Northwest European Hydrogen Monitor

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 31 member countries, 11 association countries and beyond.

Source: IEA.
International Energy Agency
Website: www.iea.org

IEA member countries:

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea
Lithuania
Luxembourg
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Republic of Türkiye
United Kingdom
United States

The European Commission also participates in the work of the IEA

IEA association countries:

Argentina
Brazil
China
Egypt
India
Indonesia
Morocco
Singapore
South Africa
Thailand
Ukraine

Abstract

Northwest Europe is at the forefront of renewable and low-emission hydrogen development. This region accounts for around half of Europe's total hydrogen demand, and has a vast and untapped renewable energy potential in the North Sea. It also has a well-developed, interconnected gas network which could be partially repurposed to facilitate the transmission and distribution of renewable and low-emission hydrogen from production sites to demand centres.

The development of renewable and low-emission hydrogen [1] in Northwest Europe is expected to gradually scale up in the short- to medium-term to reach a low-emission hydrogen production capacity target of over 30 GW by 2030. Most of the low-emission hydrogen projects are currently in the early stages of development. Their success will depend to a large extent on the supporting policy and regulatory frameworks, and continuous monitoring of progress. The cost-efficient development of renewable and low-emission hydrogen markets will also necessitate a regional approach in order to maximise the existing synergies amongst national markets.

This is the first edition of the Northwest European Hydrogen Monitor. It aims to provide an annual update of the renewable and low-emission hydrogen market developments in Northwest Europe. It is the result of a collaboration among the countries involved in the Hydrogen Initiative of the Clean Energy Ministerial (CEM-H2I) workstream entitled, "Roundtable on the North-West European Region" and the hydrogen working group of the Pentalateral Forum.

The countries analysed in this monitor are: Austria, Belgium, Denmark, France, Germany, Luxemburg, the Netherlands, Norway, Switzerland and the United Kingdom. Market monitoring is accompanied by a continuous dialogue with key stakeholders to facilitate information exchange and data collection.

[1] When the term "low-emission hydrogen" is used, the International Energy Agency refers to hydrogen produced via electrolysis where the electricity is generated from a low-emission source (renewables or nuclear), biomass or fossil fuels with carbon capture usage and storage (CCUS). This does not necessarily reflect the official definitions of the countries involved in the Monitor on the carbon intensity or sustainability of hydrogen production methods.

Table of contents

Executive summary

Low-emission hydrogen can play a significant role in decarbonising existing gas and energy systems and will be critical to the countries' efforts to achieve a climate neutral society. Besides its environmental benefits, low-emission hydrogen can already help reduce reliance on fossil fuel imports in the medium-term.

Northwest Europe[2] leads the development of low-emission hydrogen as a new energy carrier. This region accounts for around half of Europe's total hydrogen demand, and has a vast and untapped renewable energy potential in the North Sea. It also has a well-developed, interconnected gas network which could be partially repurposed to facilitate the transmission and distribution of renewable and low-emission hydrogen from production sites to demand centres.

When the term "low-emission hydrogen" is used, the International Energy Agency refers to hydrogen produced via electrolysis where the electricity is generated from a low-emission source (renewables or nuclear), biomass or fossil fuels with carbon capture usage and storage (CCUS). This does not necessarily reflect the official definitions of the countries involved in the Monitor on the carbon intensity or sustainability of hydrogen production methods.

Northwest Europe has set a target of 30-40 GW of electrolyser capacity by 2030

The adoption of hydrogen strategies, including medium- and long-term targets, is considered essential in providing the necessary impetus and guidance for the developments of hydrogen markets.

In Northwest Europe, nine of the ten countries included in the Monitor have already developed hydrogen strategies or roadmaps, and six have adopted specific production capacity targets up to 2030. Following Russia's unprovoked invasion of Ukraine, several Northwest European countries have doubled, or are considering raising their production targets. While most of the countries have adopted production targets for electrolytic hydrogen, Norway has opted for a technology-neutral approach. In all, the Northwest European countries target electrolyser capacity deployment of between 30 and 40 GW by 2030.

Low-emission hydrogen production could fully replace unabated, fossil-fuel based hydrogen by 2030 in Northwest Europe…

If all announced and planned projects become commercially operational, Northwest Europe's low-emission hydrogen production

[2] The Northwest European Hydrogen Monitor covers the following countries: Austria, Belgium, Denmark, France, Germany, Luxembourg, Netherlands, Norway, Switzerland and the United Kingdom.

capacity is expected to reach close to 14 Mt H_2/yr by 2030. This would mean that Northwest Europe would account for around 80% of the total expected production capacity of low-emission hydrogen production in OECD Europe by 2030.

Electrolytic hydrogen is set to take the lead, meeting approximately two-thirds of the total planned low-emission hydrogen production capacity by 2030, whilst the share of fossil-fuel based hydrogen projects, equipped with CCUS would account for about one-third of the projected production capacity. Taking into account assumptions relating to efficiency and utilisation factors, Northwest Europe's low-emission hydrogen production could reach close to 6.2 Mt H_2/yr by 2030, potentially enabling the replacement of the region's current use of unabated, fossil-fuel based hydrogen.

…however, over 95% of the low-emission hydrogen projects are in the early stages of development, highlighting the need for support mechanisms and subsidy schemes

According to the IEA's Hydrogen Projects Database, less than 5% of the planned capacity by 2030 has reached a final investment decision (FID) or is under construction. Over 95% of these projects are in various early stages of development, i.e. either conceptual or subject to feasibility studies.

This highlights the importance of subsidy schemes and support mechanisms. The scale-up of low-emission hydrogen will require an effective framework of support mechanisms and subsidy schemes along the entire value chain, i.e. R&D, production, transportation and demand creation. Public funding programmes and state-backed risk-sharing mechanisms (such as contracts for difference) can help to de-risk investment and improve the economic feasibility of low-emission hydrogen projects. Demand creation should be used as a key instrument to stimulate investment, including via quotas and public procurement rules.

This Hydrogen Monitor provides a detailed overview of the various subsidy schemes and support mechanisms that are available, and are given at both the level of the European Union and at the national level in Northwest European countries.

Northwest Europe is playing a key role in developing international trade in low-emission hydrogen

Based on the export-oriented projects currently under development, global hydrogen trade could reach 12 Mt H_2/yr by 2030. However, because off-take agreements and import contracts are lagging behind, the projects which have reached a more advanced stage of development represent only 0.2 Mt H_2/yr.

The role of ports in the Northwest European region will be pivotal in the development of a new import market for clean hydrogen. Major ports in the Netherlands, namely the Port of Rotterdam and the Port of Amsterdam, have plans to import a combined amount of more than 5 Mt H_2 by 2030.

In Germany, the H2Global auction-based mechanism will facilitate the conclusion of long-term import contracts for low-emission hydrogen and hydrogen derivatives. The German government has approved a grant of EUR 900 million for the scheme. Notably, the German government's draft budget for 2023 includes a budget of EUR 3.6 billion for H2Global. In October 2022, the Netherlands expressed its interest in joining H2Global.

The scale-up of international trade in hydrogen and hydrogen derivatives will also require the construction of transport infrastructure. Liquefied hydrogen trade still requires technology development. There is only one demonstration project for hydrogen transport in the world. It originates in Australia and goes to Japan, with the first shipment delivered in February 2022. In contrast to hydrogen, ammonia is already a widely traded commodity. However, using it as a hydrogen carrier would require a significant expansion of the global supply chain. For example, using ammonia as a hydrogen carrier to achieve the REPowerEU's target of 10 Mt/yr hydrogen imports by 2030, would require over 60 Mt/yr of ammonia, or three times its current global trade volume. Moreover, if the end-uses require hydrogen, ammonia must be reconverted to hydrogen via ammonia cracking, which is an energy-intensive process (consuming around 30% of the energy content of the ammonia).

Northwest Europe's hydrogen network is set to expand almost eight-fold by 2030

Northwest Europe has around 1 600 km of hydrogen pipelines, accounting for over 95% of the hydrogen pipelines operational in Europe. Most are closed systems owned by large merchant hydrogen producers and are concentrated near industrial consumer centres.

Achieving the ambitious targets in terms of low-emission hydrogen deployment will require accelerating the development of hydrogen infrastructure for transport and storage. Based on the current targets set by Northwest European countries, the region's hydrogen network could increase by almost eight-fold to over 12 000 km by 2030. Repurposing gas pipelines to hydrogen service could cut investment costs by 50-80% compared to the cost of building new pipelines.

This in turn, could translate into lower transmission tariffs and improve the cost-competitiveness of low-emission hydrogen. According to first estimates, close to two-thirds of the hydrogen pipelines operational in 2030 would be repurposed natural gas pipelines.

Low-emission hydrogen could enhance overall energy system flexibility by balancing short-term supply variability and meeting seasonal demand swings, thereby improving energy supply security. To fulfil this role, low-carbon hydrogen deployment will need to be coupled with development of cost-effective, large-scale and long-term storage solutions. Several underground hydrogen storage projects are currently under various phases of development in Northwest Europe.

Developing a harmonised regulatory framework will be crucial to enabling regional trading in low-emission hydrogen

Harmonised regulatory frameworks for hydrogen enable the development of regional trade in low-emission hydrogen. They would also benefit cross-regional synergies in terms of production and demand creation.

The European Commission published its Hydrogen and Decarbonised Gas Market Package in December 2021. This package lays down the foundations for the integration of low-emission gases, including hydrogen, into the broader European gas system. The proposed regulation provides guidelines on the gradual implementation of non-discriminatory third-party access to hydrogen networks, blending limits, tariffs, network codes and operational transparency.

Regulatory standards for low-emission hydrogen are emerging in Northwest Europe. In the United Kingdom, the Low Carbon Hydrogen Standard Policy defines low-carbon hydrogen with an emissions intensity lower than 2.4 kg CO_2-eq/kg of produced hydrogen. Hydrogen producers seeking support from certain UK Government programmes must adhere to this standard.

In the European Union, the European Commission proposed an emissions threshold of 3.38 kg CO_2-eq/kg H_2, which is 70% lower than that of the predefined fossil fuel comparator including transport and other non-production emissions. Harmonised approaches to hydrogen certification schemes – providing evidence of the emissions intensity of a given unit of hydrogen – will be key in establishing a regional hydrogen market in Northwest Europe amidst tightening regulatory standards. Similarly, hydrogen blending thresholds should be harmonised to facilitate regional trading.

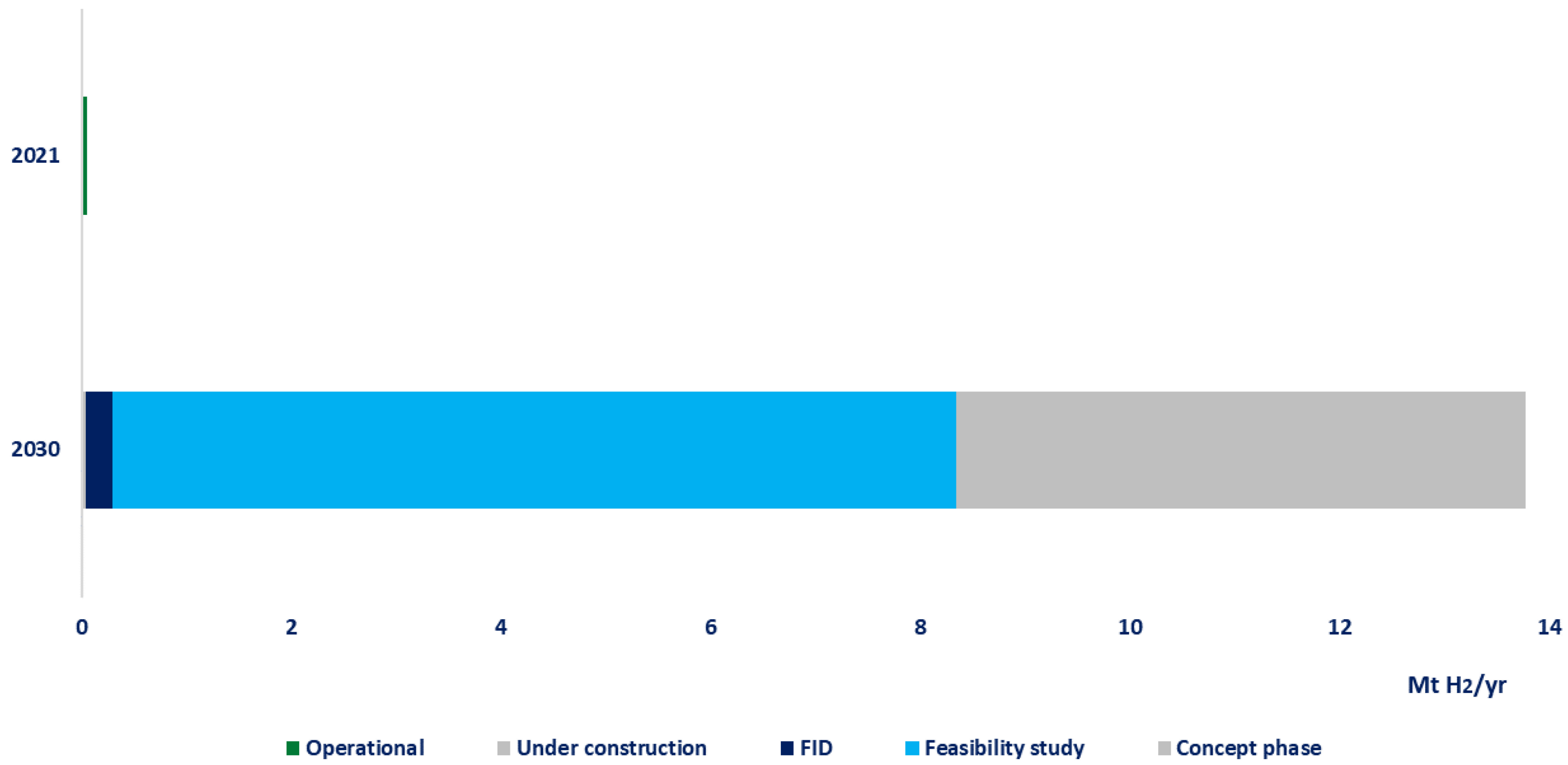
Renewable electrolytic hydrogen would be competitive with unabated gas-based hydrogen by 2030

The cost of unabated gas-based hydrogen rose above the estimated cost of wind-based electrolytic hydrogen in 2022 amidst the surge in gas prices to record levels. Natural gas markets are expected to remain tight until the mid-2020s, and this situation could accelerate the transition towards renewables-based electrolytic hydrogen.

Our projections indicate that renewable electrolytic hydrogen will be competitive with gas-based hydrogen by 2030, even if it is assumed that natural gas prices return to their pre-crisis average levels.

Over 95% of Northwest Europe's planned low-emission hydrogen production capacity is in the early stages of development and will require policy support to take off

Low-emission hydrogen project capacity in Northwest Europe by status, 2021-2030



Source: IEA (2022), Hydrogen Projects Database.

Hydrogen policies and targets

Hydrogen targets in Northwest Europe are being scaled up

The adoption of hydrogen strategies, including medium- and long-term targets, are considered essential to provide the impetus and guidance necessary for the development of hydrogen markets.

The European Union's Hydrogen Strategy, published in July 2020, provided a vision to create a European hydrogen ecosystem and to scale up production and infrastructure to an international dimension. The Strategy spans three phases for the development of low-emission hydrogen:

- In the first phase, from 2020 up to 2024, the strategic objective is to install at least 6 GW of renewable hydrogen electrolysers in the EU, with the aim to produce up to 1 Mt of renewable hydrogen in order to decarbonise existing hydrogen production (e.g. in the chemical sector).
- In the second phase, from 2025 to 2030, hydrogen is expected to become an intrinsic part of an integrated energy system. The target is to install at least 40 GW of renewable hydrogen electrolysers by 2030.
- In the third phase, from 2030 onwards and towards 2050, renewable hydrogen technologies are expected to reach maturity and be deployed at large scale to reach all hard-to-decarbonise sectors where other alternatives might not be feasible or have higher costs.

In Northwest Europe, of the ten countries included in the Monitor, six have already adopted specific production targets by 2030. Altogether, Northwest European countries foresee electrolyser capacity deployment between 30 and 40 GW by 2030.

Since Russia's unprovoked invasion of Ukraine, several Northwest European countries have doubled, or are considering increasing their production targets. Similarly, the European Union has raised its target for hydrogen production from 5.6 Mt to 10 Mt by 2030, complemented by 10 Mt of imports. Depending on the end-use sector, the rapid scale-up of low-emission hydrogen could replace 34-68 bcm/yr of natural gas by 2030 (equating to 25%-50% of the European Union's Russian piped imports in 2021). Similarly, the United Kingdom in April 2022 doubled its ambition for low-carbon hydrogen production capacity from 5 GW to up to 10 GW by 2030, with at least half of this from electrolytic hydrogen.

The following section provides an overview of the key hydrogen policies and production targets adopted by the Northwest European countries covered in this Monitor.

Most Northwest European countries have adopted hydrogen strategies

Hydrogen strategies and roadmaps adopted in Northwest Europe, 2020-2023

Sources: IEA analysis based on various policy documents (hydrogen strategies, roadmaps and papers).

Austria targets 1 GW electrolyser capacity by 2030

Austria published its National Hydrogen Strategy in June 2022. The main targets of the strategy are:

- Installation of 1 GW electrolyser capacity for the production of renewable hydrogen by 2030.

  1. Replacing fossil-based hydrogen with climate-neutral hydrogen in energy intensive industries: 80% of current consumption of fossil-based hydrogen until 2030.
  2. Creation of a supporting framework for the production of renewable hydrogen.
  3. Establishing the production of hydrogen as an integral part of the energy system.
  4. Development of a targeted hydrogen infrastructure.
  5. Enhancing international partnerships for climate-neutral hydrogen.
  6. Strengthening the innovation and technology potential in Austria through focused development of hydrogen-technologies.

The use of hydrogen must contribute to the decarbonisation of the energy system and to the achievement of climate neutrality in Austria by 2040. Therefore, a focused application in strategic priority sectors is key. The contribution of hydrogen to reach climate neutrality is maximised by focusing on sectors which are otherwise difficult to decarbonise, such as energy-intensive industries. In addition, energy efficiency and cost-effectiveness are essential guiding principles of the Hydrogen Strategy regarding the transformation of the energy system.

In order to reach these targets, the strategy foresees a number of measures, divided into eight policy fields of action:

1. Enabling a timely market ramp-up through flagship projects.

2. Support and incentives for the production of renewable hydrogen.

3. Incentivising market-based business models and the targeted application of climate-neutral hydrogen in industry.

4. Establishing an infrastructure for hydrogen and creating import opportunities.

5. Targeted advancement of hydrogen-technologies in the area of mobility.

6. Intensifying research and development activities.

7. Creation of the national hydrogen-platform H2Austria.

8. Addressing Austria's priorities at both the European and international levels.

Belgium adopted its Federal Hydrogen Strategy in 2021

In Belgium, both Wallonia and the Flanders published hydrogen papers, although without setting quantitative targets. In Wallonia, the industry sector published a government-approved hydrogen roadmap in 2018. In Flanders, the Minister for Innovation presented a Hydrogen Vision for Flanders in 2020.

The Belgian Federal Hydrogen Vision and Strategy was approved by the Council of Ministers in October 2021. An updated version of the Federal Hydrogen Vision and Strategy was published in October 2022.

The federal hydrogen policy is part of the federal government's broader energy policy, which aims to achieve the European climate neutrality goals. The strategy therefore focuses particularly on the importance of renewable hydrogen and its potential to decarbonise industry and transport. More specifically, the strategy is based on four pillars:

- positioning Belgium as an import and transit hub for renewable molecules in Europe
- expanding Belgium's leadership in hydrogen technologies
- establishing a robust hydrogen market
- investing in cooperation as a key success factor.

In its National Recovery and Resilience Plan, Belgium set the target to have at least 0.15 GW of electrolysis capacity in operation by 2026. According to the updated version of the Federal Hydrogen Vision and Strategy, the total domestic demand for both H_2-molecules and H_2-derivatives will increase to 125-200 TWh/year in Belgium by 2050 (bunkering fuels included).

Denmark targets 4-6 GW of electrolyser capacity by 2030

Denmark adopted its Power-to-X Strategy in March 2022 to accelerate the conversion of electricity into green hydrogen and other e-fuels over ten years.

The strategy aims to promote energy exports in the form of green hydrogen and e-fuels. With the announcement, Denmark aims to build 4-6 GW of electrolysis capacity by 2030. The strategy will support the use of green hydrogen particularly in hard-to-abate sectors like shipping and aviation, as well as heavy road transport and industry.

The Power-to-X Strategy includes four objectives for promoting Power-to-X in Denmark:

- Power-to-X must be able to contribute to the realisation of the objectives in the Danish Climate Act.
- The regulatory framework and infrastructure must be in place to allow Denmark's strengths to be utilised and for the Power-to-X industry to operate on market terms in the long run.
- The interaction between Power-to-X and the Danish energy system must be improved.
- Denmark must be able to export Power-to-X products and technologies.

Reaching 4-6 GW of electrolysis capacity by 2030 is expected to entail CO_2 emission reductions of 2.5-4.0 Mt.

France's Hydrogen Strategy targets 6 GW of electrolyser capacity by 2030

France was one of the first European countries to present a hydrogen plan in 2018. The National Strategy for the Development of Decarbonised and Renewable Hydrogen in France was published in September 2020 and accompanied by a commitment of EUR 7.2 billion of investments over the next decade. The 2030 targets for the decarbonised hydrogen development in France include:

- 6.5 GW of water electrolysis capacity
- clean mobility, in particular for heavy-duty vehicles, with the goal to abate more than 6 Mt of CO_2 emissions by 2030
- an industry spanning the entire value chain of hydrogen and creating between 50 000 and 150 000 jobs.

Germany targets 10 GW electrolyser capacity by 2030

Germany published its National Hydrogen Strategy (NWS) in June 2020. The Federal Government expects that around 90 to 110 TWh of hydrogen will be needed by 2030. In order to cover part of this demand, Germany plans to establish up to 5 GW of generation capacity including the offshore and onshore energy generation facilities needed for this. The implied hydrogen import gap by 2030 would be in the range of 62 to 82 TWh/yr. The coalition agreement targets 10 GW electrolyser capacity by 2030.

With the NWS, the federal government has published a number of different goals and ambitions. The 38 measures of the NWS Action Plan are derived from these overarching goals and ambitions. The goals published with the NWS are very general and correspond to priority fields of action. Thus, they do not yet form a sufficient basis for monitoring the implementation of the NWS. For this purpose, the goals need to be made more concrete. As part of the monitoring process, the ministries and departments responsible for implementing the NWS have therefore defined the following seven strategic goals in a next development step:

1. Creation of regulatory framework conditions for the market ramp-up of hydrogen, including uniform sustainability standards.

