and competitiveness today, it is certain that green hydrogen will have a key role in a decarbonised economy. Even ammonia could be used as an energy vector for many other uses, directly used at its destination point or converted back to hydrogen. Ammonia can also play a key role in decarbonisation of certain hard-to-abate transport segments, like deep-sea transportation, where it could be used as a carbon-free, sulphur-free marine fuel. All these uses will benefit from the lessons learned from the Green H2F Puertollano I project.



Project overview of Green H2F Puertollano I
Source: Iberdrola

POWER-2-GREEN HYDROGEN: INDUSTRIAL REVITALISATION AND ISLAND DECARBONISATION IN MAJORCA

The Power-2-Green Hydrogen project pioneers a solution for island decarbonisation and industrial reconversion in Majorca, Spain. Once complete, it will serve as a revitalisation project for the Balearic town of Lloseta, which was significantly impacted by the end of cement production, a major employer in the area.

The project consists of two solar PV plants making up 16 megawatts-peak (MWp) of combined generation capacity and a 2.5 MW PEM electrolyser. The output from the electrolyser will support multiple end-use applications. Although the green hydrogen produced will be mainly used to power the island's public transportation fleet, some hydrogen will also be injected into the gas grid and serve as back-up energy for buildings (public buildings, ports, hotels, etc.).

With project construction set to commence in 2021, Power-2-Green Hydrogen is expected to contribute substantially to local gross domestic product (GDP) and to the creation of local jobs during its construction and operation and maintenance phases. Once operational, the project will generate 300 tonnes of hydrogen each year and reduce annual CO_2 emissions in Majorca by over 16 000 tonnes.

As a result, the island will benefit from fuel switching and decarbonisation of the local economy (ACCIONA, 2020a).

Under a public-private alliance model, the project involves on the public side, among others, the Spanish government agency Instituto para la Diversificación y Ahorro de la Energía (IDAE), the Balearic Islands government, and the University of the Balearic Islands. From the private sector side, ACCIONA will act as co-investor of the project as well as green hydrogen trader (along with partners Enagás, IDAE and CEMEX) and developer of the two solar PV plants. Redexis will be in charge of building the hydrogen pipeline necessary to meet the consumption targets set by the project.

The European Commission's Fuel Cells and Hydrogen Joint Undertaking (FCH JU) recently selected Power-2-Green Hydrogen for a grant valued at USD 12 million (EUR 10 million), making it the second-largest grant awarded by FCH JU to a green hydrogen project and the largest grant ever offered to a Mediterranean country. In addition to this grant, the project has received public funding from IDAE. The total capital expenditure of the project, including subsidies, totals approximately USD 60 million (EUR 50 million) (ACCIONA, 2020b).

Interview with Juan Pedro Yllanes, Vice-President and Counsellor for Energy Transition and Productive Sectors at the Balearic government and Rafael Mateo Alcalá, CEO - Energy at ACCIONA

Why did the Balearic government decide to pursue hydrogen? How did the Balearic government get involved in the project?

Mr Yllanes: Tourism is the most important economic sector in the Balearic Islands, and it has been badly hit by the COVID-19 pandemic. This has highlighted the need to promote other sectors, such as the renewable energy sector. We plan to invest almost EUR 500 million (private and public funds) over the next two years in the implementation of renewables that in turn will create 17 000 jobs.

We are pursuing green hydrogen as a clean energy source and as an opportunity to re-industrialise Lloseta. It allows us to move from carbon-intensive sectors like the cement industry to other industries, which can reduce emissions, help us gain knowledge and position us as a sustainable pathfinder in Europe. This shift also offsets potential job losses from the cement plant closure.

Private companies, such as ACCIONA and Enagás, as well as the Spanish government, are involved in the project, which has been actively supported by the Balearic government and has received a EUR 10 million investment from the EU.

Why did ACCIONA decide to pursue hydrogen? How did ACCIONA get involved in the project?

Mr Mateo: ACCIONA is the largest pure-play renewable energy utility in the world, operating close to 11 GW of renewable energy capacity in over 16 countries. We are pioneers in renewables, with assets in our portfolio that have been operating for more than 25 years, and now we look forward to being part of the green hydrogen revolution – with emphasis on the word "green".