2. Building up of generation capacities for green hydrogen and derivatives to 5 GW by 2030.
3. Completion of infrastructure for hydrogen value chains, including hydrogen filling stations.
4. Improvement of the competitiveness of green hydrogen and its derivatives.
5. Progress in decarbonising the transport and industry sectors through the use of hydrogen.
6. Germany is positioned as a leading provider in the field of green hydrogen production and application technologies.
7. Establishment of international cooperation with regard to hydrogen imports and technology exports.

The Federal Government published a progress report on the NWS on 2 June 2022. The report presents developments and achievements in the field of hydrogen promotion for the reporting period June 2020 to December 2021. It shows the impact of the implemented measures and developments on the way to the market ramp-up of the German hydrogen economy.

The federal government is currently working on revising the hydrogen strategy in order to ensure that the targets from the coalition agreement (e.g. increasing the electrolyser capacity to 10 GW by 2030) are met. Publication is planned for the end of 2022.

Luxembourg's Hydrogen Strategy targets hard-to-decarbonise sectors

Luxembourg's Hydrogen Strategy was presented in September 2021, with a focus on sectors that are difficult to decarbonise through direct electrification, such as heavy industry. Luxembourg consumes about 450 tonnes of fossil hydrogen per year. The immediate objective is to substitute fossil hydrogen with renewable hydrogen to cut GHG emissions by over 5 kt/yr.

The strategy proposes the following seven key measures to promote the production, import and use of renewable hydrogen:

1. Contributing to the definition of the legal and regulatory framework at the EU level.
2. Cooperating with the EU member states and third countries.
3. Identifying opportunities in Luxembourg research and innovation.
4. Concrete flagship projects to be studied and carried out.
5. Prioritising actions towards targeted decarbonisation by renewable hydrogen.
6. Developing instruments for a renewable hydrogen market.
7. Implementing and continuously improving Taskforce H2 Luxembourg.

The Netherlands plans to increase its renewable hydrogen production and develop national-wide hydrogen infrastructure by 2030

The Netherlands' strong hydrogen ambitions, stated back in 2019 in the National Climate Agreement and reinforced in 2020 with its Hydrogen Strategy, continue to receive supportive legislation and funding. The Hydrogen Strategy focuses on scaling up hydrogen production by means of electrolysis and setting up a nation-wide hydrogen transport infrastructure. The year 2021 was marked by strong political commitment for hydrogen in the form of funding for large infrastructure projects. The new government's coalition agreement presented in December 2021 reinforced the commitment to achieve a clean energy system in which hydrogen plays a fundamental role, by providing a EUR 35 billion Climate Fund of which at least EUR 15 billion will be destined for the expansion of the production capacity of renewable energy carriers such as hydrogen. This materialised in 2022 with large budget commitments for hydrogen via the Climate Fund and National Growth Fund. In addition, the government is incentivising the development of electrolysis projects in combination with tenders for new offshore wind farms.

The Netherlands' short- to medium-term targets are as follows:

- 500 MW of electrolyser capacity in 2025 and at least 3-4 GW electrolyser capacity in 2030 (the government is evaluating an increase of the current electrolyses capacity target in 2030).
- The targets for use of renewable H_2 in the industry will align with the European Union's Fit for 55 target.
- Mobility: 50 H_2 refuelling stations in 2030, use of renewable hydrogen in line with the European Union's Fit for 55 target.
- Home heating pilot schemes for approximately 1 000 homes by 2030.
- Development of national hydrogen backbone: approximately 750-1 000 km and approximately four salt caverns for hydrogen storage to be available by 2030.

A Hydrogen Roadmap is being developed within the National Hydrogen Programme and will be published in November 2022.

Norway adopted an export-oriented Hydrogen Strategy

Norway adopted its Hydrogen Strategy in June 2020 and its Hydrogen Roadmap in June 2021. Both documents lay the necessary foundation for Norway to become a low-emissions society by 2050. Norway does not have a specific production target and has a technology-neutral approach.

According to its Strategy, hydrogen will be an important energy carrier, produced with zero or low emissions. It will help decarbonise sectors that are difficult to electrify, such as the transport sector, mainly maritime transport, and the industrial sector. The Hydrogen

Roadmap sets different, but not fully quantified, targets for hydrogen development in Norway:

- collaborate with the private sector to develop five hydrogen hubs for maritime transport
- develop “one or two” industrial projects associated with hydrogen production plants
- establish five to ten pilot projects for the development and demonstration of new, more cost-effective hydrogen solutions and technologies.

Switzerland is working on its Hydrogen Roadmap

The Swiss Hydrogen Roadmap is currently under preparation and a first outline will be published in 2023. With a view to achieving the net-zero target by 2050, the Federal Council is mandated to present a report on the importance of green hydrogen in the quest to reduce energy-related CO_2 emissions and for securing Switzerland’s long-term energy supply. The Roadmap is intended to reveal the sectors in which the use of green hydrogen is viable (mobility, industry, buildings) and which regulatory framework conditions must be fulfilled in order to ensure the gradual development of a clean domestic hydrogen economy.

The Roadmap will also provide a view of the scale and cost of the reconversion of green hydrogen into electricity, as well as how it could contribute to the security of electricity supply during the heating season. In addition, it will clarify to what extent the existing gas distribution network can become part of a future hydrogen network. This requires an analysis of future hydrogen and other power-to-X production sites as well as sites for the extraction and transport of CO_2. Finally, the Roadmap will provide a view of how the future Swiss hydrogen market can be connected to the EU’s internal hydrogen market.

In addition, a hydrogen paper was published in September 2022 by the Swiss Federal Office of Energy. It presents nine theses on the goals, role and areas of application of hydrogen in Switzerland.

The United Kingdom doubled its ambition for low-emission hydrogen production capacity to up to 10 GW by 2030

In its Hydrogen Strategy published in August 2021, the United Kingdom set an ambition of 5 GW of low carbon hydrogen production capacity by 2030. However, in April 2022, in the British Energy Security Strategy, the production capacity ambition was doubled to up to 10 GW by 2030, with at least half of this coming from electrolytic hydrogen. The Hydrogen Investor Roadmap was also published in April 2022, following several public consultations on the design of funding schemes.

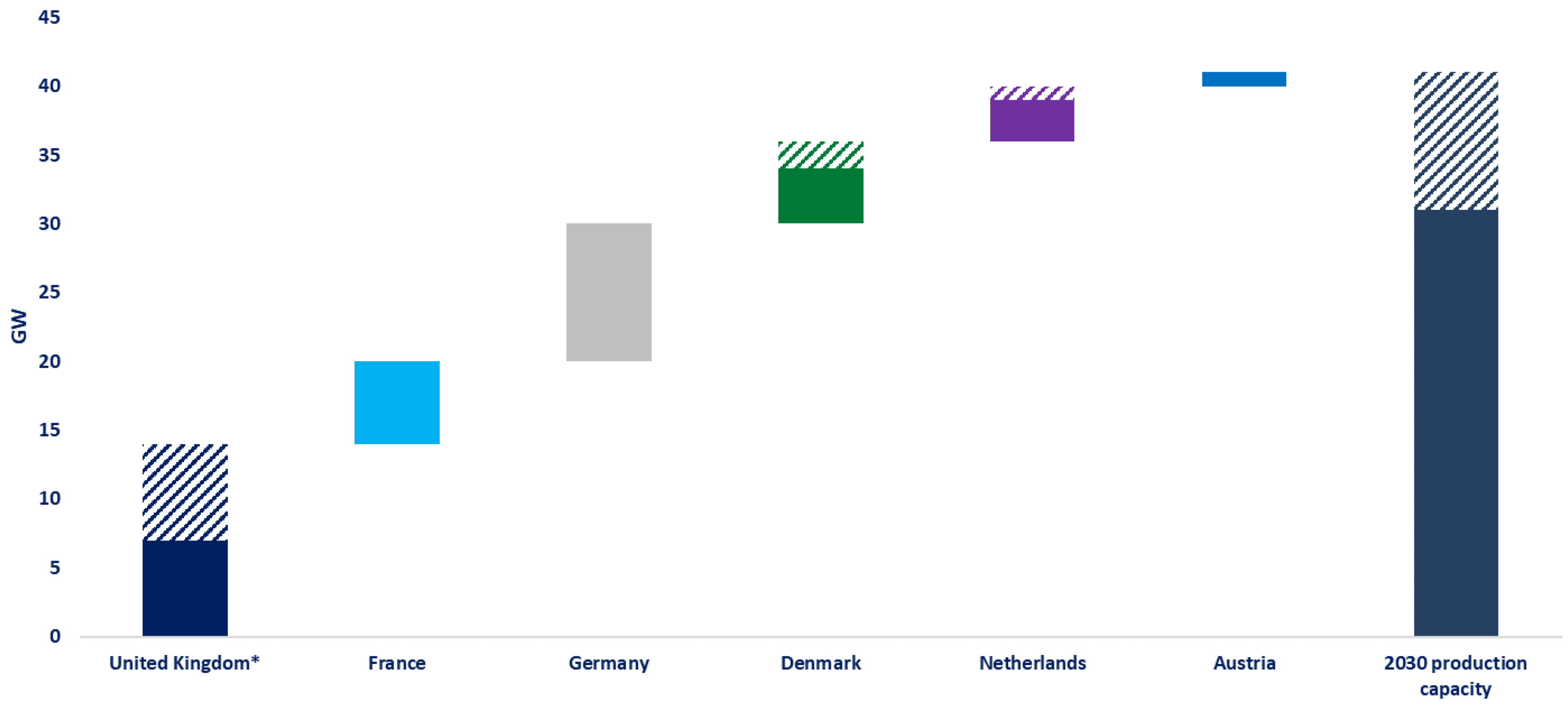
The United Kingdom’s main ambitions for hydrogen development are summarised below:

- 1 GW of electrolytic hydrogen capacity in construction or operational by 2025, with up to 2 GW of hydrogen production capacity overall (including CCUS-enabled hydrogen) in operation or construction by 2025.

- Deploy CCUS in at least two industrial clusters by the mid-2020s, identified through the CCUS Cluster Sequencing Process, and in four clusters by 2030.
- Up to 10 GW of low carbon hydrogen production capacity by 2030, with at least half of this from electrolytic hydrogen. The UK Government is also supporting a variety of low carbon hydrogen production methods, including electrolytic and CCUS-enabled hydrogen. The Hydrogen Strategy Update to the Market provided further discussion on the potential of a wide range of production routes, including nuclear-enabled and biomass/waste-related technologies. The United Kingdom's Low Carbon Hydrogen Standard sets a maximum threshold for the amount of greenhouse gas emissions allowed in the production process for hydrogen in order for it to be considered "low-carbon hydrogen".
- The Scottish Government has set an ambition of 5GW installed hydrogen production capacity by 2030.
- The UK Government is supporting industry to deliver a hydrogen neighbourhood trial by 2023, a village trial by 2025 and plans by 2025 for a possible hydrogen-heated town that would be delivered by the end of the decade. These trials, and a range of other R&D and testing projects will inform strategic decisions in 2026 on the role of 100% hydrogen in the decarbonisation of heat.
- The UK Government is aiming to reach a policy decision in 2023 on whether to allow the blending of up to 20% hydrogen by volume into the gas distribution networks.

Northwest Europe targets at least 30 GW of installed electrolysis capacity by 2030

Electrolysis capacity targets in Northwest Europe by 2030



* The United Kingdom has a target of low-carbon hydrogen production of 10 GW, with at least 5 GW being electrolysis-based, by 2030. The values for the UK have been estimated assuming 70% efficiency.

Note: The shaded area marks targets under discussion and/or higher range of announced targets.

Sources: IEA analysis based on various policy documents (hydrogen strategies, roadmaps and papers).

Subsidy schemes and support mechanisms

Subsidies and support mechanisms will be key for the early deployment of low-emission hydrogen in Northwest Europe

The scale-up of low-emission hydrogen will require an effective framework of subsidy schemes and support mechanisms along the entire value chain, i.e. R&D, production, transportation, storage and demand creation. The following section provides an overview of the various subsidy schemes and support mechanisms available that are provided at the European Union level and at the national level in each of the Northwest European countries.

European Union

Several EU funding programmes have been established for hydrogen projects.

The **Innovation Fund**, financed from the Emission Trading System revenues, leverages private financing for large EU hydrogen projects through grants in multiple rounds. It aims at supporting commercial demonstration, with the aim of bringing market industrial solutions that will help decarbonise Europe and support its transition to climate neutrality. The Innovation Fund supports up to 60% of the relevant costs of projects. For large-scale projects, the relevant costs are the net extra costs (CAPEX and OPEX) linked to the implementation during the ten years following a project's entry into operation. In the first call for large-scale projects, three projects out of a total of seven selected projects had important hydrogen components (HYBRIT, SHARC and Kairos@C). In the second call for large-scale projects, seventeen projects were invited for the EUR 1.8 billion grant preparation, of which three pertain to hydrogen production. All three production projects based in the Netherlands have capital costs above EUR 7.5 million and are sufficiently mature for deployment. The third call for large-scale projects will be launched in late 2022, accompanied by additional support for hydrogen application in industry, innovative clean tech manufacturing including electrolysers, fuel cells and heat pumps, and mid-sized demonstration projects.

In the State of the Union speech of September 2022, the President of the European Commission proposed the creation of a **Hydrogen Bank**. The Bank would use the resources available under the Innovation Fund and would help guarantee the purchase of hydrogen. The Hydrogen Bank would aim to invest EUR 3 billion to help build the future market for hydrogen.

EU member states could leverage the **Recovery and Resilience Facility (RRF) programme** to support low-emission hydrogen projects. This programme would provide up to 37% of EUR 338 billion in grants and EUR 386 billion in loans for green transition, including low-emission hydrogen. The RRF is a non-repayable financial support and loan. The assessment of national RRF plans is on-going. These mechanisms, complemented with national risk-sharing schemes and credit enhancement are necessary for large-scale demonstration projects like trade.

To develop an intra-European hydrogen market, the European Commission agreed in 2020 to launch **"Important Projects of Common European Interest" (IPCEIs)** for hydrogen value chains, covering storage, transmission and distribution as well as application in industrial sectors. The IPCEIs consist of large projects that seek to address market and regulatory failures within the EU, for which the prerequisites include the collaboration of several EU countries and engagement of private financing by the beneficiaries.

In July 2022, fifteen EU Member States – Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Italy, Netherlands, Poland, Portugal, Slovak Republic and Spain – received Commission approval to provide up to EUR 5.4 billion in public funding for 41 hydrogen technology value chain projects called the **IPCEI Hy2Tech.** In September 2022, the Commission approved a second IPCEI to support research and innovation, first industrial deployment and construction of relevant infrastructure in the hydrogen value chain. The project, called "**IPCEI Hy2Use**" was prepared and notified jointly by thirteen Member States: Austria, Belgium, Denmark, Finland, France, Greece, Italy, Netherlands, Poland, Portugal, Slovakia, Spain and Sweden. The Member States will provide up to EUR 5.2 billion in public funding, which is expected to unlock an additional EUR 7 billion in private investments.

The **Connecting Europe Facility for Energy (CEF-E)** finances Projects of Common Interest as identified under the TEN-E regulation. The TEN-E Regulation currently in force does not include hydrogen infrastructure, electrolysers, or smart gas grids as eligible projects. In December 2020, the Commission presented a legislative proposal to revise the TEN-E Regulation. The Commission's proposal envisages support for the roll-out of cross-border hydrogen infrastructure, certain types of electrolysers and smart gas grids as new projects of common interest (PCI) categories. Negotiations with the European Parliament and the Council are currently under way, with a political agreement still to be expected. The **Connecting Europe Facility for Transport (CEF-T)**, which came into force in 2021, finances hydrogen refuelling infrastructure for all modes of transport. Both CEF-E and CEF-T generally co-finance up to 50% of the CAPEX.

EU Member States receiving allocations from the **European Regional Development Fund (ERDF) and the Cohesion Fund (CF)** can spend up to 30% and 37%, respectively, to support innovation and entrepreneurship geared to the transition into a net-zero economy. Several hydrogen projects have already received funding through these support schemes. Support to hydrogen projects under the **Just Transition Fund** could be available in countries that diversify local economies or reskill/upskill workers away from fossil fuel production, transport, distribution and storage. The **Modernisation Fund,** supporting ten lower-income EU countries' transition to a net-zero economy can support retrofitting natural gas pipelines for hydrogen, developing district heating pipelines, storage, grids, hydrogen-mobility, high-efficiency hydrogen combined heat and power (CHP) as well as the production and use of renewable-based hydrogen. The Modernisation Fund is funded from the auctioning of 2% of EU Emissions Trading System (ETS) revenues and can cover up to 70% of relevant costs for non-priority investments via grants, premiums, guarantee instruments, loans or capital injections.

For more early-stage technologies, the European Commission provides research and innovation (R&I) opportunities through the **Horizon Europe 2021-2027 Programme**, administered in the form of grants, prizes and procurement. Pillar II Climate, Energy and Mobility supports several hydrogen R&I partnerships, including the Clean Hydrogen Partnership, which invests EUR 102 million for renewable hydrogen and EUR 49 million for hydrogen storage and distribution. Pillar III oversees the deployment industry applications and technologies, including hydrogen.

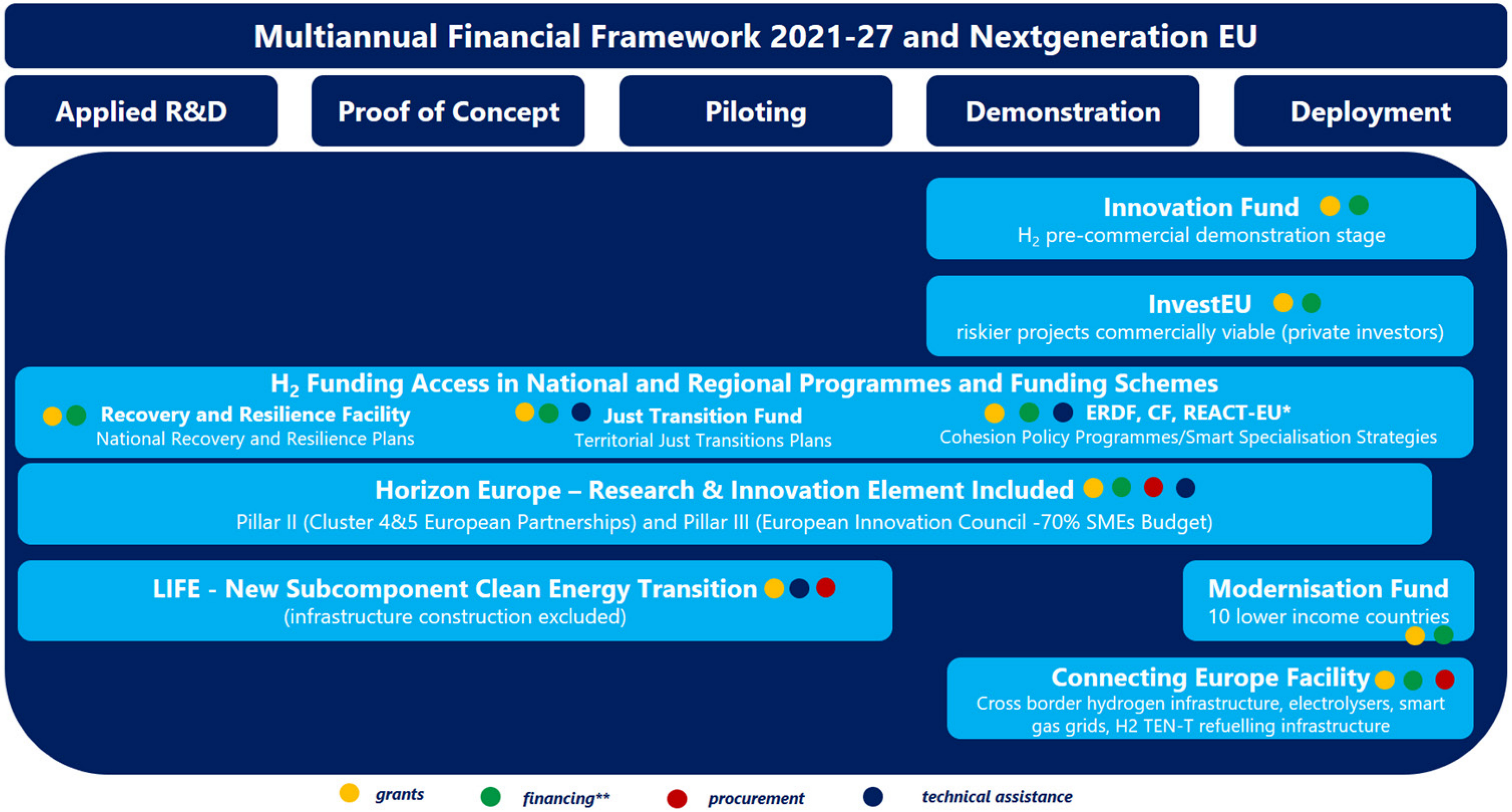
In addition, the EU facilitates dialogue and offers in-house advisory through the **InvestEU Fund** and the European Clean Hydrogen Alliance. The InvestEU Fund is expected to mobilise more than EUR 372 billion of public and private investment through an EU budget guarantee of EUR 26.2 billion that backs the investment of financial partners such as the European Investment Bank (EIB) Group and others. Clean hydrogen is part of the main policy priority of the Invest EU programme. Repayable support can be provided to projects targeting the use of low-carbon gas such as clean hydrogen production, commercial-scale supply, on-site storage, low-carbon technologies and all modes of transport from the innovation stage to proven technological solutions at the deployment stage, as well as equity type investments. The InvestEU fund is accompanied by an Advisory Hub which can support potential project applicants seeking financial advisory support for InvestEU or other financial envelopes. In 2019 the Hydrogen Council and the EIB launched the InnovFin Advisory Programme to advise companies to structure their R&I projects in ways which improve their access to riskier projects though corporate loans, project finance or venture debt.

The **European Clean Hydrogen Alliance** was established in 2020 and organises a bi-annual roundtable for over 1 500 stakeholders to discuss the key challenges for large-scale deployment. Through the Alliance, the EIB and European Institute of Innovation and Technology (EIT), InnoEnergy advises project promoters on bankability and de-risking strategies, investment readiness and due diligence preparations, and invests in individual projects.

Countries can combine EU funds with national financial measures via energy and carbon taxes, penalties and subsidies in the form of grants, tax credits, low-cost loans and feed-in tariffs.

Several EU funding programmes are available for hydrogen projects

Key EU funding programmes available for hydrogen under the Multiannual Financial Framework, 2021-2027



****Regional Cohesion Policy Funds: European Regional Development Fund; Cohesion Fund; REACT-EU is part of the recovery funds.***
***** Equity/loans/guarantees.***

Sources: IEA analysis based on European Commission (2021), Hydrogen Public Funding Compass.