Hydrogen has many colours, but the focus should be on hydrogen produced through electrolysis, via green electricity, which is going to be the substitute of fossil fuels in industry, transport and many other activities. Green hydrogen will be the solution in the many sectors where electrification is difficult and sometimes not possible.

This is why we are happy to be part of the first hydrogen project in Spain with the participation of our partners, the Spanish government, the Balearic government and the EU, who have been key in supporting us.

What role do local and regional authorities play in addressing the challenges of the project?

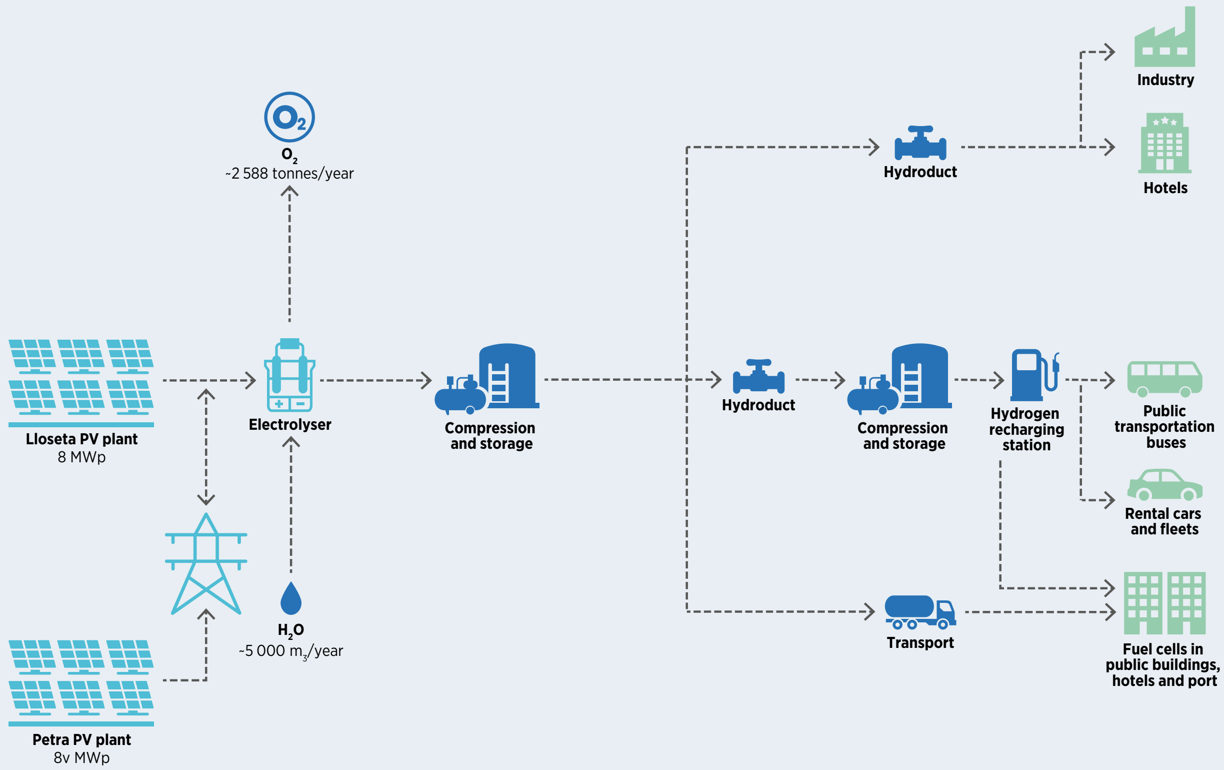
Mr Yllanes: The Balearic government has helped make the project a reality, working with the companies involved to make it a project that deserves EU investment. For example, we declared the project a strategic industrial project of the Balearic government, which speeds bureaucratic processing. We have also leased public land for the construction of solar PV plants that will power green hydrogen production. Now we are working with the city of Palma's public bus company to purchase a fleet of hydrogen-powered buses and estimating the potential investment needed.