Austria

In Austria, a number of support measures have been implemented through the Renewable Expansion Act (EAG) in 2021. The act foresees EUR 40 million per year in investment subsidies for electrolysis facilities producing renewable hydrogen (minimum of 1 MW capacity, with a focus on industrial use). The subsidy scheme is expected to run until 2030. Austria is creating a new funding program for the transformation of the industry, which will include hydrogen projects (EUR 2.975 billion until 2030).

Hydrogen is part of the funding programme, "Umweltförderung im Inland" (UFI), which provides funding for pilot and demonstration facilities (EUR 150 million per year until 2025). Hydrogen projects can also benefit from investment subsidies under the framework of the Recovery and Resilience Facility (EUR 100 million until 2026). The "Vorzeigeregion Energie" Programme provides funding for the analysis, realisation, development and demonstration along the entire hydrogen value chain. From 2018 to 2025, the Climate and Energy Fund will invest up to EUR 120 million, endowed with funds of the Ministry of Climate Action and Energy, in the three "energy flagship regions" (one of them focuses on hydrogen).

Hydrogen is also included in the funding programmes for zero-emission buses, commercial vehicles and the e-mobility programme. Hydrogen technology competes with other existing zero-emission technologies (in particular battery electric vehicles) to ensure that the most efficient technology for the respective application is used.

In addition, Austria is taking part in both the first and second wave of IPCEI Hydrogen (Hy2Use and Hy2Tech) and has allocated EUR 125 million for its participation.

Furthermore, Austria is currently preparing a quota for the domestic production of renewables gases. The details regarding this quota are currently under discussion.

Austria's EAG provides exemptions for hydrogen from renewable energy subsidy fees, grid fees for electricity and grid fees for natural gas used for blending purposes.

To ensure a regular dialogue between relevant stakeholders and decision makers on the implementation of the hydrogen strategy, a national hydrogen platform, H2Austria, has been established. The platform intends to strengthen cooperation and synergies between local, regional and national actors from various fields, facilitate the exchange of information, provide evidence-based foundations for the strategic implementation of the Hydrogen Strategy and create greater awareness for climate-neutral hydrogen through communication.

Belgium

Several funding instruments are available in Belgium for the support of low-emission hydrogen projects and R&D, including:

- **The Energy Transition Fund** supports, among other things, R&D in the production, transport and storage of hydrogen and its derivatives. Active since 2017, the Fund subsidises various projects with EUR 20 to 30 million per year and is set to operate until 2025.

- **The call for projects Clean Hydrogen for Clean Industry** is organised within the framework of Belgium's national recovery and resilience plan. It focusses on the development of promising technologies for the production and use of hydrogen and its derivatives with a relatively high maturity level. Through this instrument, the federal government aims to support investments that will enable a faster scaling of commercial applications of low-emission hydrogen. A first call was launched in April 2022 for a total of EUR 50 million. A second call will be launched in 2023 for a total of EUR 10 million.

- **The H2 Import Call** focuses on the development and demonstration of technologies that enable the import of hydrogen and hydrogen-derivatives. This call will be launched in early 2023, with funding of EUR 10 million.

Belgium also allocated EUR 95 million from Belgium's National Recovery and Resilience Plan to support the development of a low-emission hydrogen network. The first phase will be started with the commissioning of a minimum of 100 to 160 km of pipelines by 2026.

The federal government also supports the development of the VKHyLab (a test infrastructure which will help research institutes and companies scale up their hydrogen technologies). The government is investing EUR 1.5 million in the acquisition of the site and is subsidising the Von Karman Institute of fluid dynamics with an additional EUR 14.7 million to develop this project. This test facility is expected to be operational by 2025.

Given the importance of developing the first electrolysis capacities in Belgium to enable companies and research institutions to gain experience in this field, the electrolysis activity is exempted from excises on electricity.

Denmark

Denmark has several support mechanisms in place for hydrogen development. In the aftermath of the Climate Agreement for Energy and Industry of June 2020, an agreement was reached that at least DKK 750 million (close to EUR 100 million) can be allocated for tenders to support the production of chemical fuels or products from electricity (Power-to-X). The purpose of the tenders is to promote the production of Power-to-X in an efficient manner and promote the use of electricity based on renewable energy for the production of green products which can be used in difficult-to-electrify sectors.

Denmark reached an agreement in June 2021 to allocate DKK 850 million (~EUR 110 million) for Danish participation in the IPCEI Hydrogen project.

In March 2022, Denmark agreed on subsidies worth DKK 1.25 billion (~EUR 161 million) through one tender aimed at supporting production and making green hydrogen more commercially viable. The Danish government will also earmark DKK 344 million (~EUR 45 million) for innovative green technologies via funds from the REACT-EU initiative and the Just Transition Fund.

Denmark's Energy Technology Development and Demonstration Programme is providing DKK 622 million (~EUR 84 million) funding for green projects including hydrogen.

France

The overall budget of the National French Decarbonised Hydrogen Strategy is about EUR 9 billion for the entire value chain and for all the technology readiness levels (TRL) (1 to 9). The budget is to be spent through calls for projects to support R&D, technological innovation, as well as the deployment of local hydrogen hubs and a support mechanism for decarbonised hydrogen production facilities.

The following subsidy schemes planned for 2023 are ongoing:

- "demonstration and technology bricks" hydrogen call for projects
- "local hydrogen hubs" call for projects
- hydrogen IPCEI procedure
- French Energy Regulatory Commission's support scheme for Non-interconnected areas
- multi-annual research programme with an overall budget of EUR 80 million until 2030. There are two key action points under the multi-annual research programme: (1) Strategic Projects and Hydrogen Technologies Durability Test benchmark operated by the National Research Centre (CNRS) and the French Alternative Energies and Atomic Energy Commission (CEA) supporting R&D hydrogen projects in production, storage and transport, and end-use; (2) To complement the first action, a call for projects is also in place, but operated by the National Research Agency.

A decarbonised hydrogen production support mechanism is expected to be operational in 2023 at the latest. A tax break is planned for 2023, applicable to biofuels and renewable fuels of non-biological origin (RNFBOs), including renewable hydrogen. This tax break pertains to the following renewable hydrogen uses: (1) direct use in fuel cell electric vehicles, (2) oil refining (desulfurisation), and (3) biofuels production (hydrotreated vegetable oil).

Germany

The following subsidy schemes and support mechanisms are available in Germany:

- **Carbon Contracts for Difference (CCfD) for Industrial Transformation:** runs from January 2022 to December 2031 with a budget of around EUR 550 million. This mechanism supports industrial companies (initially in the steel, ammonia, cement and lime sectors) balance the operating cost differences between conventional and low-CO_2 or CO_2-free processes, taking into account the actual CO_2 price, thus enabling an economic market entry earlier. CCfDs create a level-cost playing field for the use of green hydrogen in various downstream sectors and thus generate a demand for hydrogen use that would not exist today without KSVs (Climate Protection Contracts or CCfD for Industrial Transformation).

- **Overall Support Concept Renewable Fuels**: runs from January 2021, with a total budget of EUR 1.5 billion. It comprises four funding schemes listed in detail below. The overall support concept for renewable fuels covers the entire spectrum of (further) development of electricity-based fuels and advanced biofuels up to their production and market ramp-up. The concept provides for four funding measures: (1) funding guidelines for measures to develop renewable fuels, (2) promotion of a development platform for power-to-liquids for air and water transport, (3) funding guidelines for investments in plants for the production of renewable fuels, and (4) funding guidelines for the market ramp-up of power-to-liquids kerosene production.
- **Decarbonisation in industry funding programme:** runs from January 2021 to June 2024, with a budget of approximately EUR 3 billion. The funding programme supports the energy-intensive (basic materials) industry (e.g. steel, cement) in the R&D and large-scale application of innovative climate protection technologies to avoid process emissions.
- **Living laboratories of the energy transition** (funding format within the 7th Energy Research Programme) intends to close the technological development gap for innovations between application-oriented research and broad implementation.
- **Hydrogen Innovation and Technology Centre** (ITZ) runs from 2021 to 2024, with a budget up to EUR 290 million. It aims to create joint development environments, especially for companies, which reduce the need for investment (e.g. in test benches) by the individual players and to initiate cooperation for product development. The services offered by the ITZ are meant to contribute to increasing the product availability of fuel cell applications (components, vehicles, tank infrastructure). A central goal of the ITZ is to strengthen the competitiveness of start-ups and small- and medium-sized enterprises.
- **H2Global** is an auction-based mechanism that runs from January 2022 to December 2033 with a budget of EUR 900 million. It was established with the objective to promote a timely and effective power-to-X market ramp-up on an industrial scale. Under the H2Global mechanism, the Hydrogen Intermediary Network Company GmbH (HINT.CO) concludes long-term purchase contracts on the supply side

and short-term sales contracts on the demand side. The difference between supply prices (production and transport) and demand prices will be compensated by HINT.CO using grant funding from the German government. The German government's draft budget for 2023 includes EUR 3.6 billion for H2Global. The long-term purchase contracts signed by HINT.CO effectively de-risk initial investments and enable companies on the supply side to set up production facilities on an industrial scale. On the user side, companies will be able to purchase green energy sources at economic prices for the first time and thus drive forward their decarbonisation.

- There are also other subsidies that **support cooperation in the field of hydrogen with third countries**. These include HySupply, a German-Australian feasibility study on hydrogen from renewable energies with a budget of EUR 1.7 million, the implementation of the German-Moroccan Hydrogen Alliance with a budget of up to EUR 88.5 million in grant funding, and the promotion of green hydrogen in Brazil (EUR 34 million) and South Africa (EUR 40 million) between 2021 and 2023.

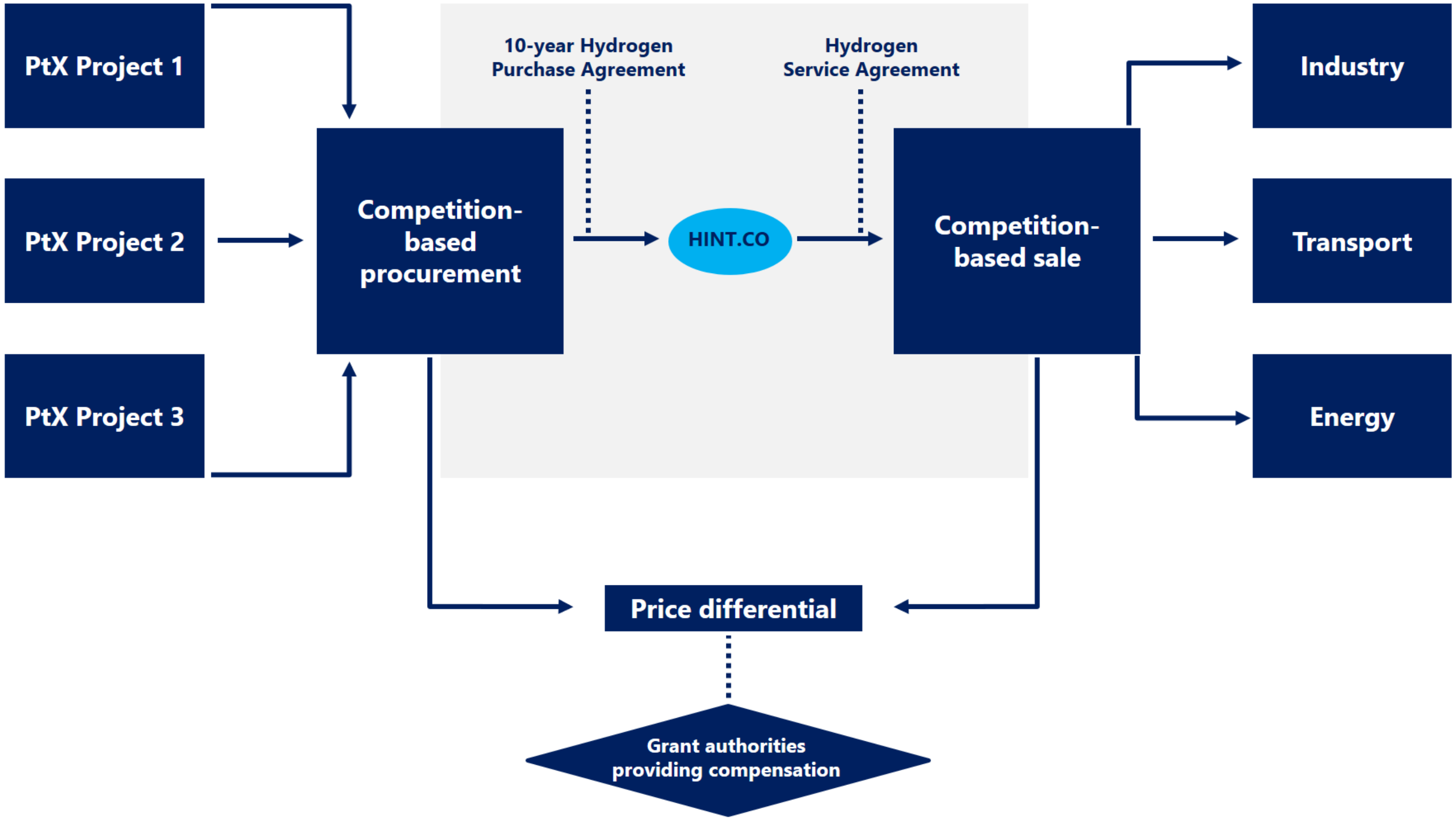
- **The H2-Uppp programme,** funded by the German Federal Ministry for Economic Affairs and Climate Action supports investments, via the German Agency for International Cooperation, in green hydrogen or its derivatives in developing and emerging countries.

- **Funding guidelines for international hydrogen projects** within the framework of the National Hydrogen Strategy and the Economic Recovery Plan establish an offer of support for international projects (outside the EU and European Free Trade Association states) for the construction of production plants for green hydrogen and its derivatives, as well as for the storage, transport and integrated application of hydrogen, and for accompanying research projects aligned with the National Hydrogen Strategy. Project outlines were submitted in three funding rounds (the submission deadlines were 31 October 2021, 31 December 2021 and 28 February 2022).

- **Important Projects of Common European Interest IPCEI on Hydrogen** runs from January 2021 to December 2027 with a budget of approximately EUR 11 billion (federal and state funds). It aim to establish a German and European market for green hydrogen at all levels of the value chain, in particular by expanding initial electrolysis capacities, a hydrogen network and hydrogen applications (e.g. in transport). This is to be accompanied by improvements in hydrogen technologies and cost degression.

H2Global aims to de-risk hydrogen investment via long-term hydrogen purchase agreements

Simplified scheme of the H2Global instrument



HINT.CO = Hydrogen Intermediary Network Company GmbH (HINT.CO).
Sources: IEA analysis based on H2Global (2022), The H2Global Mechanism.

Luxembourg

The Luxembourg government is currently developing a subsidy scheme for the production of renewable hydrogen. A final concept paper is expected to be published in early 2023 by the Ministry of Energy and Spatial Planning. There are several CAPEX funding possibilities which are available from the Ministry of Economic Affairs.

Luxembourg is also in contact with H2Global and is looking forward to further information regarding the Global European Hydrogen Facility (REPowerEU).

Netherlands

In the Netherlands, while most subsidy programmes are not solely focused on hydrogen, the leaders of hydrogen projects can apply for funding via a variety of subsidy instruments made available through the Ministry of Economic Affairs and Climate Policy, and the Ministry of Infrastructure and Water Management. In total, around EUR 60 million was spent via subsidy schemes between 2020-2021 for hydrogen projects. Up to EUR 15 billion is expected to be allocated to hydrogen up to 2030.

The following support schemes are available for hydrogen:

- **MOOI scheme** (Mission-Driven Research, Development and Innovation) supports industrial research and experimental development. It supports integrated solutions that contribute to climate goals.
- **DKTI scheme** (Demonstration of Climate Technologies and Innovations in Transport) supports projects that focus on mobility and transport. A total of EUR 64.8 million was spent on hydrogen between 2017 and 2021.
- **DEI+ scheme** (Demonstration of Energy and Climate Innovation) supports practical experiments, pilots and demos. As of June 2022, there was a specific call, with a budget of EUR 30 million, for hydrogen and green chemistry via the DEI+;
- **TSE Scheme (**Top Sector Energy Scheme) supports projects that focus on feasibility studies carried out prior to the finalisation of investment decisions relating to an innovative pilot or demonstration project. The TSE Scheme was established specifically for R&D and supports R&D projects that can cost effectively reduce CO_2 emissions in industry by 2030.
- **SDE++ scheme** (Sustainable energy transition subsidy scheme) supports the deployment of renewable energy generation techniques and other CO_2-reducing techniques.
- **HER+ scheme** (Renewable Energy Transition) is intended to achieve cost reductions for technology categories that are supported under the SDE++ scheme. These projects lead to CO_2 reduction by 2030 and save on future expenditure on subsidies in accordance with the SDE++ scheme.

- **MIT scheme** (Innovation Stimulation Region and Top Sectors) is available for small- and medium-size enterprises.
- **GroenvermogenNL (Green PowerNL)** is a programme that focuses on accelerating the scaling up of hydrogen and green chemistry, with a maximum budget of EUR 838 million between 2021 and 2028. It will focus on R&D, pilots, demonstration projects and human capital development, including training. The aforementioned DEI+ call of EUR 30 million is part of this programme.

The government has assigned EUR 750 million to develop a national hydrogen transport network, EUR 35 million to develop storage locations and EUR 250 million to support electrolysis. Another EUR 35 million have been assigned for the first **IPCEI** wave, and it was announced recently that EUR 1.3 billion is to be devoted to the IPCEI waves on hydrogen production and imports.

In addition to the subsidy schemes, **tax benefits** are available to support hydrogen-related investments. Under the Energy Investment Allowance Scheme entrepreneurs can reduce their taxable profits. They may deduct 45.5% of the cost of the energy investment from their taxable profit. Given that hydrogen plays an important role in the transition to a climate-neutral society, three new operating assets have been included in the scheme to support these developments: (1) production of hydrogen by means of electrolysis, (2) stationary storage of hydrogen, and (3) connection to private hydrogen networks.

Norway

Enova, Innovation Norway, Forskningsrådet (Research Council of Norway) and Gassnova cooperate closely in the funding of hydrogen R&D through their various support schemes, such as PILOT-E and Grønn Plattform. In 2020, these agencies allocated a total of NOK 1 574 million (over EUR 150 million) to hydrogen projects. These projects are expected to span several years. The reported amount of funding is meant to cover the entire duration of the projects. The amount allocated to hydrogen projects in 2021 was NOK 1 604 million (~EUR 155 million). In 2022, the Research Council of Norway (RCN) established two new Centres for Environment-Friendly Energy Research (FME) on hydrogen. They will receive a total of NOK 310 million (over ~EUR 30 million) public funding over an eight-year period.

Switzerland

In Switzerland, there are no direct subsidy/supporting schemes in place as of yet to support the production and deployment of low-carbon hydrogen. Switzerland has several research funds at its disposal to finance R&D projects. The public funding for R&D projects in the hydrogen and fuel cell sector amounts to approximately CHF 25 million (~EUR 25.5 million) per year.

A number of tax exemptions provide support for the end-uses of hydrogen:

- Fuel cell electric vehicles are exempted from the mineral oil tax. In addition, heavy-duty fuel cell trucks are also exempted from the heavy vehicle fee.
- Hydrogen is exempted from the CO_2 levy imposed on fossil heating fuels (currently 120 CHF/t CO_2).
- There is no CO_2 levy on transport fuel. Instead, importers of transport fuels must compensate part of the CO_2 emissions of the imported fuels. Replacing fossil fuels with hydrogen (e.g. for buses and trucks) is one of many possible compensation programmes.
- Switzerland has CO_2 emissions targets for passenger cars and light duty vehicles similar to the EU where fuel cell electric vehicles (FCEVs) count as zero-emission vehicles.

Switzerland is currently investigating additional incentives and supporting schemes which could support the Swiss hydrogen market ramp-up.

United Kingdom

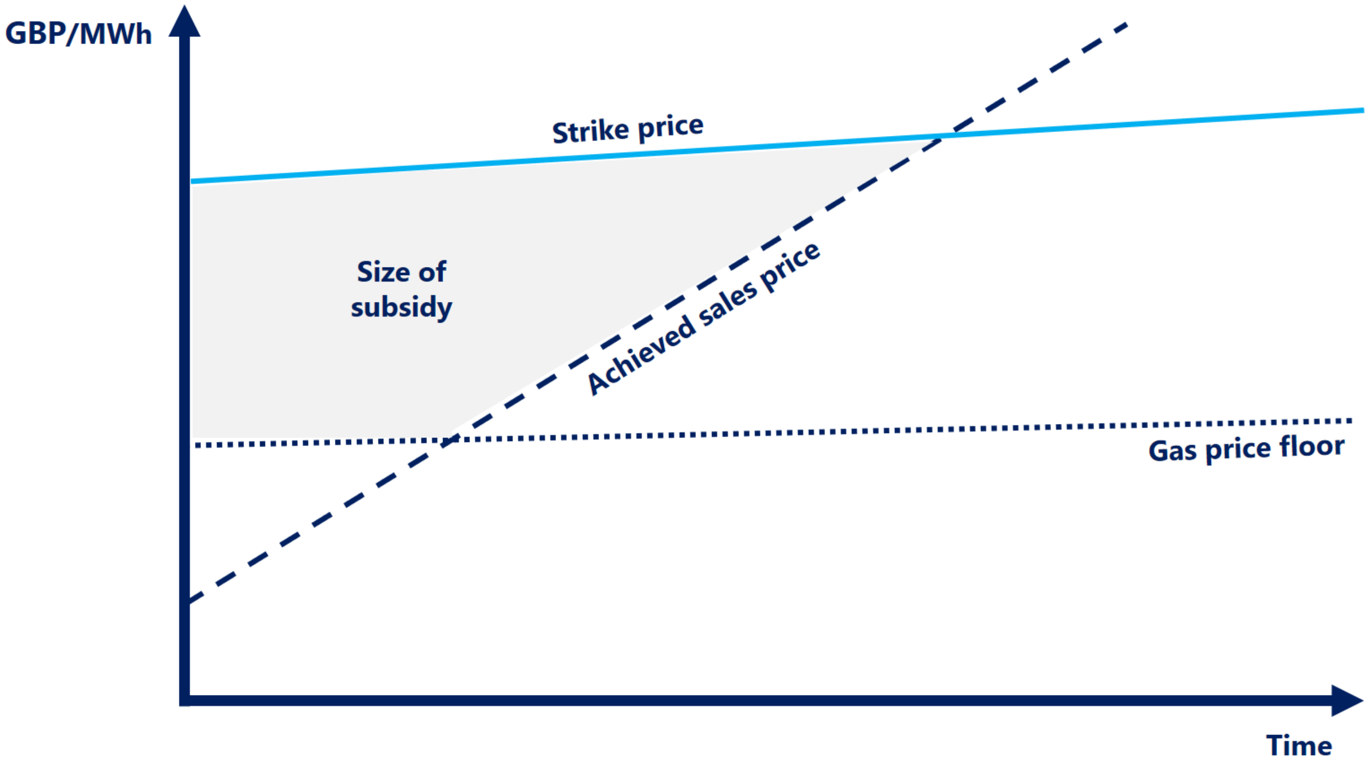
The **Net Zero Hydrogen Fund** will provide up to GBP 240 million (close to EUR 280 million) to support the development and construction of new low-carbon hydrogen production plants throughout the United Kingdom between 2022 and 2025. The Fund is open to multiple production technologies, including CCUS-enabled and electrolytic hydrogen, and is targeted at projects that can become operational during the 2020s. It forms part of a suite of measures designed to stimulate the deployment of scalable low-emission hydrogen production. The Fund has four strands: (1) Support for front-end engineering and design (FEED) studies and post-FEED costs, (2) CAPEX for projects that do not require hydrogen business model support, (3) CAPEX for non-CCUS enabled projects that require hydrogen business model support, and (4) CAPEX for CCUS-enabled projects that require hydrogen business model support.