We will also help to sell hydrogen to industries, especially to hotels in Majorca, and to promote green hydrogen use as added value. It is an enormous opportunity for the Balearic Islands.

From a private sector perspective, what are some of the major challenges of developing and operating the project?

Mr Mateo: Hydrogen is a raw material for industry with many applications, or a new vector to store electricity. The main challenge is to adapt regulations appropriately so that green hydrogen is not treated as a hydrocarbon. Green hydrogen is a new product in the market, and it needs to be deployed jointly with the help of governments and regulators to facilitate easier deployment.

The learning curve for green hydrogen technology will be similar to that of solar PV panels and batteries. Higher penetration of the technology will drive down prices, which in turn will promote even more adoption. Hence, our obligation is to start quickly, in order to reduce the cost curve for the technology and its applications.



Project overview of Green-2-Power Hydrogen
Source: ACCIONA

With this project, we are also pioneering the use of blockchain to verify the green origin of the electricity used to produce hydrogen. Currently, we have no regulation in this field, making it important to establish mechanisms that can verify green hydrogen is in fact green hydrogen and not any other type of product.

What economic and social impacts do you expect the project to create in your region?

Mr Yllanes: One of the goals of this project is to be pioneers in this economic diversification. It is essential for us, because we can no longer only rely on tourism. Renewables, industry, innovation, research – that is the model we want to achieve in the Balearic Islands. We are involving research and academia, such as the Balearic Islands University, to create further economic impact. We hope this will be the first of many sustainable energy innovation projects to be implemented in our islands.

Are there any unique aspects of this hydrogen project you would like to highlight?

Mr Mateo: Since this is the first green hydrogen project in Southern Europe, it can serve as a future reference and drive faster penetration of hydrogen. We are in the implementation phase as we speak and are buying the electrolyser in the upcoming weeks.[7] In some months, the project will create jobs and make a positive contribution to the local economy. The plant will produce more than 300 tonnes of green hydrogen per year.

Another differential aspect is that the project will be replicable. Many industrial companies are asking us about the feasibility of having small and local green hydrogen onsite for own consumption. Finally, the project is being built under a PPP (public-private partnership), which provides a clear example of the partnerships that are needed.

7 The interview was conducted on 28 October 2020, and the electrolyser for the Power-2-Green Hydrogen project was purchased in December 2020.

What role will green hydrogen play in the Balearic Islands' energy transition?

Mr Yllanes: Green hydrogen can be a perfect companion for renewable energy.

Here in the Balearic Islands, the energy transition is mostly based on solar, which is an intermittent source of energy. Hydrogen can be used to store renewable energy at times of excess energy supply. On the other hand, the main disadvantage of green hydrogen is the low efficiency of its production processes, which currently stand at around 50%.

To maintain high performance in future energy systems, hydrogen should be: 1) used in a highly efficient way; and 2) used in sectors for which we do not currently have any alternative renewable energy sources. Regarding highly efficient uses, combined heat and power systems with fuel cells are an interesting alternative in some sectors (e.g., hotels for the tourism sector). On the second point, sectors without renewable alternatives include heavy load transport, high-temperature industry and marine mobility. We do not foresee the use of hydrogen in passenger cars, as the size of our islands makes electric vehicles an efficient alternative.

How do you expect the market for green hydrogen to grow? What do you see as the major drivers?

Mr Mateo: By demonstrating green hydrogen's value as a real product in the market, the demand will follow. The next decade will see massive penetration of renewables and a learning curve for green hydrogen. The expectation is that green hydrogen will become cost-competitive by 2030.

To meet the potential growth of green hydrogen in Spain from now to 2030 would require approximately 35 000 Power-2-Green Hydrogen projects. The potential is huge, not just in the Balearic Islands but also in the rest of the country. This is why we are so interested in leading and creating an example for the rest of the market.

Furthermore, we are trying to develop electrolyser components locally. This technology will probably allow, much like wind did in the past, the deployment of local manufacturing of some components. By enabling a domestic supply chain, we can also contribute to the recovery of the renewable energy industry in Spain.

WESTKÜSTE 100: GREEN HYDROGEN AND SECTOR COUPLING IN GERMANY

The Westküste 100 project aims to produce and use green hydrogen at an industrial scale by integrating the energy and material streams of regional industries and showcasing green hydrogen's potential as a catalyst for sector coupling. The project was initiated by a consortium including EDF Germany, Holcim Germany, Open Grid Europe, Ørsted, Raffinerie Heide, Stadtwerke Heide, Thüga and thyssenkrupp Industrial Solutions – together with the Region Heide Development Agency and the Fachhochschule Westküste (West Coast University of Applied Sciences).

In the first phase of the Westküste 100 project, a 30 MW electrolyser powered by offshore wind energy will be installed at Heide Refinery, situated on the western coast of Schleswig-Holstein. For more than 150 years, the area has been home to extraction and refining of oil chalk and later liquid crude oil into lighting oil, fuels and other petrochemical products. The area's close proximity to the vast offshore wind resources of the German North Sea, together with its strong link to the German power transmission grid and the potential for geological cavern storage, makes Heide Refinery well-situated for green hydrogen production.

Once the first phase is complete, the electrolyser will be one of the first large-scale green hydrogen projects in Germany with an estimated yearly output of 3 500-5 000 tonnes of hydrogen (tH_2).[8]

The first phase will focus on developing and testing solutions to produce green hydrogen and replace fossil-based hydrogen, serving as a real-life platform to review the technical, operational, economic and regulatory challenges of scaling green hydrogen production. Areas of focus include operation and maintenance of the electrolyser plant; the plant's interface with the power grid; the production, transportation and storage of hydrogen; and the overall system integration of material flows and business models.

The consortium plans to build on the experiences from developing, integrating and operating the initial 30 MW electrolyser to scale up hydrogen production to 700 MW and combine hydrogen produced with captured CO_2 from the nearby Lägerdorf cement plant to produce synthetic methanol. This syn-methanol can then be further processed into other synthetic hydrocarbons – for example, as an industrial raw material or as aviation fuel for nearby Hamburg Airport.

As part of this effort, the Westküste 100 project is also exploring the feasibility of feeding surplus

8 Estimated yearly output is subject to implementation of the revised Renewable Energy Directive II (RED-II). Article 27 of RED-II stipulates a delegated act (a piece of legislation passed by the European Commission which enters into force directly in member states) which will define the renewable character of the output (hydrogen) from grid-connected electrolysers and how it contributes towards the 2030 EU target of 14% renewable energy in the transport sector. The European Commission shall adopt this delegated

oxygen from the electrolyser into the combustion process at the plant. When fully realised, this would potentially reduce NOx emissions from the cement plant by up to 60% and turn carbon emissions from a waste product into a resource that could substitute for fossil feedstocks elsewhere. Excess heat from the electrolyser will furthermore be used to heat local residences and businesses in the Heide area.

The first phase of the Westküste 100 project has a total budget of USD 108 million (EUR 89 million). The project is financed by consortium partners, along with approved funding of USD 36 million (EUR 30 million) from the Reallabor (real-world laboratory) programme under the Federal Ministry for Economic Affairs and Energy in Germany. The project partners received funding confirmation from the German government in August 2020 and are now working towards a final investment decision on the first phase of the project. This is still, however, subject to final implementation of the EU Renewable Energy Directive recast (RED-II) in national law and its delegated act.[9]

Interview with Anders Nordstrøm, Vice-President, Hydrogen, Ørsted

Why did Ørsted decide to pursue hydrogen? How did Ørsted first get involved in the project?

At Ørsted, we have witnessed first-hand how industrialising and scaling of renewable energy – in our case, especially offshore wind generation – have driven down costs and made green electricity cheaper than coal, gas or nuclear power plants in most parts of the world.

However, while wind and solar energy will be the backbone of the global efforts to limit climate change, hard work remains to complete the green transformation of our societies. Sectors such as certain heavy industries and heavy-duty road transport, deep-sea shipping, and aviation are still reliant on fossil fuels for energy or as feedstock and cannot feasibly be electrified directly.