In addition, the **Hydrogen Production Business Model** will provide revenue support to producers to overcome the operating cost gap between low-emission hydrogen and high-carbon counterfactual fuels. The hydrogen production business model will be critical to unlocking private investment, by providing a subsidy to close the gap between the cost of producing hydrogen (strike price) and the price it can be sold for (achieved sales price). UK Government support for hydrogen production will only be available to pathways that are sufficiently "low carbon" which will be defined by the Low Carbon Hydrogen Standard.

The **Energy Innovation Portfolio** and **Net Zero Innovation Portfolio** funds are supporting a number of hydrogen innovation projects to accelerate the commercialisation of hydrogen-related technologies.

The Hydrogen Production Business Model will provide a subsidy to close the gap between hydrogen production costs and the sales price

Illustrative price support through the variable premium design of the Hydrogen Production Business Model



Sources: IEA analysis based on presentation of the United Kingdom at the First Hydrogen Monitoring Study Expert Panel Meeting held 25 May 2022, in Brussels, Belgium.

Hydrogen supply

Low-emission hydrogen is at the intersection of decarbonisation efforts and energy supply security

Low-emission hydrogen can play a significant role in decarbonising existing gas and energy systems and will be critical to the countries' efforts to achieve a climate neutral society. Besides its environmental benefits, low-emission hydrogen can help reduce reliance on fossil fuel imports already in the medium-term.

Hydrogen can be produced through a wide variety of technologies (e.g. reforming, gasification, electrolysis, pyrolysis, water splitting and many others from a range of primary and secondary fuels (including coal, oil, natural gas, biomass, renewables- and nuclear-based electricity).

There is currently no international agreement on the definition of low-emission hydrogen. As for the IEA's Global Hydrogen Review, low-emission hydrogen in this Monitor includes hydrogen[3] produced via the following technology routes:

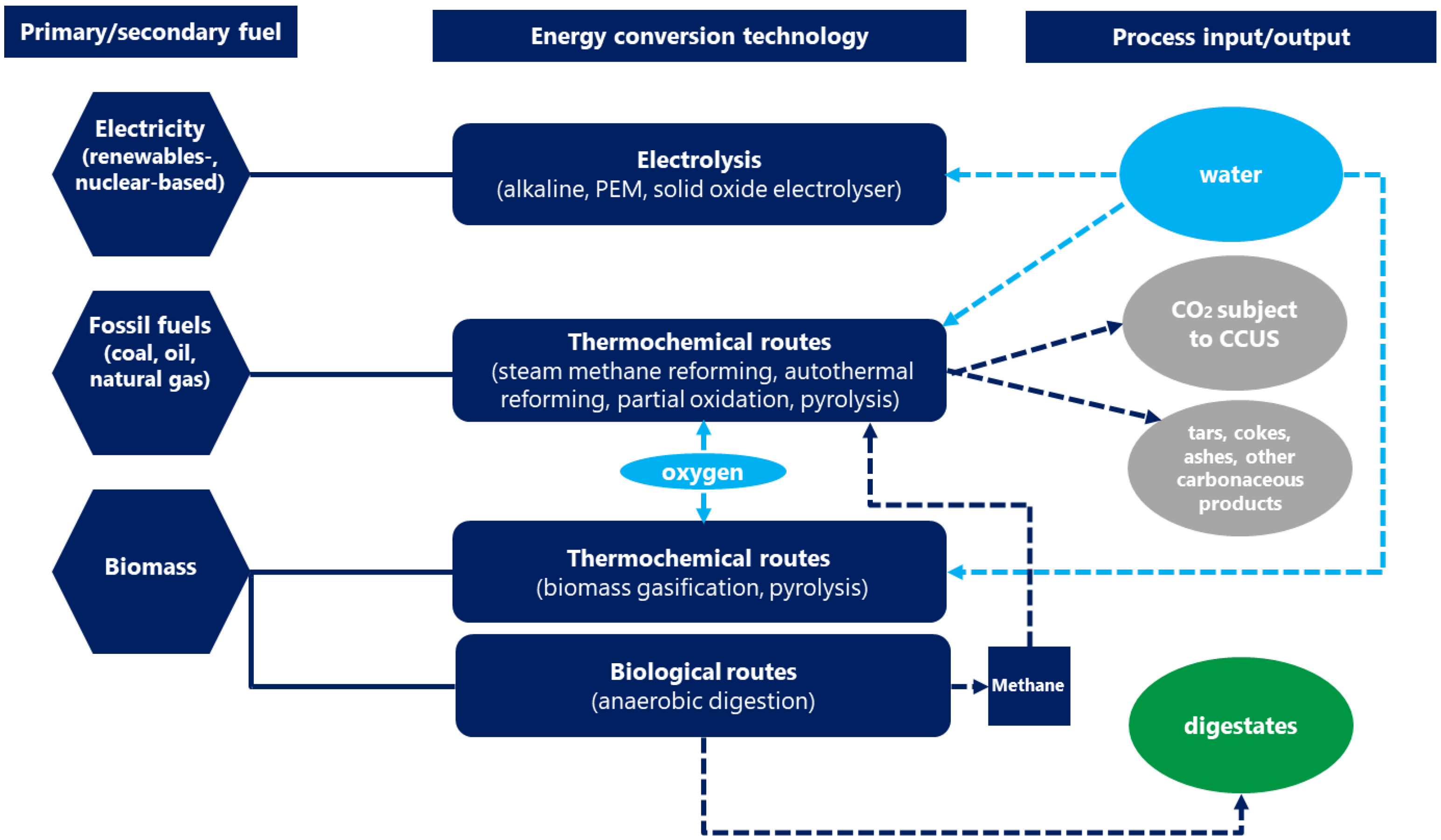
- from renewables-based and nuclear electricity via electrolysis
- from fossil fuels via steam methane reforming (SMR) or autothermal reforming (ATR) with CCUS. Notably, production from fossil fuels with CCUS is included only if upstream emissions are sufficiently low, if capture – at high rates – is applied to all CO_2 streams associated with the production route, and if all CO_2 emissions are permanently stored to prevent their release into the atmosphere
- from bioenergy via pyrolysis, anaerobic digestion and other technologies.

The choice of technology will depend largely on the country where the hydrogen is to be produced and its resource availability. For example, the cost-competitiveness of electrolytic hydrogen will be to a large extent determined by the availability of variable renewable energy sources, while CCUS-based solutions might be considered as more competitive in markets with greater fossil fuel and/or biomass availability. In this regard, several Northwest European countries have included electrolyser capacity deployment targets in their national hydrogen strategies, while Norway have chosen a technology neutral approach. In all, the Northwest European countries target electrolyser capacity deployment of between 30 and 40 GW by 2030.

[3] The current analysis includes planned production projects of low-emission hydrogen and excludes planned projects related to low-emission hydrogen-derived fuels.

Low-emission hydrogen can be produced through a variety of production routes

Simplified scheme of selected low-emission hydrogen production routes



Note: PEM= Polymer electrolyte membrane.

Northwest Europe leads the world in low-emission hydrogen production development

The ten countries considered in the Hydrogen Monitor use over 4 Mt of hydrogen every year, mainly in the refining and chemical industries. Close to 100% of the hydrogen used in the region is produced from unabated fossil fuels.

Northwest European countries are at the forefront of low-emission hydrogen production development. The region accounts for close to 85% of OECD Europe's operational low-emission hydrogen capacity. As per the IEA's Hydrogen Projects Database, the electrolytic hydrogen production capacity of Northwest Europe reached 17 kt/year in 2022. Most of the operating capacity is located in Germany, accounting for close to 65% of the total. Two gas-based hydrogen production projects capture CO_2 for use in industrial or agricultural applications in the region. In the Netherlands, the Shell's Pernis refinery in the Rotterdam area captures carbon emissions from hydrogen production as part of the OPAC project, which re-uses CO_2 for enhanced crop growth. In France, Air Liquide equipped its Port-Jérôme hydrogen production facility in 2015 with a cryogenic CO_2 purification system (~0.1 Mtpa). For the purposes of this Monitor, these projects are not classified as low-emission hydrogen.

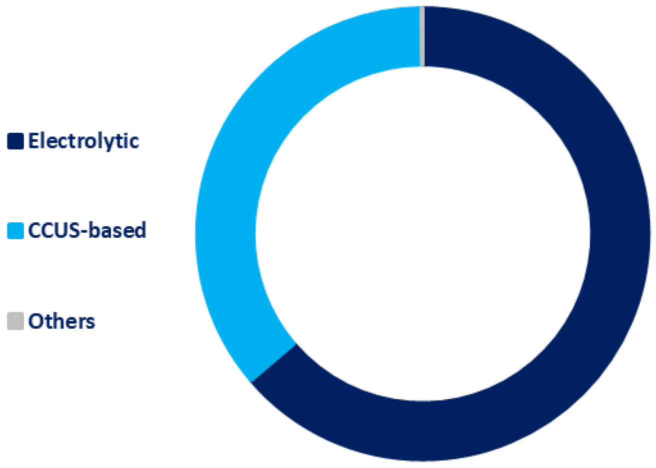
Assuming that all of the announced and planned projects become commercially operational, the total low-carbon hydrogen production capacity of the ten countries considered in the Hydrogen Monitor is expected to reach close to 14 Mt/year by 2030. This would mean that Northwest Europe would account for around 80% of the total expected production capacity of low-emission hydrogen production in OECD Europe by 2030. Fossil-fuel based hydrogen projects, equipped with CCUS, account for over one-third of the total planned low-emission hydrogen production capacity by 2030, whilst electrolytic hydrogen production capacity accounts for almost two-thirds. If all planned projects become commercially operational, and taking the assumptions on efficiency and utilisation factors into account, Northwest Europe's low-emission hydrogen production could reach close to 6.2 Mt/yr by 2030.

However, less than 1% of these projects are currently operational. According to the IEA's Hydrogen Projects Database, just 2% of the expected capacity by 2030 has already reached a FID or is under construction. Over 95% of these projects are currently either conceptual or subject to feasibility studies.

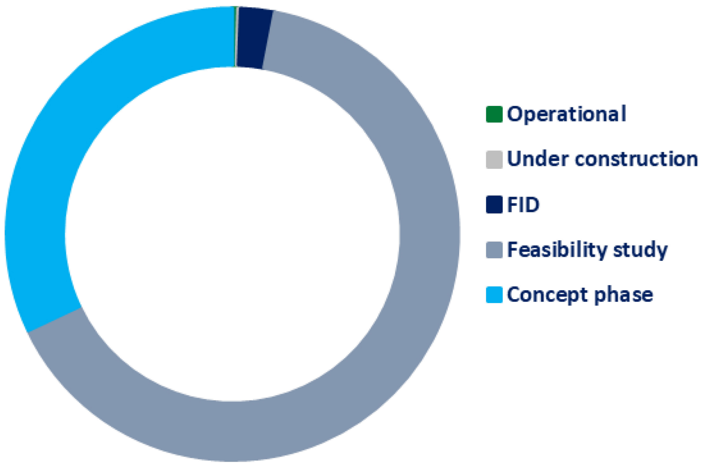
Accelerating the deployment of low-emission hydrogen will require stronger policy support, to "pull" investment along the entire value chain of hydrogen supply. Public funding programmes and state-backed risk-sharing mechanisms can help to de-risk investment and improve the economic feasibility of low-emission hydrogen projects. Demand creation should be a key instrument to stimulate investment, including via quotas and public procurement rules.

Electrolytic hydrogen accounts for two-thirds of Northwest Europe's low-emission hydrogen production capacity in 2030, but 95% of the projects are still in the early stages of development

Low-emission hydrogen projects in Northwest Europe by type (2030)



Low-emission hydrogen projects in Northwest Europe by status (2030)



Source: IEA (2022), Hydrogen Projects Database.

Low-emission hydrogen production development varies by country

The following section provides an overview of the low-emission hydrogen projects in Northwest Europe and the outlook to 2030.

Austria

Austria has set a target for 1 GW of electrolyser capacity for the production of renewable hydrogen by 2030. The country's National Hydrogen Strategy aims to replace 80% of fossil-based hydrogen with climate-neutral hydrogen in energy intensive industries by 2030.

Austria has several demonstration projects for renewable hydrogen production via electrolysis, including the "Hydrogen Village in Burgenland" project launched in 2006, and the Wind2Hydrogen and HyCentA projects in 2015. The DEMO4GRID project is currently under commissioning and will be supported by a 4 MW alkaline electrolyser. The DEMO4GRID project will produce green hydrogen for the food retail company, MPREIS, to replace fossil-based natural gas for heating.

Several electrolytic renewable hydrogen projects have reached a FID or are in their conceptual phase. They include the installation of a 10 MW electrolyser at the OMV Schwechat Refinery by 2025. In 2022, plans for a large-scale renewable electrolysis plant in Burgenland were announced. The project will be implemented in several phases, towards a 300 MW electrolyser capacity in 2030.

Altogether, the combined capacity of Austria's renewable hydrogen projects would stand at around 400 MW by 2030, falling short of Austria's 1 GW target. If all planned projects start commercial operations by then, it is estimated that Austria could produce over to 70 kt of renewable hydrogen by 2030.

Belgium

The Belgian Federal Hydrogen Strategy does not specify a low-emission hydrogen production target. In its National Recovery and Resilience Plan, Belgium set a target of at least 0.15 GW of electrolysis capacity in operation by 2026.

According to the IEA's Hydrogen Projects Database, the country has four operational low-emission hydrogen production facilities, with a combined capacity of 2.5 MW. Projects which are under construction have a total capacity of 1.3 MW while the ones that have reached a FID have a capacity of close to 75 MW. This includes the HyPort Project in Ostend, which is expected to become operational in 2025. This project would consist of a 50 MW electrolyser and would use offshore wind to produce low-emission hydrogen.

Several projects are either in the midst of feasibility studies or are in their conceptual phase. They could add 0.8 GW and 1.9 GW of low-emission hydrogen production capacity, respectively, by 2030.

Together, all of the low-emission hydrogen projects under development in Belgium could produce 0.17 Mt by 2030.

Denmark

Denmark adopted its Power-to-X Strategy in March 2022 which targets 4-6 GW of electrolyser capacity by 2030.

Denmark has several operational electrolytic hydrogen projects. The majority are small-scale, pilot projects with a combined installed electrolysis capacity of over 5 MW. There are several projects under construction, including the HySynergy Project, which is expected to begin producing hydrogen late in 2022 from the initial 20 MW electrolyser. The facility could be expanded to 300 MW in 2025 and 1 GW in 2030.

Projects in the midst of feasibility studies or are in their concept phase (including the HySynergy project's Phase II & III and the BrintØ - Hydrogen Island project) could add 4.1 GW and 7.4 GW of electrolysis capacity, respectively, by 2030. Together, all of the low-emission hydrogen projects currently under development in Denmark could produce around 0.7 Mt by 2030.

France

A target of 6.5 GW of water electrolysis capacity by 2030 is given in France's National Strategy for the Development of Decarbonised and Renewable Hydrogen.

France has several small-scale low-emission hydrogen production projects. In all, the country has over 4 MW of electrolysis capacity in operational status. In addition, the Port-Jérôme hydrogen production facility was equipped with a cryogenic CO_2 purification system (~0.1 Mtpa) in 2015. For the purposes of this Monitor, this project is not classified as a low-emission hydrogen project. Projects currently under construction could add close to 4 MW, and those which have reached a FID could contribute over 11 MW of electrolysis capacity by 2025. The Masshylia hydrogen project, consisting of a 125 MW electrolyser, is scheduled to begin operating in 2026. This facility will be able to produce close to 22 kt/yr of low-emission hydrogen to meet the needs of the biofuel production process at the biorefinery.

Projects undergoing feasibility studies or are in their concept phase could add close to 2.9 GW and 6.8 GW of electrolysis capacity, respectively, by 2030. They include the giant Lacq Hydrogen Project which is being developed by France's and Spain's gas transmission system operators, Enagás and Teréga. In addition to electrolytic hydrogen, several gas-based low-emission hydrogen projects are under consideration. According to the IEA's Hydrogen Projects Database, they could add 0.18 Mt of low-emission hydrogen production by 2030.

Together, all of the low-emission hydrogen projects currently under development in France could produce over 0.63 Mt by 2030.

Germany

Under its National Hydrogen Strategy, Germany plans to establish up to 5 GW of electrolytic hydrogen production capacity by 2030. The federal government is currently working on revising the hydrogen strategy in order to secure the targets from the coalition agreement, e.g. increasing the electrolyser capacity to 10 GW by 2030.

Germany alone accounts for close to 65% of Northwest Europe's currently operational electrolysis capacity. Distributed among several small-scale (1-2 MW) projects, the country has close to 70 MW capacity of electrolysers.

The projects which are under construction could add close to 57 MW, while the ones which have reached a FID could add almost 1.1 GW of electrolysis capacity by 2026. This includes the ArcelorMittal Project to use low-emission hydrogen in the production of direct reduced iron (DRI) at its Hamburg steel plant. The project will consist of a 50 MW electrolyser using renewable electricity supply and is expected to begin operation by 2025.

Projects that are in the midst of feasibility studies or are in their concept phase could add 3.5 GW and 9 GW of electrolysis capacity, respectively, by 2030. This would put Germany on track to reach its 10 GW target of electrolyser capacity.

In addition, Germany has several gas-based low-emission hydrogen projects in the conceptual phase of project development. They include the H2morrow Project, developed jointly by Norway's Equinor and Germany's Open Grid Europe. Under the project scheme, Norwegian gas would be converted into low-emission hydrogen in Germany via autothermal reforming subject to carbon, capture and offshore storage (CCOS). The CO_2 emissions would be stored in the Norwegian continental shelf.

Taken together, all of the low-emission hydrogen projects currently under development in Germany could produce close to 1 Mt by 2030.

Luxembourg

At the time of writing, though Luxembourg had not set quantified targets for low-emission hydrogen production, the government had stated that it is aiming to replace fossil-based hydrogen with low-emission hydrogen to reduce greenhouse gas emissions by more than 5kt CO_2/year.

Netherlands

The Netherlands has set a target of 3-4 GW electrolyser capacity by 2030, with an intermediate target of 0.5 GW by 2025. The ruling parties in the Netherlands proposed increasing the country's 4 GW target to 8 GW by 2030 and this is being evaluated within the National Hydrogen Programme.

At present, the Netherlands has around 3 MW of operational electrolytic low-emission hydrogen production capacity installed. In addition, Shell's Pernis refinery in the Rotterdam area captures carbon emissions from hydrogen production as part of the OPAC project. The resulting hydrogen production is estimated at 17 kt/year but for the purposes of this Monitor, it is not classified as low-emission hydrogen.

Projects which are under construction could add 12 MW, and one project, the Holland Hydrogen I project (which would consist of 200 MW of electrolyser capacity to supply low-emission hydrogen to Shell's Pernis refinery) has reached a FID aiming to be operational by 2025. The electricity would be sourced from the future Hollandse Kust North offshore wind farm.

Projects which are in their concept phase could add 2.7 GW of electrolysis capacity, while the ones currently carrying out feasibility studies could add 8.2 GW by 2030. They include the giant NorthH2 (4 GW) and HyNetherlands Phase 2 Projects (1 GW). In addition, there are several gas- and oil-based low-emission hydrogen projects in the early phases of development. If they reach commercial maturity, they could add around 0.4 Mt of low-emission hydrogen production by 2030.

Together, all of the low-emission hydrogen projects currently under development in the Netherlands could produce close to 1.1 Mt by 2030.

Norway

Norway adopted its Hydrogen Strategy in June 2020 and its Hydrogen Roadmap in June 2021. The country does not have a specific production target and has a technology-neutral approach towards low-emission hydrogen production.

Currently, Norway has just over 6 MW of electrolysis capacity. FIDs have been reached on the installation of almost an additional 60 MW.

Projects in their early phases of development could add over 150 MW while others in the midst of feasibility studies could add over 3 GW of electrolysis capacity by 2030. In addition, gas-based low-emission hydrogen projects are being considered. The planned HyDemo Project, currently undergoing a feasibility study, would supply close to 180 kt H_2/year by 2025, sourced via steam methane reforming subject to CCUS.

Together, all of the low-emission hydrogen projects currently under development in Norway could produce almost 0.5 Mt by 2030.

Switzerland

Switzerland has not yet set any low-emission hydrogen production targets. The country's Hydrogen Roadmap is currently under preparation and will be published in 2023.

Switzerland has several small-scale, low-emission hydrogen production projects in operation, with a total capacity of 3.5 MW.

Electrolytic projects which are under construction and/or have reached FID could add around 2.5 MW and 5 MW, respectively, in the coming years. Electricity would be sourced mainly from hydropower.

Projects which are currently in the midst of feasibility studies could add 25 MW of electrolysis capacity by 2025.

Together, all of the low-emission hydrogen projects currently under development in Switzerland could produce over 2 kt/year by 2030.

United Kingdom

In its British Energy Security Strategy, the United Kingdom doubled its low-emission hydrogen production ambition to up to 10 GW by 2030, with electrolytic hydrogen accounting for at least half of it. The Strategy sets, as intermediary targets, 1 GW of electrolytic hydrogen capacity in construction or operational by 2025, and 1 GW of CCUS-enabled hydrogen capacity in construction or operational by 2025.

The United Kingdom currently has over 8 MW of electrolysis capacity, mostly in the form of small-scale, pilot projects. If projects in development are considered, overall electrolysis capacity could reach over 1 GW by 2025. The gap between capacity under construction/FID and capacity in the early stages of development, indicates that policy support, including funding, will be important in order for the United Kingdom to deliver its hydrogen production ambitions. The Net Zero Hydrogen Fund is expected to accelerate project development in the near term, facilitating final investment decisions.