Renewable hydrogen[10] can act as a bridge to the green transformation for these sectors, either as pure hydrogen or in combination with sustainably sourced carbon or nitrogen, as sustainable e-fuels. Building on our experience developing and operating renewable generation assets, we have an ambition to help accelerate the development and deployment of renewable hydrogen production and power-to-X technologies, and to help grow the market for sustainable e-fuels.

To this end, refineries – with their established demand and infrastructure for hydrogen – are relevant for the first projects. Ørsted is already present in the German market, where we operate approximately 1.3 GW of generation capacity across four offshore wind farms.

The Heide region's demonstrated demand for hydrogen, existing infrastructure, and industrial and political environment committed to developing a functioning hydrogen economy make it an ideal location to establish and scale renewable hydrogen production.

What have been some of the major challenges of developing and operating the project? How were these challenges overcome?

The project is still in its early stages, but one main challenge, as is the case with any renewable hydrogen project, is to overcome the cost barrier. Hydrogen produced in water electrolysis plants is significantly more expensive than fossil-based hydrogen. One reason is that electrolyser technology is still relatively expensive.

The largest electrolysers in operation today are in the 10 MW scale. But with Westküste 100 and other projects like it being announced, we hope to see economies of scale and an industrialisation of the supply chain bring down costs over the next decade.

act by 31 December 2021 at the latest.

9 See footnote 8.

10 "Renewable hydrogen" refers to green hydrogen.

Furthermore, most of the fossil hydrogen produced today is based on natural gas, which is a cheaper feedstock than electricity. To close the cost gap between renewable and fossil hydrogen and enable a viable business case for projects, regulatory incentives to off-take renewable hydrogen and to foster cost convergence are needed. For the Westküste 100 project, the most important lever is expected to come from the RED-II, which mandates at least 14% of renewable energy in transport in 2030, including the option of using renewable hydrogen to achieve this target.

What role did local or national authorities play in addressing these challenges?

Westküste 100 is the first large-scale hydrogen project to receive funding through the federal German Reallabor programme, which has enabled us to go forward with the engineering of the first phase.

This funding confirms the support of political actors to overcome regulatory barriers and uncertainties while also exploring what potential future regulation of the German hydrogen economy could look like. Special attention will be focused on the transposition of RED-II into national legislation and on the delegated act defining what it takes for hydrogen to count as "renewable". This will carry important weight in the project.

While scaling up production and utilisation of renewable hydrogen in Germany – and elsewhere in Europe – still faces much technical, economic and regulatory uncertainty, the active engagement of regional and federal policy makers in bringing this project to fruition has greatly increased our chance of success and of developing the next phases of the project.

Meanwhile, the project has also been actively promoted by local authorities and co ordinated through the Heide Region Development Agency, including managing networking activities and links to other institutions, academia and projects in the area.

What are some of the key lessons learned from the project?

The consortium has already learned valuable lessons from the early development phase of this prototype project.

Most importantly, the Westküste 100 project underlines the benefits of a holistic approach to establishing industrial production of renewable hydrogen. To overcome the cost gap, projects must identify applications with high added value of renewable hydrogen and with end users who are willing to pay the premium for it. This may be off-takers of hydrogen who want to or must reduce their carbon footprint. In the longer run, if the transparency is in place, it could be private consumers willing to pay more, e.g., for a "green" airline ticket.

In addition, the value of flagship projects with participation from both producers and consumers is high. Partnerships can significantly reduce investor risk. The consumer will know supply is available before investing in infrastructure to off-take and use renewable hydrogen, and the developer of the electrolyser will know there is demand. Going forward, this is also a noteworthy lesson to policy makers seeking to promote renewable hydrogen.

Finally, when analysing the business case of renewable hydrogen and power-to-X in the Heide region, it became apparent that incentives have an important role to play to help projects such as Westküste 100 get off the ground and more generally to create a market for renewable hydrogen.

How do you expect the market for renewable hydrogen to grow? What do you see as the major drivers?