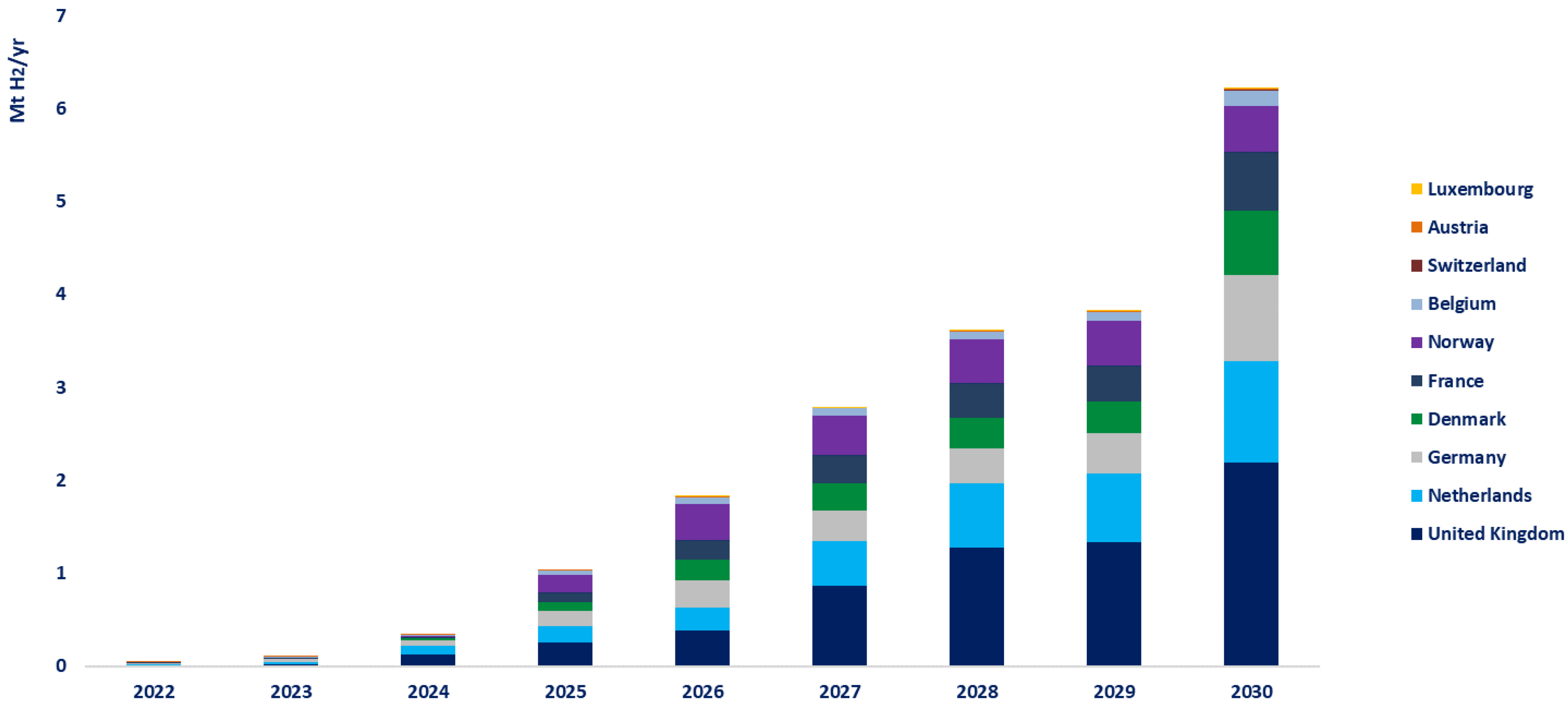
Projects in the early stages of development could add close to 3.5 GW, while the ones in the midst of feasibility studies could add 2.5 GW of electrolysis capacity by 2030. This includes giant projects such as Gigastack-Hornsea 2 (1 GW), Cerulean Winds (1.5 GW) and the Freeport East Hydrogen Hub (1 GW). In addition, several gas-based low-emission hydrogen projects are being considered. Though most of them are currently in the early stages of project development, they could add around 3 Mt of low-emission hydrogen production capacity by 2030.

This includes the HyNet North West Project, which alone could account for over 30% of the country's gas-based low-emission hydrogen supply by 2030. This Project aims to decarbonise the industries located in Northwest England and North Wales by providing low-emission hydrogen produced from natural gas via autothermal reforming subject to CCS. According to the project's developer's, HyNet North West could reduce carbon emissions by 10 Mt/year by 2030.

Based on the IEA's Hydrogen Projects Database, all of the low-emission hydrogen production projects currently under development in the United Kingdom's could produce nearly to 2.2 Mt by 2030.

Low-emission hydrogen production could reach close to 6.2 Mt/year by 2030

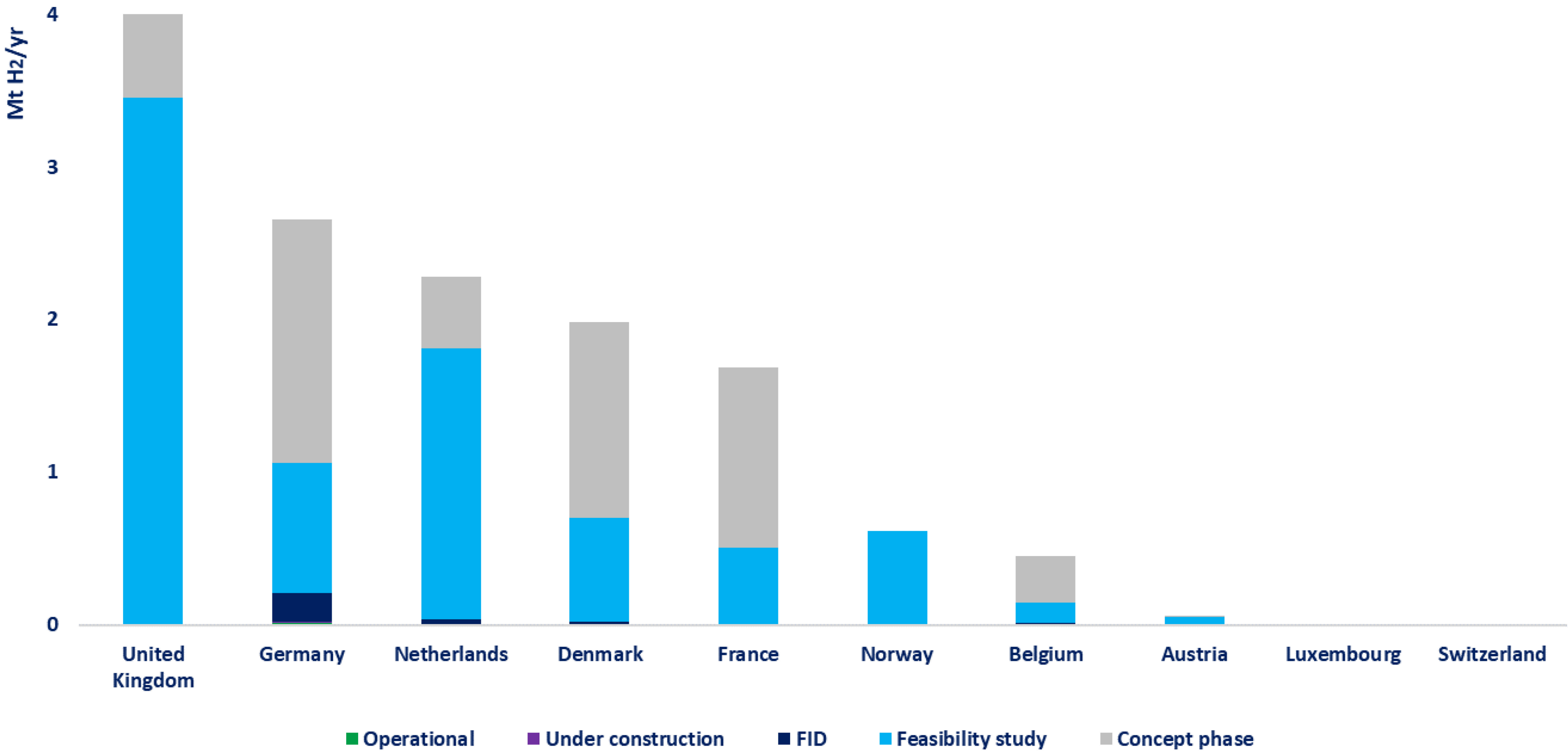
Projected low-emission hydrogen production in Northwest Europe by country, 2022- 2030



Source: IEA (2022), Hydrogen Projects Database.

United Kingdom, Germany and the Netherlands could account for 75% of the total low-emission hydrogen production capacity in Northwest Europe in 2030

Installed capacity and new capacity based on projects' status by Northwest European country



Source: IEA (2022), Hydrogen Projects Database.

Hydrogen trade

European countries could play a central role in a nascent hydrogen trade market

Today hydrogen is mainly produced and used in the same location, especially in industrial areas for the production of fertilisers, methanol and in oil refineries. It is produced onsite or obtained as a by-product (for example, from the chlor-alkali industry or from petrochemical processes) and is used as a feedstock in industrial processes. Cross-border trade has started to take place in small-quantities in Japan and could become an important feature in the coming decades.

The increasing demand for low-emission hydrogen, both to replace fossil-based hydrogen in current uses and for new applications where direct electrification is difficult, is needed to reach the decarbonisation goals at the global level. This, together with potential production increases in geograpichal locations with abundant renewable resources or access to CO_2 storage, as seen in national plans and in companies projects, could pave the way for international trade of low-emission hydrogen and derivatives.

This is the case for the highly industrialised Northwest European region, with clusters like the Antwerp-Rotterdam-Rhine-Ruhr area, where about 40% of the European Union's chemical production is concentrated. While the region is, already today, a center of hydrogen demand and production (mainly from unabated natural gas), it not only has excellent port infrastructure with access to international trade routes, but also the potential to develop into clean hydrogen hubs.

The Port of Rotterdam is actively positioning itself as the main import hydrogen hub in Europe. To this end, it is working on exploring opportunities and cooperation on new hydrogen and derivative trade routes, with more than 20 agreements signed with international counterparts. The Belgian ports of Antwerp and Zeebrugge have signed a Memorandum of Understanding (MoU) with Chile in the interests of setting up a hydrogen import corridor, and Germany sees Hamburg as the strategic pioneer in hydrogen imports to the country.

While, globally, an estimated 12 Mt of hydrogen per year could be exported by 2030, based on project annoucements, more than 80% of this volume still has no off-taker defined. And with the EU target of 10 Mt per year of renewable hydrogen imports by 2030 proposed in the REPowerEU plan, it is clear that the coming years will be pivotal for the deployment of a hydrogen trade market in this decade, in which the Northwest European region has a central role to play.

Dedicated financial instruments will be key to facilitating hydrogen imports

The low-emission hydrogen market is in its infancy, and it will be crucial to establish the format of transactions between producers and consumers correctly, especially for international trade. Bilateral contracts between the importer and the exporter, usually companies, are the most widely used instruments today.

At this point in time, the infrastructure needed to transport hydrogen via sea is practically non-existant. Ideally it should be built in parallel with production facilities. The development of low-emission hydrogen production plants and related infrastructure are highly capital intensive investments. Companies may seek long-term contracts, with pre-defined pricing mechanisms, in order to provide financial security for the the development of the projects. In the longer term, once the market has been established, more open models for trade such as the ones used for liquefied natural gas (LNG) could also develop.

Awarding contracts through auctions, on the demand or supply side or both, could help reduce the low-emission hydrogen price gap. It could guarantee the seller a fixed price for a certain period of time, which may also stimulate investment on the production side: in this way, the production cost could decrease faster and reduce the need for government funds in the mid to long term. One of the most advanced programmes today is the German H2Global auction-based mechanism. Through a dedicated intermediary, HINT.CO, ten-year purchase contract auctions are concluded on the supply side, at the lower price for electrolytic hydrogen and its derivatives from producers outside the European Union. Short term contracts are then auctioned on the demand side, and the difference is compensated by the intermediary itself through German government funding. This compensation will potentially decline over time as the market develops. The German government has approved a grant of EUR 900 million for the scheme, and the first auctions are planned for the second half of 2022 with product deliveries expected to start in 2024. Notably, the German government's draft budget for 2023 includes a budget of EUR 3.6 billion for H2Global. In October 2022, the Netherlands also expressed its interest in cooperating in the H2Global funding instrument.

As the focus is on renewable hydrogen, clarity on standards and certification is needed in order to guarantee a consistent definition of the hydrogen produced inside and outside the European Union, and to provide certainty to importers. The rules formulated for the European energy market may not be easily applied to other countries, where the electricity markets are structured differently or where different renewable certification systems exist.

The number of planned export-oriented projects is growing, but a considerable margin exists for securing off-take agreements

Based on the export-oriented projects currently under development, the global hydrogen trade flow could reach 12 Mt per year by 2030. A fifth of this amount is planned to come online in the next four years. However, the majority of the projects are currently in the early stages of planning or in the midst of feasibility studies. Projects that have reached a more advanced stage of development represent only 0.2 Mt H_2/year. While the scale of planned exports is expected to grow through the remainder of this decade and beyond, it is apparent that off-take agreements and import contracts lag behind. In fact, of the total export-oriented projects planned, those representing 7 Mt H_2 per year have not yet announced a delivery destination.

The Northwest European region, together with a few Asian countries, account for the majority of the projects for which the import destination is defined. The Netherlands and Germany lead the development of the import projects, with a combined volume of imports expected to reach about half a million tonnes of hydrogen by 2030. Project Nour, in Mauritania, completed its pre-feasibility study in May 2022. This project is expected to deploy 10 GW of electrolysis powered by wind and solar power by 2030. Chariot, the project developer, signed a partnership agreement with the Port of Rotterdam for the sale of the renewable molecules to Europe. The Icelandic company Landsvirkjun and the Port of Rotterdam are working closely to carry out a pre-feasibility study on the shipment of 2-4 TWh of renewable hydrogen from Iceland to Rotterdam before 2030. This hydrogen would be produced via electrolysis powered by a combination of hydropower, geothermal and wind power, and it would be either liquefied or converted into another carrier for transport purposes.

Angola could become the first supplier to Germany. The energy firm Sonangol announced plans to develop an electrolytic ammonia plant in the African country by 2024, with an expected capacity of 280 kt NH_3 (about 50 kt H_2) to be exported. Uniper has signed a Letter of Intent (LoI) with the Chilean company HIF Global to negotiate off-take agreements for the sale of synthetic fuels, to be produced in the plants under development in the Magallanes. The plants will be scaled up in several phases during this decade, with a potential capacity of about 190 kt H_2 equivalent per year, though the shipping destination is not yet defined. A group of companies from Germany and the United Arab Emirates (UAE) are exploring the feasibility of transporting hydrogen, in the form of liquid organic hydrogen carrier (LOHC), to Europe by the end of the decade. The first shipment of ammonia (produced from natural gas with CCS) from the UAE destined for Hamburg left Abu Dhabi's Ruwais industrial site in September 2022.

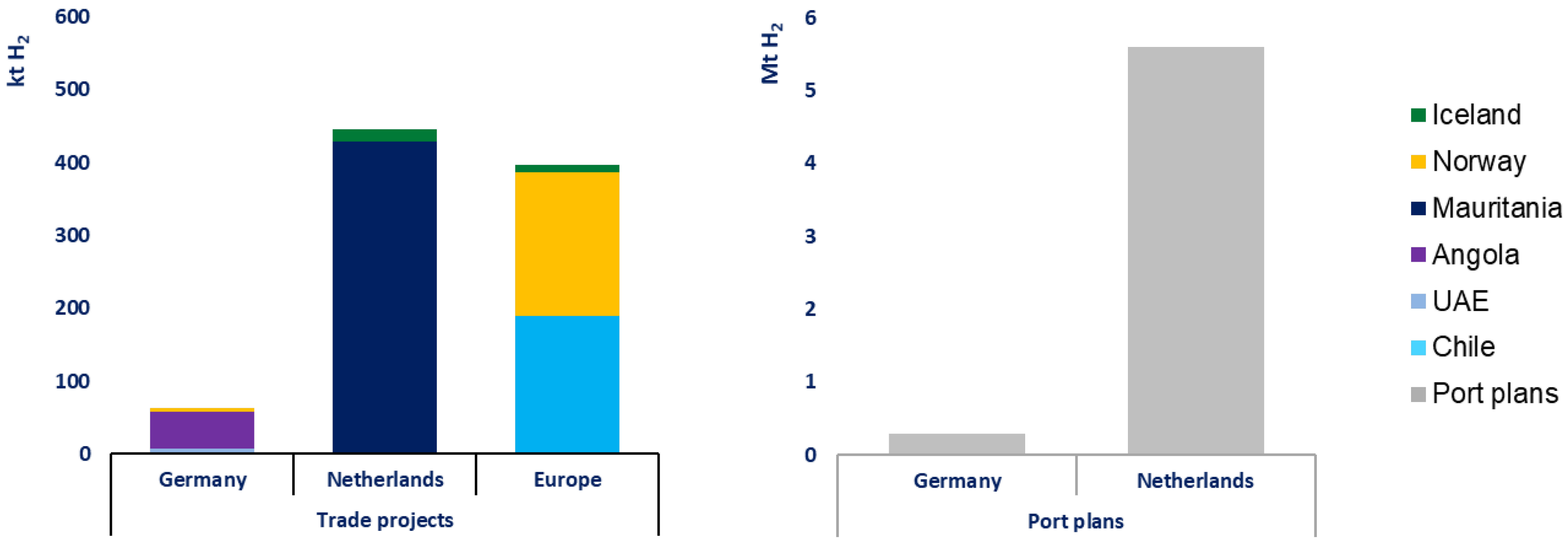
It was recently announced that some companies and governments are studying the possibility of hydrogen trade between Northwest European countries. The company Nordic Electrofuel plans to build a power-to-liquid plant in Porsgrunn, Norway by 2024, with electricity sourced from wind and hydropower and having an intial capacity of 8 kt of synthetic liquid fuels and waxes per year. The representatives of a joint venture among German energy and chemical companies have agreed to purchase the products. The Barents Blue Project, in northern Norway, is expected to start construction in the second half of this year. In the first phase, it will produce 1 Mt ammonia per year from natural gas, with the CO_2 being captured and stored. The product could be exported to the European market.

The role of the ports in the Northwest European region is fundamental in the creation of a new import market for clean hydrogen. The major ports in the Netherlands, namely the Port of Rotterdam and the Port of Amsterdam, have plans for importing a combined amount of more than 5 Mt H_2 by 2030. In addition, the Port of Rotterdam has signed more than 20 MoUs and partnerships with partners all around the globe, to explore the potential and feasibility of exporting low-emission hydrogen to Northwest Europe. The Clean Energy Ministerial launched the Global Ports Hydrogen Coalition in June 2021. This Coalition is the first global forum that brings representatives from ports together with decision makers from governments as well as industry in order to accelerate low-carbon hydrogen deployment. It builds upon already existing dialogues about the potential for adopting hydrogen in ports operation, including, but not limited to, those at the International Association of Ports and Harbours (IAPH), the World Ports Climate Action Program (WPCAP) and the Hydrogen Council. Countries have also started, over the past three years, to establish cooperation agreements in the field of clean energy, hydrogen technologies, and also hydrogen trade, with counterparts mainly in Africa, Australia and the Middle East. These non-binding agreements help to identify the potential hydrogen trade routes and a geographical map of this nascent market.

The expansion of international trade in hydrogen and hydrogen derivatives will also require the build-up of transport infrastructure. Liquefied hydrogen trade still requires technology development. There is only one liquefied hydrogen demonstration project for hydrogen transport from Australia to Japan, with the first shipment delivered in February 2022. In comparison to hydrogen, ammonia is already a widely traded commodity. However, using ammonia as a hydrogen carrier would require a significant scale-up of the global supply chain. Using ammonia as a hydrogen carrier to achieve the REPowerEU's target of 10 Mt/yr hydrogen imports by 2030, would require over 60 Mt/yr of ammonia, or three times the current global trade volume. Moreover, if the end-uses require hydrogen, ammonia must be reconverted to hydrogen via ammonia cracking, which is an energy intensive process (consuming around 30% of the energy content of the ammonia).

The ports in Northwest Europe have a fundamental role to play in the nascent hydrogen trade market, but import projects will still be behind schedule at the end of the decade

Trade projects and port plans for hydrogen imports to the Northwest European Region by 2030



Notes: UAE= United Arab Emirates. The quantities of hydrogen carriers or derivatives are given in hydrogen equivalent terms. All projects are assumed to reach 50% of full output in the intended start year, and 100% in all subsequent years. For electrolytic hydrogen production powered by a combination of dedicated renewable sources, a capacity factor of 50% is assumed. Port plans refer to the Port of Rotterdam, Port of Amsterdam and Wilhelmshaven Hub, all of which have announced plans relating to the importing of hydrogen.

Interest in renewable energy-rich regions has increased in recent years, and new hydrogen trade routes could take shape

Selected agreements on hydrogen trade and cooperation between Northwest European countries and partner countries

Country	Country	Year	Type	Description
Netherlands	Portugal	2020	trade	Portugal and the Netherlands signed an MoU to strengthen cooperation in the development of green hydrogen. Their aim is to advance the strategic value chain of production and transport of renewable hydrogen, for which the ports of Sines and Rotterdam are expected to play an important role.
Netherlands	Canada	2021	cooperation, trade	The Prime Minister of Canada and the Prime Minister of the Netherlands agreed to the Canada-Netherlands Hydrogen MoU, with the aim to cooperate and further expand the role of hydrogen in building a cleaner future.
Netherlands	Uruguay	2021	cooperation, trade	In a joint agreement, the Netherlands and Uruguay agreed to establish a structured dialogue for cooperation in establishing export-import corridors for green hydrogen between Uruguay and The Netherlands.
Netherlands	Namibia	2021	cooperation, trade	During COP26, the Netherlands and Namibia agreed to sign a LoI on collaboration in the field of energy, in particular, green hydrogen. The goal is to stimulate the development of export-import hydrogen supply chains between both countries.
Netherlands	UAE, Oman	2022	trade	The Netherlands signed an agreement to cooperate more closely with the UAE and Oman in the field of clean hydrogen. The collaboration focuses, among other aspects, on setting up transport routes for hydrogen to the Netherlands as a gateway to Europe and developing technologies and standards for hydrogen.
Germany	Australia	2020	trade	Australia and Germany signed an agreement for a joint feasibility study to examine the development of a hydrogen supply chain between the two countries, covering production, transport, storage and use. The joint study will also examine technology research and identification of possible barriers for hydrogen development.
Germany	Saudi Arabia	2021	cooperation, trade	Germany and Saudi Arabia signed a declaration of intent aimed at fostering cooperation in the production, processing and transport of hydrogen from renewable energy sources, and in working together on specific projects.