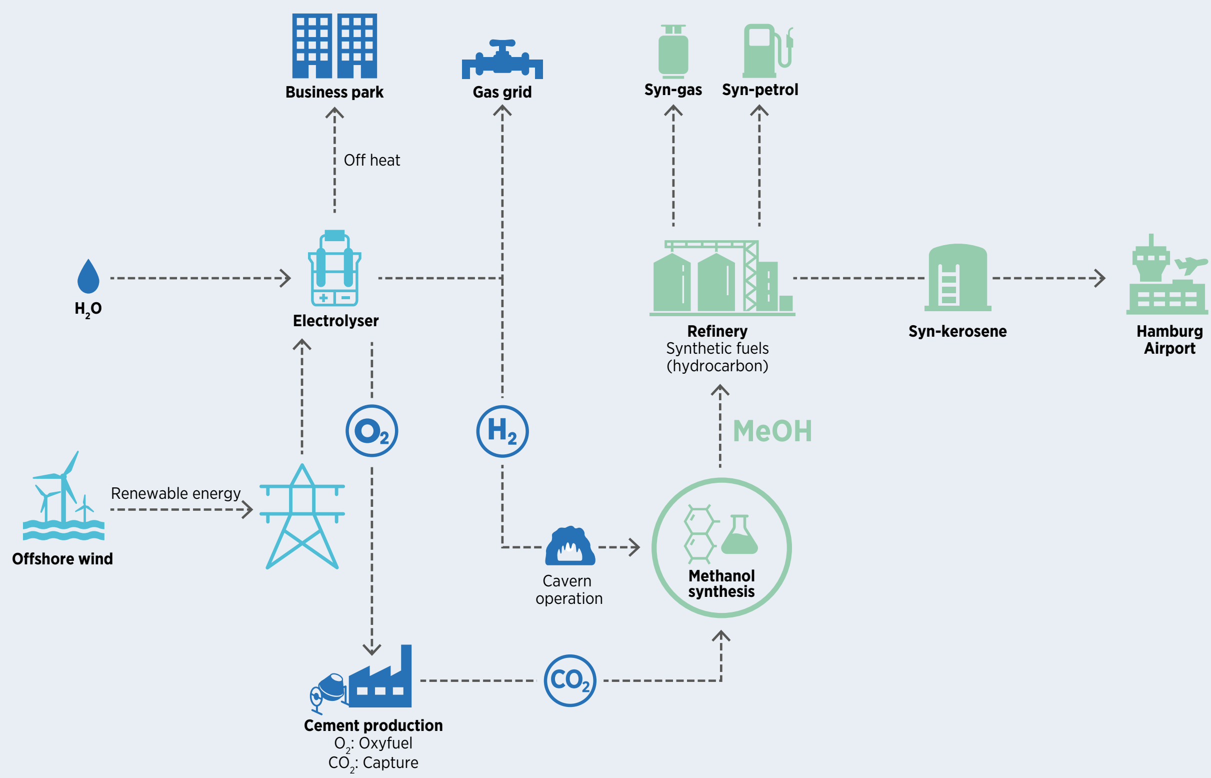
Renewable hydrogen has an important role to play in decarbonising our society. This can be by replacing consumption of fossil hydrogen as industrial feedstock or as an energy carrier for industry and heavy transport – either in its pure form or, combined with either carbon or nitrogen, as other sustainable e fuels such as e-methanol or e-kerosene.

Developing renewable hydrogen relies on three important factors. A high renewable share of power generation, competitive power costs, and political determination to achieve deep decarbonisation will create general incentives to decarbonise, e.g., through carbon pricing, as well as explicit support for renewable hydrogen and power-to-X technologies.

In markets and geographies where all three are present, using northwestern Europe as an example, we see a future market starting with local peer-to-peer projects, where renewable hydrogen projects are developed to match a specific use-case, and with the participation of both producers and consumers.

In the run-up to 2030, we hope these projects will proliferate and, where successful, grow in size and scope into regional hydrogen clusters. These might typically include one or more large-scale electrolysers connected to a dedicated hydrogen infrastructure, perhaps including storage, with hydrogen being used for large-scale e-fuel production.

In the longer term, beyond 2030, such clusters could connect to a national or even trans-national "backbone" – a hydrogen transmission grid and market. Here, hydrogen produced from electrolysers situated near areas with large renewable resource potential could be piped to industrial users, thereby also saving costs on electrical transmission infrastructure.



Project overview of Westküste 100

Source: Ørsted

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