Country	Country	Year	Type	Description
Germany	Chile	2021	cooperation, trade	The Ministers of Energy from Germany and Chile signed an agreement to boost cooperation on green hydrogen and announced the creation of a working group to identify viable projects and develop the supply chain, within the framework of the German-Chilean Energy Association.
Germany	Australia	2021	trade, technology	Germany and Australia aim to facilitate renewable hydrogen production in Australia and trade to Germany. In September 2020, the two countries had signed an agreement for a joint feasibility study on the hydrogen supply chain.
Germany	Norway	2022	trade	Norway and Germany signed a joint statement pertaining to cooperation on energy issues in order to implement large-volume hydrogen imports to Germany as quickly as possible. Both countries plan to examine how a pipeline connecting Norway to Germany would be constructed to transport low-emission hydrogen from Norway.
Germany	Namibia	2022	trade	Namibia's Mines and Energy Minister and Germany's Economic Affairs and Climate Action Minister signed a Joint Declaration of Intent (JDI) to cooperate in the production, applications and transport of green hydrogen and synthetic fuels. In 2021, Germany provided EUR 40 million in funding to boost Namibia's low-emission hydrogen production.
Belgium	Oman	2021	cooperation, projects	Belgium and Oman agreed to cooperate in the green energy sector, notably in the development of the Hyport Duqm Project in Duqm, Oman. Companies from both countries will create an international consortium for renewable hydrogen production and call for the implementation of standards for green certification at the same time.
Belgium	Namibia	2021	trade	The Minister of Energy of Belgium and the Minister of Mine and Energy of Namibia signed an MoU during COP26 in Glasgow, on cooperation in the field of green hydrogen, especially on import routes to Belgium.

Hydrogen demand

Demand creation will be crucial in creating a low-emission hydrogen market

Northwest Europe, mainly its refining and chemical industries, consumes over 4 Mt H_2 of hydrogen[4] each year. This equates to nearly 5% of global hydrogen demand and around half of European hydrogen consumption. Germany and the Netherlands together account for over half of the region's hydrogen demand, owing to their large refining and ammonia industries. Belgium and France together account for over 30% of the region's hydrogen consumption, while the share of the United Kingdom is around 10%.

Increasing the use of low-emission hydrogen will require not only the development of hydrogen production projects but also the willingness of the end-use customers to utilise it. The uptake of low-emission hydrogen will be a gradual process and necessitate the support of governments to incentivise demand creation since the early stages of market development.

The European Union's Hydrogen Strategy targets transport and mobility as the two main sectors in which the low-emission hydrogen has an immediate application to reduce and/or replace carbon-intensive hydrogen. In its Fit for 55 Package, the European Commission proposed a 50% renewable hydrogen target by 2030 for all hydrogen used in industry. The Council agreed in June 2022 that 35% of the hydrogen used in industry should come from renewable fuels of non-biological origin by 2030, and 50% by 2035. In the Fit for 55 Package, a 2.6% target was set for renewable fuels of non-biological origin in transport. The Council agreed on the target in June 2022.

Based on the announced targets, Northwest Europe's low-emission hydrogen consumption could reach close to 6 Mt H_2/year by 2030, with demand almost entirely concentrated in industry. Several steelmaking companies announced targets to use low-emission hydrogen by 2030. In all, this alone could create 40 TWh/year (1.2 Mt H_2/year) demand by 2030 in the Northwest European region.

Not all Northwest European countries have low-carbon hydrogen consumption targets or strategies. Those countries that set demand targets are aiming, in the first stage, to replace the current hydrogen consumption from fossil fuels with low-emission hydrogen.

[4] This excludes around 2 Mt of hydrogen present in residual gases from industrial processes used for heat and electricity generation, as this use is linked to the inherent presence of hydrogen in these residual streams, rather than to any hydrogen requirement. Hence, these gases are not considered here as hydrogen demand.

Austria

Austria's current hydrogen consumption is estimated at approximately 150 kt H2/year. It is largely concentrated in the industrial sector and is produced primarily from natural gas. The country is aiming to replace up to 80% of its fossil-based hydrogen with climate-neutral hydrogen in energy intensive industries by 2030. Replacing 80% of the current 150 kt H2/year consumption would translate into 120 kt H2/year (4 TWh/year) of carbon-neutral hydrogen demand by 2030.

Belgium

Belgium's total current hydrogen consumption, most of which is in the industrial sector, is around 15 TWh/year (0.5 Mt/yr). The updated version of Belgium's Federal Hydrogen Vision and Strategy does not include a forecast of future demand to 2030. It instead forecasts to 2050, estimating it to be between 125 and 200 TWh/year (3.75 – 6 Mt/yr, including hydrogen and hydrogen-derivatives).

The Strategy estimates that Belgium will import around 20 TWh of low-emission hydrogen (and hydrogen derivatives) by 2030 to cover its domestic demand as well as the transit to neighbouring countries.

The federal strategy also identifies four sectors in which hydrogen will play a key role, including industry, transport, buildings and flexibility services provided for the electricity grid.

France

According to France's National Strategy for the Development of Decarbonised and Renewable Hydrogen, the country's hydrogen consumption amounts to approximately 0.9 Mt H_2/year, and is concentrated in the oil refining, ammonia and fertiliser industries. The Law on Energy and Climate published on 8 November 2019 aims for the development of low-emission hydrogen with the prospect of meeting 20% to 40% of total industrial hydrogen consumption by 2030. This would translate into low-emission hydrogen consumption of between 200 and 400 kt H2/year by 2030.

Germany

Germany's current hydrogen consumption is around 55 TWh/year. The country's National Hydrogen Strategy foresees low-emission hydrogen demand between 90 and 110 TWh/year by 2030 (or 2.7-3.3 Mt H_2/year).

The German government has set up a number of policies to support the creation of demand for low-emission hydrogen. With the Act on the Further Development of the Greenhouse Gas Reduction Quota within the Scope of the Amendment of the Federal Emission Control Act (BImSchG) of May 2021, Germany transposed the EU Renewable Energies Directive (RED II) in transport into national law. By setting a greenhouse gas reduction quota of 25% by 2030, the EU requirements will be significantly exceeded. With the implementation of the EU Clean Vehicles Directive (Directive (EU) 2019/1161) binding minimum quotas for low-emission and zero-emission passenger cars, as well as light and heavy commercial vehicles (including buses in public transport) are specified for public procurement. From August 2021, the national law on the procurement of clean road vehicles (SaubFahrzeugBeschG) required minimum targets for the public procurement of low- and zero-emission road vehicles and for certain services with road vehicles. The EU Alternative Fuels Infrastructure Directive (RL 2014/94/EU-Alternative Fuels Infrastructure Directive - AFID) regulates the technical requirements of public refuelling and charging infrastructure for alternative fuels. As part of the implementation of the AFID, the Federal Government examined various implementation paths for the development of hydrogen refuelling stations.

The amendment to the CHP Act also aims to ensure that new biomethane and CHP plants are geared towards the use of hydrogen ("H2-ready"). It is envisaged that the existing paragraph 6 of the CHP Act will be expanded to new CHP plants with an electrical output of more than 10 MW that generate electricity on the basis of gaseous fuels and that have been approved under the Federal Emission Control Act after 30 June 2023. The plants can be converted as of 1 January 2028 to generate their electricity exclusively on the basis of hydrogen at a maximum of 10% of the costs that a possible new CHP plant with the same capacity would incur according to the current state of the art.

Luxembourg

Luxembourg's industrial hydrogen consumption is around 15 GWh/year (or 0.5 kt H_2/year). According to its Hydrogen Strategy, the country aims to switch 100% of its fossil-based hydrogen consumption to low-emission hydrogen by 2030. This would cause greenhouse gas emissions to drop by over 5 000 tonnes/year.

Netherlands

The Netherlands uses approximately 48 TWh/yr (or 1.4 Mt/yr) of fossil fuel-based hydrogen as feedstock in the industrial sector. The country's target is to substitute this and to generate incremental hydrogen demand in other sectors supplementing it with low-emission hydrogen.

In May 2022 the government announced that the use of renewable hydrogen in refinery processes will count for the renewable fuel transport obligation in place ("raffinageroute"). A sectoral quota for the industry is now being investigated, in line with the European proposal within the Fit for 55 Package.

The application of hydrogen as an energy carrier for mobility is an important and promising opportunity to contribute to zero emissions, as well as battery-electric options. The possibilities for the application of hydrogen as an energy carrier for mobility are still in an early phase of market development, and therefore the government has developed support schemes to stimulate the market uptake, similar to the one for hydrogen trucks. To this end, a covenant is being drawn which will be further developed into an action programme. In addition, several consortia have submitted project proposals for the development of hydrogen in mobility within the framework of the IPCEI mobility wave for hydrogen. The elaboration of these IPCEI projects is an integral part of the action programme.

Switzerland

Switzerland currently uses around 430 GWh/year (13 kt H_2/year) of hydrogen as feedstock in industry. The Swiss Energy Perspectives 2050+ anticipates a hydrogen demand of around 480 GWh/year (or 14.5 kt H_2/year) in the transport sector. Domestic low-emission hydrogen production should be able to cover the Swiss hydrogen demand until 2035.

United Kingdom

The United Kingdom envisions hydrogen being used to decarbonise heavy industry and provide greener, flexible energy across power, transport, and potentially heat through the 2020s and beyond. As set out in the UK Net Zero Strategy, the United Kingdom expects low carbon hydrogen demand to reach up to 40TWh by 2030, then increase significantly to 80-140 TWh in 2035 and to 240-500TWh by 2050.

UK policy development to support early demand from the industrial sector is initially focused on areas such as fuel switching in large "anchor sites" in industrial clusters and exploring the potential for electrolytic hydrogen use in dispersed industrial sites. The United Kingdom uses approximately 0.7 Mt of fossil-fuel based hydrogen per year, largely concentrated in the petrochemical industry. According to the country's Hydrogen Strategy, demand from industry for low-emission hydrogen as a fuel could range from 10 to 20 TWh/year (or 0.3-0.6 Mt/year) by 2030. Reaching 20 TWh/year would depend on the development of hydrogen transmission pipelines, enabling the connection of more dispersed industrial sites to low-emission hydrogen supply. Industrial fuel switching to low-emission hydrogen could translate to carbon savings of around 3 Mt/year by 2030.

Work across the United Kingdom continues to facilitate early rollout of hydrogen in transport applications, such as buses. It is also accelerating research, trials and demonstration of hydrogen use in an integrated manner across multiple transport modes such as heavy goods vehicles (HGVs), and in the maritime and aviation sectors. An example is the Tees Valley Hydrogen Transport Hub. The Renewable Transport Fuel Obligation (RTFO) aims to increase the use of renewables as a transport fuel. Hydrogen produced by electrolysis using renewable electricity, as well as biohydrogen, for example produced through methane reformation of biomethane, are supported through the scheme. The Department for Transport engaged with industry to provide more flexibility for renewable hydrogen suppliers in the support it provides under the RTFO, to unlock further investments.

In March 2021, the UK Government published a consultation paper on the amendments to the scheme which sought views on a number of issues related to hydrogen support, including expanding the scope of the RTFO to make renewable fuels of non-biological origin used in maritime, rail and non-road vehicles eligible for support. The Government's response to the consultation was published in July 2022. The increased flexibility of renewable power purchase agreement (PPA) supply was effective immediately through a guidance change.

The UK Government announced in its Net Zero Strategy that the United Kingdom would introduce a zero emissions vehicle (ZEV) mandate setting targets requiring a percentage of manufacturers' new car and van sales to be zero emissions each year from 2024, which could include hydrogen.

The UK aims to decarbonise its power system by 2035. In the winter of 2022, the UK Government intends to publish a consultation on Decarbonisation Readiness which would require all new build and substantially refurbished combustion power plants to demonstrate that they have a viable plan to decarbonise in future by converting to either CCUS or hydrogen generation technology. This will provide a decarbonisation pathway for unabated combustion power plants and could stimulate demand for hydrogen in power generation.

The UK Government is actioning its Net Zero Strategy commitment to explore the need and case for market intervention to support hydrogen to power applications. The UK Government's engagement with industry has demonstrated that the power sector has the potential to deliver a pipeline of both new and refurbished power projects that could provide a significant source of hydrogen demand and aid the development of the hydrogen economy. By 2030, it is hoped that 100%-capable hydrogen firing generation equipment will be available on the open market.

A consultation is being planned for late 2022 on design changes to the UK Capacity Market to better align it with net zero, including by supporting investment in low carbon technologies such as hydrogen-fired generation and creating pathways for the decarbonisation of unabated gas generation.

A range of research, development and testing projects are underway to assess the feasibility, costs and benefits of using 100% hydrogen for heating, ahead of a strategic decision in 2026 on the role of hydrogen in decarbonising heat. This includes first-of-a-kind heating trials – beginning with a hydrogen neighbourhood trial involving 300 homes (SGN's H100 Fife project in Levenmouth), followed by a larger hydrogen village trial by 2025, and potentially a hydrogen town pilot before the end of the decade.

The option of blending up to 20% hydrogen into the existing gas distribution network is also being explored, with a decision targeted in 2023 subject to the outcomes of the safety, technical and economic case and wider strategic considerations.

Low-emission hydrogen demand in Northwest Europe could reach close to 7 Mt/yr by 2030

Expected low-emission hydrogen consumption by Northwest European countries to 2030 based on the Northwest European countries' hydrogen strategies and roadmaps

Sources: IEA analysis based on various policy documents (hydrogen strategies, roadmaps and papers).

Infrastructure

Dedicated hydrogen infrastructure will be key for the large-scale deployment of low-emission hydrogen

The large-scale deployment of low-emission hydrogen will need to be underpinned by an effective and cost-efficient system for transmission and storage, strategically designed to connect supply sources to demand centres. Transmitting hydrogen by onshore pipelines is a mature technology. The first hydrogen pipeline system was commissioned in the Rhine-Ruhr metropolitan area in Germany in 1938 and remains operational. There are currently more than 5 000 km of hydrogen pipelines in the world, with more than 90% of them located in Europe and the United States.

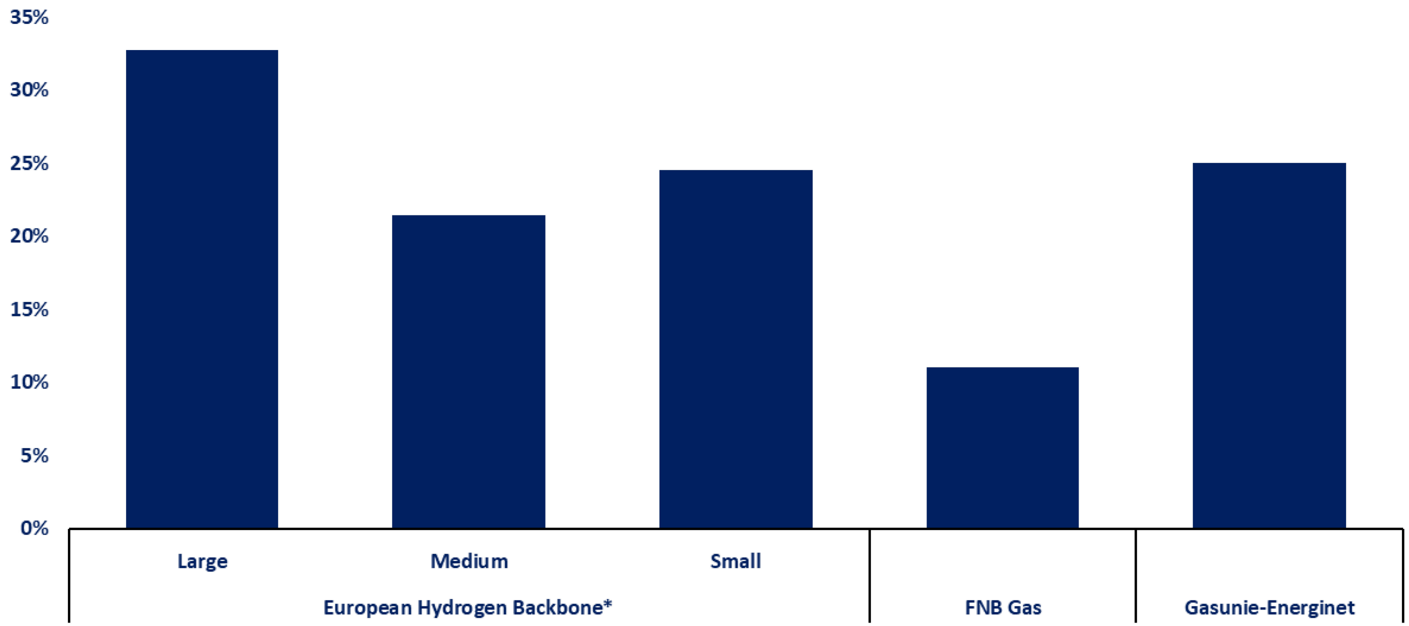
The development of a dedicated hydrogen transmission system will require the construction of new hydrogen pipelines and the conversion of existing natural gas pipelines into hydrogen service. According to the IEA's Gas Market Report Q3-2022, converting existing methane pipelines to hydrogen service can result in a substantial cost savings and shorter lead times when compared with new-build hydrogen networks. Repurposing gas pipelines to hydrogen service can cut investment costs by 50-80% compared to new pipelines. This in turn, could translate into lower transmission tariffs and improve the cost-competitiveness of low-emission hydrogen.

Recognising the strategic importance of developing a hydrogen network, governments are setting targets for hydrogen infrastructure development, often embedded in their hydrogen strategies. In addition, a group of 31 European gas infrastructure companies launched the European Hydrogen Backbone (EHB) initiative. The EHB aims initially to develop a hydrogen network of new and existing gas pipelines to connect local supply and demand, and later progressively connect European and neighbouring regions with export potential.

Low-emission hydrogen, as an energy vector could, like natural gas, enhance overall energy system flexibility by balancing short-term supply variability and meeting seasonal demand swings, thereby improving energy supply security. To fulfil this role, low-carbon hydrogen deployment will need to be coupled with the development of cost-effective, large-scale and long-term storage solutions. Hydrogen storage in salt caverns is a proven technology that has been used by the petrochemical industry since the early 1970s. In Northwest Europe there are currently three operational hydrogen salt caverns, all located in the United Kingdom. In addition, several pilot and demonstration projects are under development, including the repurposing of natural gas caverns into hydrogen service. The experience, to date, in storing hydrogen in porous reservoirs such as depleted fields or aquifers is limited, apart from demonstration projects for blending hydrogen in natural gas storage sites.

Gas-to-hydrogen pipeline conversions can result in substantial investment cost savings

Cost of repurposing natural gas pipelines for hydrogen as a percentage of building new hydrogen pipelines



* Including compressor station CAPEX costs. Notes: FNB = FNB Gas (Association of Supra-regional Gas transmission Companies in Germany).
Sources: IEA analysis based on FNB (2020), Netzentwicklungsplan (Network Development Plan) 2020; Gas For Climate (2022), European Hydrogen Backbone 2022; Gasunie-Energinet (2021), Pre-feasibility Study for a Danish-German Hydrogen Network.

Northwest European countries lead the way in infrastructure development

Northwest Europe has close to 1 600 km of hydrogen pipelines, accounting for over 95% of hydrogen pipelines operational in Europe. Most are closed systems owned by large merchant hydrogen producers and are concentrated near industrial consumer centres (such as petroleum refineries and chemical plants).

Achieving the ambitious targets for low-emission hydrogen deployment will require accelerating the development of hydrogen infrastructure. Based on the current targets set by Northwest European countries, the region's hydrogen network could increase by almost eight-fold to over 12 000 km by 2030. According to first estimates, close to two-thirds of the hydrogen pipelines operational by 2030 would be repurposed natural gas pipelines.

Austria

Austria is preparing an "Integrated Austrian Grid Infrastructure Plan" (NIP) which will be published by June 2023. To identify the flexibility options of Austria's future energy system, the plan integrates the planning of power and gas grids with the expansion of renewable energy. It analyses Austria's energy infrastructure needs until 2030 with an outlook to 2040. In addition , the Ministry for Climate Action and Energy has commissioned the "Gas Infrastructure in a Climate-neutral Austria 2040" study which will form the basis for a gas infrastructure roadmap for Austria, including hydrogen infrastructure.

With respect to hydrogen storage, Austria was one of the countries that pioneered the storage of hydrogen. From 2013 to 2017, Austria's Underground Sun Storage Project demonstrated the possibility of storing a blend of up to 20% of hydrogen and 80% methane in depleted fields. Currently, the continuation of the Project, called Underground Sun Storage 2030, explores the possibility of storing pure hydrogen.

Belgium

Belgium has over 600 km of operational hydrogen pipelines, with junctions around the ports of Ghent (North Sea Port) and Antwerp. The first hydrogen pipelines in Belgium were constructed in 1938 and were further developed through the 1960s and 1970s.

As noted in the Government's Hydrogen Strategy published in October 2021, given that Belgium already has 18 interconnection points with its European neighbours, the country is positioning itself as a relevant import and transit hub in Europe for low-emission hydrogen. The Government expects the future hydrogen network to connect the ports of Zeebrugge, Ghent and Antwerpen with the country's industrial areas and the adjacent countries.

Belgium allocated EUR 95 million to support the development of a low-emission hydrogen network. The first phase will be started with the commissioning of a minimum of 100 to 160 km of pipelines by

2026. At the time of writing, Fluxys, the country's gas transmission system operator (TSO), had already published five specific infrastructure proposals, of which two were still open for market participants to express their interest. According to the TSO, the necessary dimensioning of the network and the capacity, as well as the timing and phases, will be further defined during the Open Season based upon participants' feedback. Fluxys expects the first phase to be developed by mid-2026 and the open access hydrogen network by 2030. In addition to this, Belgium's TSO, the Port of Antwerp and the Port of Zeebrugge, and other relevant partners, are part of the Green Octopus project, which aims to create a hydrogen backbone between Belgium, the Netherlands and Germany with connections to both France and Denmark, fostering cross-border cooperation.

Denmark

In Denmark, Energinet, the Danish gas TSO, is considering the conversion of one of the two pipelines connecting Denmark and Germany. This would allow for the export of low-emission hydrogen by taking advantage of Denmark's renewables potential. There are two options being studied at present: (1) a hydrogen pipeline system running from Esbjerg with a length of 350 km (63% repurposed), and (2) a pipeline running from Holstebro with a length of 440 km (48% repurposed).

The Green Hydrogen Hub project, promoted by Corre Energy, Eurowind Energy and Gas Storage Denmark, is exploring the feasibility of hydrogen storage in a salt cavern with a working capacity of 200 GWh.

France

France has over 300 km of operational hydrogen pipelines. GRTgaz, the country's largest gas TSO, foresees the development of a hydrogen network of around 1 000 km by 2030. This will be made up of new infrastructure, as well as by converting part of the existing gas network. GRTgaz's Hy-Fen Project would consist of 800 km of pipeline between Fos-Marseille and the Grand-Est region, guaranteeing the connection between geographically distant production and consumption sites.

The mosaHYc (Moselle-Saar-Hydrogen Conversion) project is being developed in partnership between GRTgaz, the distribution network operator Creos Deutschland (Germany) and the energy company Encevo (Luxembourg). The aim is to convert two existing gas pipelines to 100% hydrogen transmission, connecting Völklingen, Perl (Sarre), Bouzonville and Carling (Moselle) over a distance of 70 km.

In April 2022, GRTgaz announced its RHYn project, which aims to promote the hydrogen ecosystem of the Upper Rhine by connecting the Dessenheim area with the Chalampé-Ottmarsheim industrial zone by 2028, as well as the Mulhouse agglomeration for its mobility needs. Out of a total of 100 km of hydrogen pipelines, at least 60 km will be converted pipelines.

France is also exploring the possibilities of hydrogen storage. The HyGéo Project aims to explore the possibility of hydrogen storage in a repurposed salt cavern with a capacity of 1.5 GWh. The HyGreen Provence Project is expected to be in operation in 2028 with a planned working storage capacity of 200 GWh. Engineering studies for the HyPSTER Storage Project began in 2021. The salt cavern would have a planned working capacity of 0.1 GWh during its first stage of development and would operate with multiple annual storage cycles. The first tests are expected to start in 2023. The Lacq Hydrogen Project considers the storage of hydrogen produced in Spain by water electrolysis using solar energy in Teréga's aquifers.

Germany

Germany has over 370 km of operational hydrogen pipelines. According to the Association of Supra-regional Gas Transmission Operators of Germany (FNB), Germany's hydrogen network would consist of 5 100 km of pipelines by 2030, with over 70% of them being converted natural gas pipelines. Fifteen infrastructure projects, with a planned total network length of around 1 700 km were pre-selected for the IPCEI on hydrogen. They are currently being prepared for formal notification by the European Commission.

Several pipeline repurposing projects are currently taking place. Under the HyPerLink Project, a 610 km repurposed pipeline will connect low-emission hydrogen production points with industrial clusters and storage facilities in the north of Germany and with its neighbouring European countries (including Denmark and the Netherlands). The H2ercules Project is expected to have a length of 1 500 km, mostly using repurposed pipelines, and is expected to start between 2026 and 2030. In addition, the Get H2 Nukleus Project, which is part of the H2ercules project, is expected to be in operation in 2024, repurposing 122 km of existing pipelines and constructing 14 km of new hydrogen pipeline to supply hydrogen to refineries and a chemical park. In addition, the Delta Corridor project aims to link major industrial clusters in the Netherlands and Germany by 2026, with a length of approximately 400 km.

In terms of underground hydrogen storage, there are several projects under development. EWE, a major German utility, and the German aerospace centre DLR are developing the HyCAVmobil Project which involves the drilling of a cavern in Rüdersdorf at a depth of 1 000 m in order to verify the hydrogen's quality during and after its storage. The project started leaching in 2021 and testing was to begin by the end of 2022. The investment costs are estimated at EUR 10 million. The Gronau-EPE Salt Cavern Project is expected to be operational by 2027 with a capacity of 115 GWh. The Energiepark Bad Lauchstädt Storage Project is set to have a capacity of 150 GWh and become operational by 2027. In addition, several projects are considering the repurposing of salt caverns, which currently store natural gas, into hydrogen service. Uniper plans to convert the former Krummhörn salt cavern storage facility to serve hydrogen with a storage volume up to 250 000 m^3. The project is expected to start commercial operations in 2024, with investment costs estimated at EUR 10 million.

Luxembourg

Luxembourg states in its Hydrogen Strategy published in September 2021, that it will rely primarily on interconnected infrastructure through its neighbouring countries – Belgium, France and Germany – to satisfy its potential green hydrogen demand. At the European level, the country will allow hydrogen to flow from West to East.

Netherlands

The Netherlands is one of the most advanced countries with respect to hydrogen infrastructure development, with a dedicated hydrogen network of around 300 km. The Netherlands was also the first country to undertake the conversion of a natural gas pipeline for full hydrogen service. The 12 km Yara-Dow pipeline has a throughput capacity of 4 kt H_2/yr and was put into commercial hydrogen service in November 2018. Gasunie carried out the repurposing, which took six to seven months.

In June 2022, the Netherlands announced the construction of a national hydrogen transportation network. According to the Ministry for Climate and Energy, EUR 750 million will be invested through 2031, with an additional EUR 35 million to be invested in storage. Approximately 85% of the network will consist of repurposed natural gas pipelines. The hydrogen network will be developed in three stages:

- 2022-2026: attention will be given to connecting the main industrial clusters located along the Dutch coast, as it is expected that the demand and supply of low-emission hydrogen will increase rapidly here. Connections with storage sites in the northern part of the Netherlands and interconnectors to Germany are also planned within this phase.
- 2026-2027/28: The rest of the industrial clusters will be connected in this phase. The already connected clusters in Rotterdam, the North Sea Canal area near Amsterdam and the northern part of the Netherlands will be further connected to the southeastern part of the Netherlands and also with Belgium.
- 2028-2030: the hydrogen network will be complemented by the southern route, or "loop" connecting all main industrial sites with each other, with the storage locations and neighbouring countries.

In addition, Gasunie is developing underground hydrogen storage, through its HyStock subsidiary. Between April 2021 and the summer of 2022, potential hydrogen storage was confirmed by a borehole into a salt cavern in Zuidwending. According to the company's plan, the first hydrogen storage cavern will be operational in 2026, with another four by 2030. Their combined capacity will be over 660 GWh.

Norway

Gassco, the Norwegian gas TSO, is exploring the possibility of repurposing the existing natural gas pipelines to hydrogen service, as well as developing newly built hydrogen pipelines to enable exports from Norway to Europe. In March 2022, Germany and Norway issued a Joint Statement on cooperation on hydrogen imports, including via offshore pipelines.

Switzerland

Switzerland has approximately 2 km of hydrogen pipelines, located in Monthey. Switzerland does not yet have a hydrogen strategy with specific targets, but it is developing a roadmap that will be launched in March 2023. This roadmap is expected to provide guidelines on the future hydrogen network and will also clarify to what extent the existing natural gas pipeline system can be repurposed. The country is currently assessing legislation related to hydrogen transportation.

United Kingdom

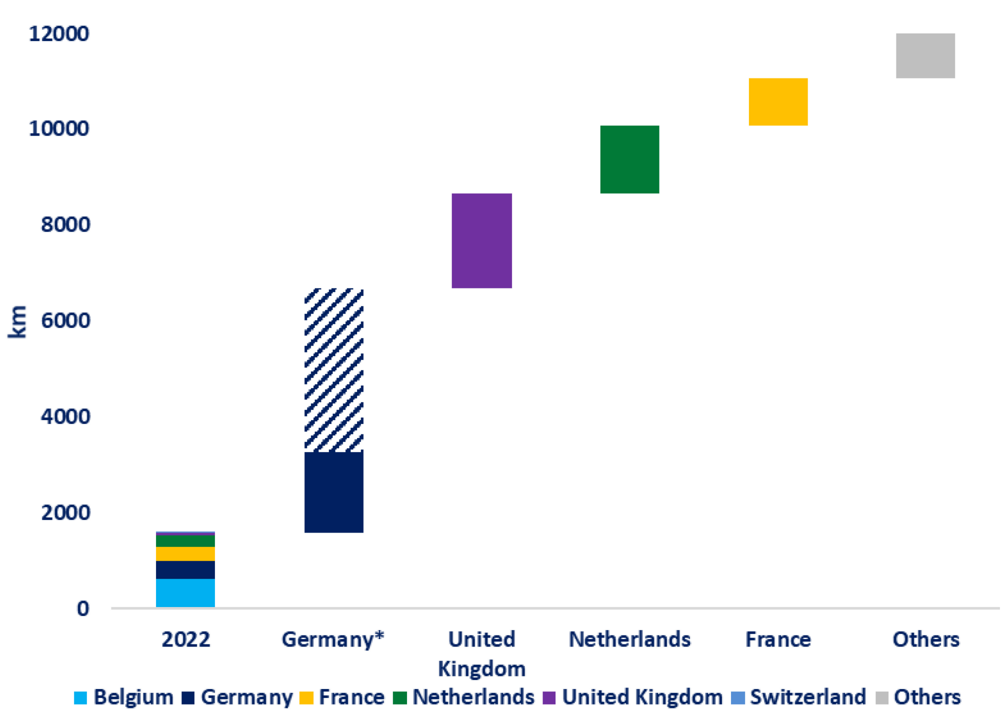
The United Kingdom has approximately 40 km of operational hydrogen pipelines. It has also one operational hydrogen salt cavern facility with three salt caverns, commissioned in 1972 at Teesside by Sabic Petrochemicals.

National Grid's Project Union is exploring the development of a UK hydrogen network to connect strategic hydrogen production centres with storage and consumption to support the creation of a UK hydrogen market. This project will identify potential pipelines routes, assess the readiness of existing natural gas assets and determine a potential transition plan for some of National Grid's transmission pipelines. The result could see the existing national transmission system repurposed in a phased approach to create a 2 000 km hydrogen network for the United Kingdom.

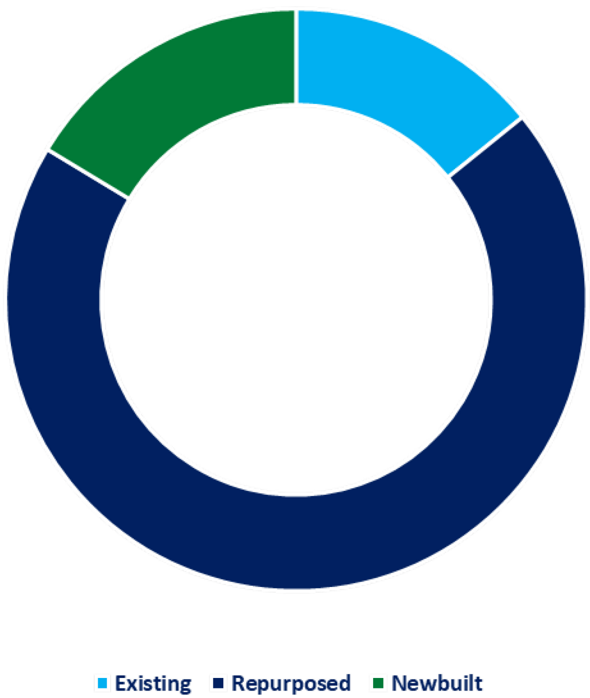
Some industrial clusters will produce CCUS-enabled hydrogen, and the UK government has recently identified the East Coast Cluster (Teesside and Humber) and HyNet North West clusters as a priority. There are also proposals to develop hydrogen pipelines to these clusters. The United Kingdom is also making progress in storage. Two salt cavern projects are undergoing feasibility tests for hydrogen storage: Humber Hydrogen Storage and HyNet (HyKeuper), with capacities of 320 GWh and 1,300 GWh, respectively.

Northwest Europe's hydrogen network could expand to over 12 000 km by 2030, largely supported by the repurposing of existing natural gas pipelines

Existing and planned hydrogen pipelines in Northwest Europe, 2021 and 2030



Hydrogen pipelines in Northwest Europe in 2030, by origin



* Fifteen infrastructure projects with a planned total network length of around 1 700 km were pre-selected in Germany for the IPCEI on hydrogen (indicated as solid fill). An additional 3 400 km were included as tentative projects based on scenarios developed by TSOs.
Sources: IEA analysis based on various reports from TSOs, announcements and media releases.

Planned projects for repurposing natural gas transmission pipelines to hydrogen

Name	Country	Start year	Institution	Length (km)	Description
Hydrogen Network Netherlands	**Netherlands**	2022	Gasunie	1 400	Gasunie will develop and operate the hydrogen network, which will consist of 85% repurposed natural gas pipelines. It will connect seaports with large industrial clusters in the Netherlands, storage facilities as well as neighbouring countries, Germany (Ruhr area and Hamburg) and Belgium.
Project Union	**United Kingdom**	2030	National Grid	2 000	The hydrogen network aims to link industrial clusters, repurposing around 25% of the current gas transmission pipelines. In 2022-23, National Grid will carry out a feasibility study to assess which pipelines could be repurposed and additional infrastructure needs.
Get H2 Nukleus	**Germany**	2024	OGE, RWE, BP, Evonik, Nowega	134	Repurposing 122 km of existing pipelines from Evonik and OGE to transport 100% hydrogen and construction of 14 km of a new hydrogen pipeline to connect to the Get H_2 Nukleus. It would supply hydrogen to the BP refineries in Lingen and Ruhr Oel refinery in Gelsenkirchen, and to the Marl Chemical Park.
H_2ercules	**Germany**	2026-2030	OGE, RWE	1 500	H_2ercules aims to link electrolysers, import terminals and storage facilities from the North with industrial consumers in the west and south of Germany, using mostly repurposed pipelines at an estimated cost of EUR 3.5 billion. The Get H_2 Nukleus project is part of H_2ercules.
HyPerLink	**Germany**	2025-2030	Gasunie	610	HyPerLink envisions a hydrogen pipeline network, connecting wind-based hydrogen producers, to storage and consumers in industrial and urban centres in Northern Germany. It will mostly repurpose existing gas infrastructure.
Danish-German Hydrogen network	**Germany, Denmark**	2030	Energinet, Gasunie	330-440	From Esbjerg (340 km, 63% repurposed) or Holstebro (440 km, 48% repurposed) in Denmark to industrial demand centres in Hamburg, Germany. The pre-feasibility study has been completed.
Green Octopus	**Belgium, Netherlands, Germany**	2022-2030	WaterstofNet, Gasunie, Fluxys, Ports of Rotterdam, Antwerp, Zeebrugge, etc.	-	Collaboration between Belgium, the Netherlands and Germany to establish a hydrogen network to integrate low-emission hydrogen produced from offshore wind and imports, with storage facilities and demand centres.
Hy-Fen	**France**	2030	GRTGaz	800	Hy-Fen will connect geographically distant production and consumption sites between Fos-Marseille and the Grand-Est region.

Planned underground hydrogen storage facilities

Name	Country	Project start year	Operator/developer	Working storage (GWh)	Type	Status
Green Hydrogen Hub	Denmark	2025	Gas Storage Denmark A/S, Corre Energy BV, Eurowind Energy A/S	250	Salt cavern	Feasibility study
HyGreen Provence	France	2028	Engie, Storengy	200	Salt cavern	Feasibility study
Stor'Hy Cerville	France	2026	Storengy	0.3	Salt cavern	Concept phase
Lacq Hydrogen	France	2026	Enagás, Teréga, DH2, GazelEnergie		Aquifer	Concept phase
HyGéo	France	2027	Teréga, Hydrogène de France	1.5	Salt cavern (repurposed)	Concept phase
H2 Gronau-EPE	Germany	2026	RWE Gas Storage West		Salt cavern	Feasibility study
Salthy	Germany				Salt cavern	Concept phase
WestKüste 100	Germany				Salt cavern	Concept phase
Energiepark Bad Lauchstädt	Germany		VNG Gasspeicher, ONTRAS Gastransport, Linde, Terrawatt, etc.	126	Salt cavern	Feasibility study
Krummhörn NG Storage	Germany	2024	Uniper	30	Salt Cavern	Concept phase
Rehden	Germany		Astora		Depleted gas field	Concept phase
HyStock	Netherlands	2027	Gasunie	670	Salt cavern	FID
HyKeuper	United Kingdom				Salt cavern	Concept phase
HySecure	United Kingdom	Mid-20s	Storengy, Inovvn	40	Salt cavern	Concept phase
Humber Hydrogen Storage	United Kingdom	2028	Equinor, SSE Thermal	320	Salt cavern	Feasibility study
HyNet	United Kingdom	2030	ENI, Liverpool Bay CCS Ltd., Cadent, CF Fertilisers, etc.	1000	Salt cavern	Feasibility study
Jemgum	Germany	-	Astora	250 (per cavern, 9 natural gas caverns)	Salt cavern	Concept phase

Note: Projects at the concept stage have been publicly announced, e.g., through the signing of an MOU, but for which the feasibility study has not yet started.

Regulation

Developing an effective regulatory framework will be crucial to fast-tracking the deployment of low-emission hydrogen

The regulatory framework for low-emission hydrogen is still nascent both at the level of the European Union and at the national level in Northwest Europe. While local specificities need to be taken into account, the development of national regulations should be harmonised in order to enable the development of an effective regional trade in low-emission hydrogen in Northwest Europe. Harmonised regulatory frameworks would also benefit cross-regional synergies in terms of production and demand creation.

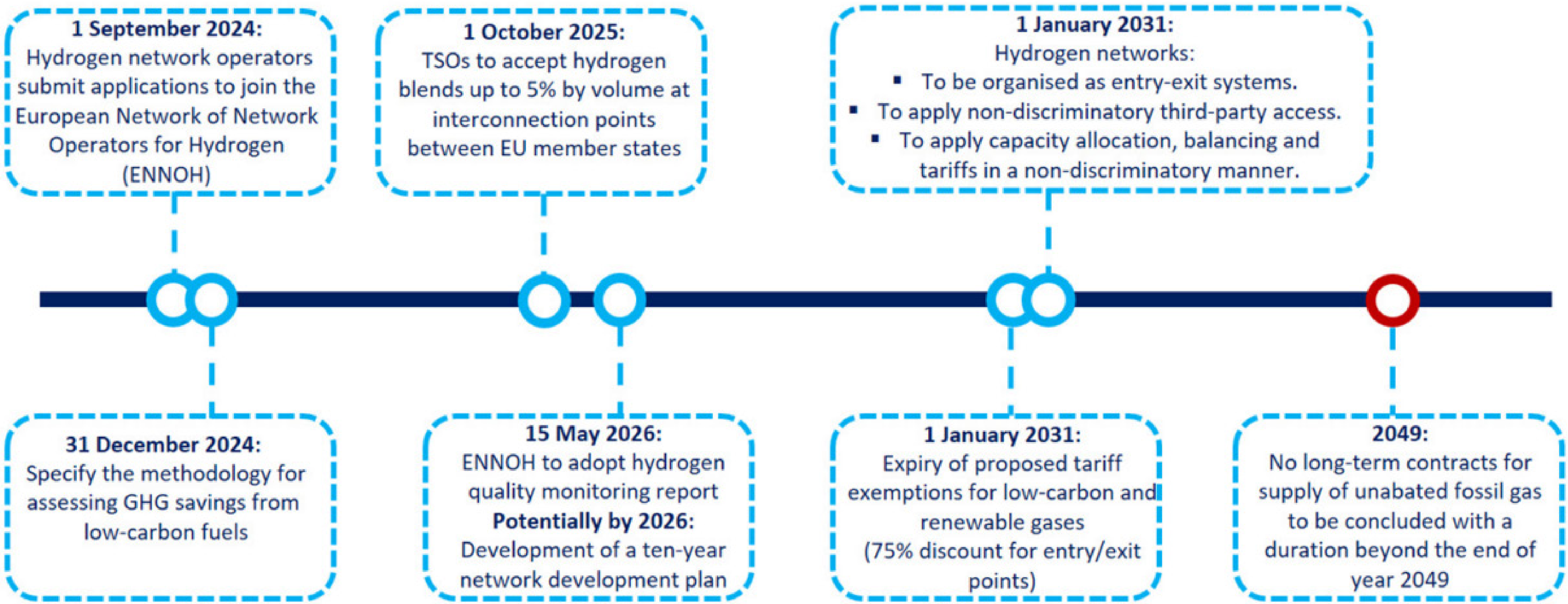
The Hydrogen and Decarbonised Gas Market Package

The European Commission published its Hydrogen and Decarbonised Gas Market Package in December 2021, including proposed amendments to the regulation on natural gas transmission networks and revision of the directive on common rules for the internal market for natural gas. The package lays down the foundations for the integration of low-emission gases, including hydrogen, into the broader European gas system.

The proposed regulation provides guidelines on the gradual implementation of non-discriminatory third-party access to hydrogen networks, blending limits, tariffs, network codes and operational transparency. To facilitate the initial integration of low-emission and renewable gases, the proposed regulation foresees abolishing cross-border tariffs and reducing injection costs by 75%. The tariff exemptions would remain in place until 1 January 2031. In addition, a 5% cap on hydrogen blends would be introduced by 1 October 2025 at interconnection points between member states to avoid cross-border flow restrictions due to differences in gas quality. To ensure the optimal management of an EU-wide hydrogen network and facilitate cross-border trade, a European Network of Network Operators for Hydrogen (ENNOH) would be established. Notably, ENNOH would publish non-binding, EU-wide, ten-year network development plans for hydrogen. Starting on 1 January 2031, hydrogen network operators would be organised under entry–exit systems and should allow non-discriminatory third-party access. Capacity allocation mechanisms, balancing rules and tariffs should also be set in a non-discriminatory manner.

As part of the European Union's legislative process, the proposed Hydrogen and Decarbonised Gas Market Package was referred to the Committee on Industry, Research and Energy (ITRE) of the European Parliament. ITRE provided amendments that are currently being negotiated. In the Council of the EU, the file has been discussed in the Working Party on Energy. The trialogue between the European Commission, European Parliament and the Council is expected to start in Q4 2022.

The European Commission’s Hydrogen and Decarbonised Gas Markets Package lays down the basic principles for the future regulatory framework on low-emission gases



Note: TSO = transmission system operator.
Sources: IEA analysis based on European Commission (2021), Hydrogen and decarbonised gas market package.

Harmonised hydrogen standards and certification schemes will be key to establishing a regional hydrogen market in Northwest Europe

The transition to low-emission hydrogen, both as feedstock and an energy carrier, will require the development of harmonised standards and certification schemes. Standards detail the methodology to calculate the carbon footprint of hydrogen production, transmission and distribution. Certification schemes can provide evidence of the emission intensity of a given unit of hydrogen.

Certification systems can be compliance driven or voluntary. Compliance-driven systems are used by market participants to evidence compliance with specific criteria set in the legislative acts of a given country or market area. Voluntary systems are used by market participants on a voluntary basis for reporting and disclosure purposes. Certification schemes and guarantees of origin will be key to enabling future regional trading of low-emission hydrogen.

Regulations for low-emission hydrogen are emerging in Northwest Europe

In the United Kingdom, the Low Carbon Hydrogen Standard Policy was published in April 2022 following a public consultation launched in August 2021. The regulation defines low-carbon hydrogen with an emissions intensity lower than 2.4 kg CO_2-eq/kg hydrogen. Hydrogen producers seeking support from certain UK Government programmes must comply with this standard.

In the European Union, the Commission published two drafts for delegated acts of the Renewable Energy Directive in May 2022: one to set out requirements for electricity used to produce hydrogen and its derived fuels, and one for a methodology to assess GHG emissions savings from renewable fuels of non-biological origin (including hydrogen and its derivatives) to contribute to national renewables targets. The drafts include an emissions threshold of 3.38 kg CO_2-eq/kg H_2 which is 70% lower than that of the predefined fossil fuel comparator including transport and other non-production emissions. The draft delegated act also incorporates the principle of additionality, i.e. electrolytic hydrogen production must use electricity from renewable power installations that were built no more than 36 months prior in order to ensure hydrogen's renewable electricity use is additional to existing generation. In September 2022, the European Parliament voted in favour of removing the principle of additionality. The final version of the delegated acts is expected by end-2022/early 2023.

Pilot certification schemes for low-emission hydrogen are being developed at the national level in the majority of the Northwest European countries covered in the Monitor. They remain in the early stages of development and are currently not harmonised. The table below provides a summary of the different certification schemes which are in place or planned in Northwest Europe.

Various national hydrogen certification schemes are being developed in Northwest Europe

Hydrogen certification schemes in the Northwest European countries

Country	Regulatory framework	National pilots	Guarantees of Origin (GoOs)	Issuing bodies	Remarks
Austria	Green gas certification and quotas for gas suppliers (quotas are still being discussed at the political level)	Not information provided	For renewable electricity and renewable gases	National Regulatory Authority (E-Control)	
Belgium	Federal Hydrogen Vision and Strategy supports development of a European voluntary certification scheme	Started a project to expand the existing register for RFNBOs to hydrogen	Electricity GoOs given out by the regions. H_2 product registrar in Flanders is Fluxys.	VREG (in Flanders)	
Denmark					
France	In early phase of development	Not being considered	Expected in 2023	To be designated in 2023	Besides GoOs, the French traceability system will also have guaranties of physical traceability (GTs).
Germany	Legislation (basic act) for implementation is presently in Parliament, finalisation expected by November 2022, entry into force by end of 2022. Ordinance with further operational detail presently under preparation, in Parliament before end of 2022.	To a limited extent on a voluntary basis within « dena Biogasregister »	For green and optionally for blue low-carbon H_2, (with CO_2 criterion).	To be determined. Most likely it will be Umweltbundesamt-herkunftsnachweis-register (Proof of Origin Register), already in charge of GoOs for electricity.	Proposal for future Gas/H_2 Market Directive Art. 8 adds reference to sustainability requirements, to mass balancing and to additionality criteria (DA). This will be subject to the Ordinance mentioned.
Luxembourg	Projet de Règlement grand-ducal	Not yet Developed	GoOs for renewable gases introduced	Institut Luxembourgeois de Régulation	Not yet Published

Country	Regulatory framework	National pilots	Guarantees of Origin (GoOs)	Issuing bodies	Remarks
Netherlands	Not yet. RED II and delegated acts are leading for the development of certification schemes.	Hydrogen GoO pilot was performed summer 2022. RFNBO certification pilot (based on draft delegated acts) to be performed in fall 2022.	Bill approved in May 2022 for renewable energy GoOs[5], including hydrogen.	Vertogas	Report over RFNBO pilot expected at the end of 2022.
Norway					
United Kingdom	The UK Low Carbon Hydrogen Standard (LCHS) guidance sets a maximum threshold for the amount of greenhouse gas emissions and the sustainability criteria around feedstocks allowed in the production process for hydrogen to be considered “low carbon hydrogen”. The LCHS guidance was published in April 2022.	The British Energy Security Strategy committed to introducing a hydrogen certification scheme by 2025.	Not yet developed.	Not yet determined.	The scheme should demonstrate high-grade British hydrogen for export and ensure that any imported hydrogen meets the same high standards that UK companies expect..
Switzerland	Legal basis for introducing GoOs for renewable gases is in place. An implementation concept and implementing provisions are being planned.		A basic certification system is in place under the oversight of the gas industry association, but Switzerland is planning a new system.	Pronovo (already issuing body for electricity GoOs. Provided for in the Swiss Energy Law).	At the beginning only the renewable gases will be covered. Later on the system will cover the low-emission carbon fuels as well.

[5] The bill regulates the legal basis and preconditions for the introduction of a system for guarantees of origin for other gas from renewable sources, such as hydrogen. Traders and suppliers can use guarantees of origin to prove that energy comes from renewable sources.

Harmonised hydrogen blending thresholds could facilitate the development of low-emission hydrogen trade in Northwest Europe

Blending low-carbon hydrogen into the existing methane stream can provide a transitional solution in the early phases of hydrogen market development and/or in cases where hydrogen demand cannot justify the development of a pure hydrogen network. Hydrogen can be injected in its pure form into the gas grid or as a premix with methane.

In Northwest Europe, of the ten countries included in the Monitor, six allow the injection of hydrogen into gas networks. Current blending thresholds in Northwest Europe range from 0.02% to 10% hydrogen by volume at the transmission level. Without the harmonisation of blending thresholds, the divergence of gas qualities in adjacent markets could occur and consequently lead to interoperability issues. While deblending is a promising technology (i.e. separation of hydrogen from the methane stream at a given exit point), national regulators and network operators should consider the harmonisation of blending thresholds so as to limit interoperability issues in the future.

The following section provides an overview of hydrogen blending limits in Northwest Europe:

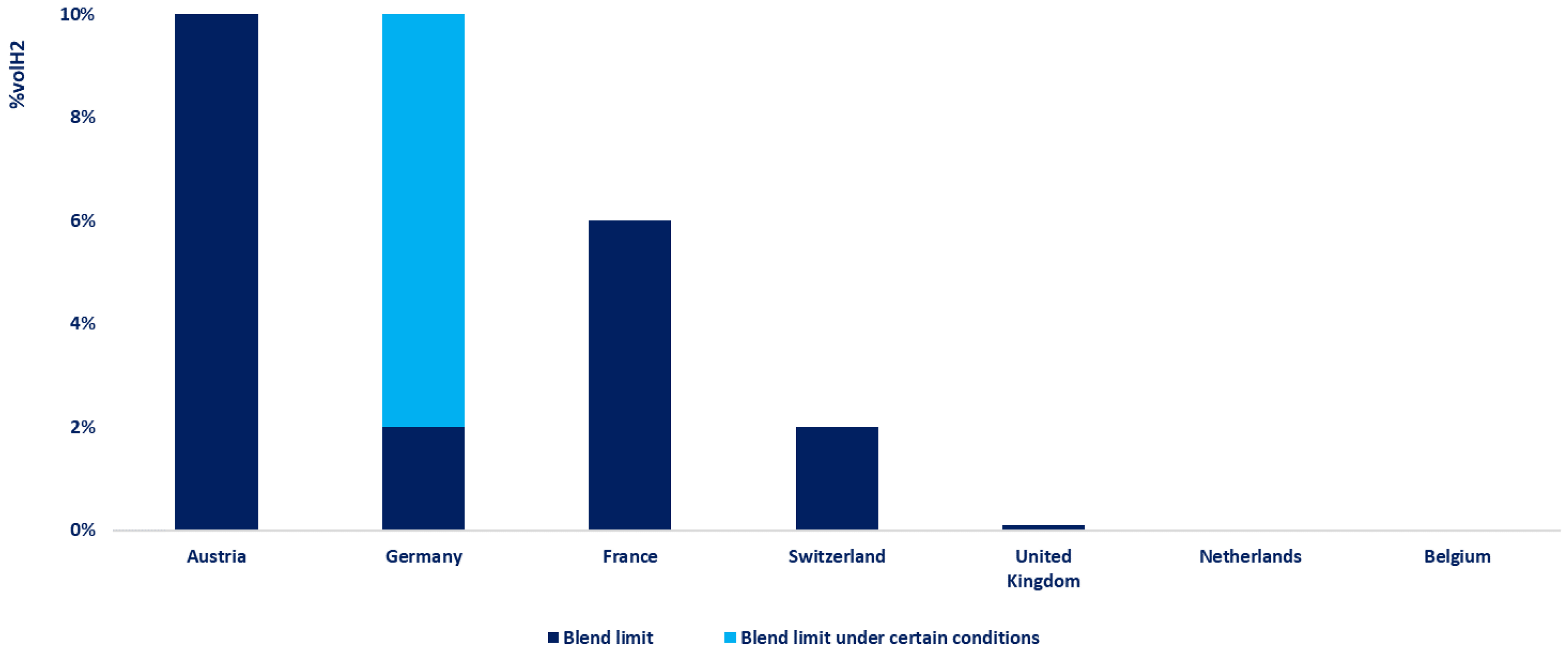
- In **Austria**, hydrogen can be injected into the gas grid as a premix. Until recently the hydrogen blending threshold was set at 4 vol%. With the new gas quality guideline G B210, which came into force on 1 June 2021, up to 10 vol% hydrogen can be fed into the gas network.
- In **Belgium**, hydrogen blending is not allowed, with the regulatory framework currently under revision. Belgium's National Development Plan includes a programme to install chromatographs that are able to measure the concentration of hydrogen in the transported gas.
- Similar to Belgium, no hydrogen blending is permitted in **Denmark**, although the TSO's own studies indicate that the network could withstand a hydrogen blend of 10 vol%.
- In **France**, gas quality standards allow for up to 6 vol% hydrogen concentration in the gas transmission system. A dedicated working group (including the regulator, French public administration, associations and gas operators) is assessing the rules and technical requirements for connection and injection. French TSOs are to promote a 10 vol% blending target by 2030.
- In **Germany**, hydrogen blending limits are defined by the German Technical and Scientific Association for Gas and Water (DVGW). According to the current DVWG rules

(Worksheet G 260 2021-09), a hydrogen content of less than 10 vol% in the natural gas network is possible, if no “sensitive” customer is connected to the network (e.g. gas filling stations for vehicles connected to the gas network limit hydrogen blending to 2 vol%). The technical rules are currently being revised and tested in initial pilots to enable blending rates of up to 20 vol% in the future.

- In **Luxembourg**, no regulatory framework is in place regarding hydrogen blending. The TSO is assessing the technical constraints and necessary measures to cope with different volumes of hydrogen in the gas transmission network.
- In **the Netherlands**, the current legislation (Gas Act) does not allow the TSO to accept pure hydrogen injection into the gas grid. As such, hydrogen can be injected as a premix with natural gas. At exit points, the limit in the high pressure grid is only 0.02 vol%. The Netherlands’ main focus is to develop a pure hydrogen backbone.
- In **Norway**, hydrogen blending is not permitted. The possibilities for injection hydrogen into the natural gas pipeline transmission system are being investigated.
- In **Switzerland** a hydrogen blend limit of 2 vol% is defined.
- In the **United Kingdom**, the Gas Safety Regulations 1996, define the concentration of hydrogen that can be injected into the gas networks at 0.1 vol%. The government is currently assessing whether to enable blending of up to 20 vol% into the gas networks. A policy decision is expected in 2023, subject to the outcomes of ongoing economic and safety assessments and wider strategic considerations.

Hydrogen blending thresholds are not currently harmonised in Northwest Europe

Current limits on hydrogen blending in natural gas networks in Northwest European countries



Source: IEA analysis based on various sources, including ACER (2020), ACER Report on NRAs Survey - Hydrogen, Biomethane, and Related Network Adaptations.

Costs of hydrogen production

High gas prices in the short- and mid-term can enhance low-emissions hydrogen competitiveness in the region

The reduction of production costs will be a key factor for enabling the large-scale deployment of low-emission hydrogen. This section provides an overview of the recent production cost dynamics of hydrogen in Northwest Europe and an outlook to 2030.

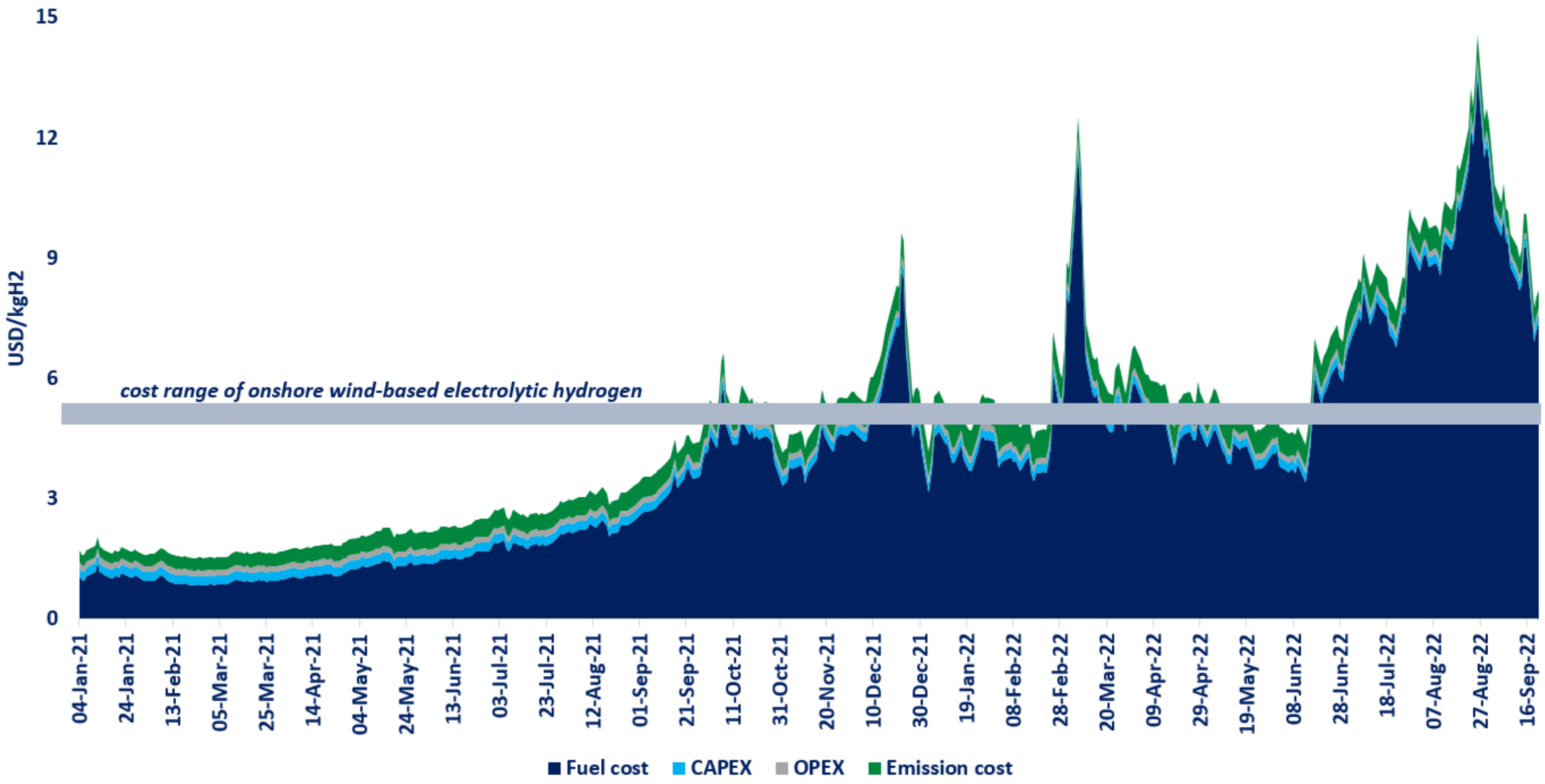
Recent production cost dynamics

The majority of hydrogen in Northwest Europe is currently produced via steam methane reforming (SMR) or autothermal reforming (ATR). Natural gas typically accounts for 70% of the levelised cost of production and for about 80% of the operating expenses. Considering the average natural gas prices of 2021, the levelised cost of hydrogen production (LCOH) via SMR was in the range of USD 1.7-2.4/kgH_2. Hence, low-emission hydrogen production routes were still not competitive with unabated production in Northwest Europe. The estimated levelised cost of hydrogen production considering solar PV-powered electrolysis prices in 2021 was about USD 8-11/kgH_2. Leveraging on the wind power potential of this group of countries, the estimated LCOH using wind power-based electrolysis was about USD 5/kgH_2 for onshore wind and roughly over USD 6 for offshore wind. The estimated LCOH for gas-based supply with CCUS was about USD 2.5-3/kgH_2.

Russia's strategic behaviour of using natural gas as a political weapon has intensified since its brutal invasion of Ukraine. Russia reduced its piped gas supplies to the European Union by over 50% year-on-year from the beginning of 2022. The steep reduction in Russian gas drove up European hub prices to all-time highs in 2022. Gas prices on the TTF – Europe's most liquid and widely traded hub – averaged USD 40/MMBtu through Q1-3 2022 which was more than six times the five-year average. In addition, carbon prices rose significantly in the region, driving up the production costs of unabated gas-based hydrogen further. Consequently, the assessed LCOH of unabated gas-based hydrogen production, considering the recent gas-price trajectories, rose from USD 1.7-2.4/kgH_2 in 2021 to over USD 5/kgH_2 through Q1-3 2022. The surge in gas prices contributed to 90% of the increase in estimated hydrogen production costs. Hence, the cost-competitiveness of hydrogen produced via SMR could be contested, both abated and unabated. The estimated LCOH of wind-powered electrolytic hydrogen, stood at USD 2/kgH_2 below the unabated SMR production route costs. Gas-based hydrogen production via unabated SMR would be competitive against onshore wind-powered electrolysis assuming a gas price below USD 20/MMBtu. As near-term gas futures indicate that the natural gas market will continue to be tight until at least the mid-2020s, this could provide incentives for industries to replace SMRs with electrolysers.

Record high gas prices could erode the cost-competitiveness of gas-based hydrogen in Northwest Europe in 2022

LCOH of gas-based hydrogen produced via SMR without CCUS
vs wind-based electrolytic hydrogen considering gas prices in 2021 and 2022



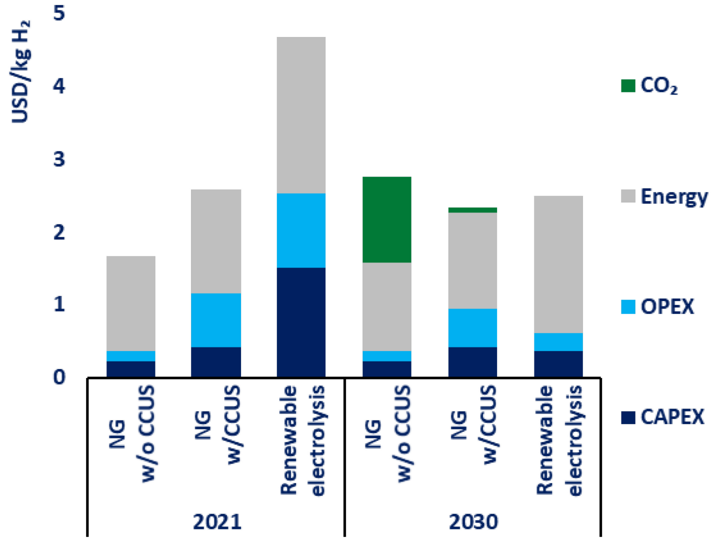
Hydrogen production cost outlook in Northwest Europe

By 2030, with a high-enough carbon price, hydrogen production via renewable electrolysis and gas-based supply with CCUS could both be cheaper than unabated gas-based supply in the region. Under the Announced Pledges Scenario (APS), renewable electrolytic hydrogen production costs could be in the range of USD 2.5-3.5/kgH_2. Natural gas with CCUS could be the cheapest production alternative at USD 2.3-2.7/kgH_2, below natural gas without CCUS (which we estimate at around USD 3/kgH_2), assuming that CO_2 prices reach USD 135/t CO_2.

The strong decline in the LCOH of low-emission hydrogen production relates to several factors, including decreasing electrolysis and renewable technologies' costs. Moreover, expectations of higher carbon prices benefit the prospective competitiveness of low-emission hydrogen. For example, we estimated the total cost of installing a European- or American-manufactured electrolyser in 2021 was about USD 1500/kW, and that it could decline to below USD 400/kW by 2030 in the APS. However, the cost evolution of these technologies is uncertain even in the near-term due to the current issues in clean energy technology supply chains and high raw material prices.

Energy costs are expected to play a more dominant role in the LCOH of renewable electrolysis, as electrolyser capital costs decrease. While the share of CAPEX costs over the total LCOH could remain at around 10-20% for natural gas-based production (unabated and with CCUS), the share of CAPEX costs in renewable electrolysis could go from around a third today to under 15% by 2030. By 2030, in the case of natural-gas-based production, the higher CAPEX and OPEX costs associated with CCUS systems could be more than offset by higher carbon prices. By 2030, having a carbon price over USD 135/tCO_2eq could ensure that the lowest renewable electrolysis LCOH is below the lowest unabated natural gas LCOH estimate in the region.

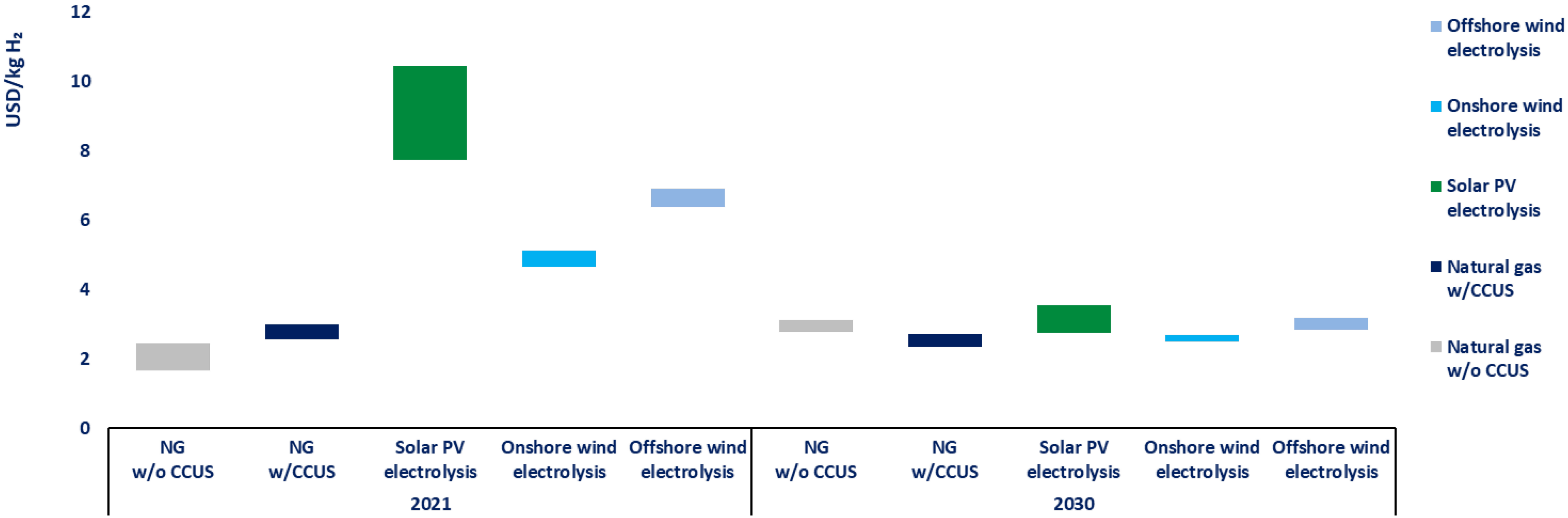
Cost-component breakdown for selected technologies, Northwest Europe, 2021-2030



Notes: NG = natural gas, CCUS = carbon capture, utilisation and storage. Renewable technologies considered included solar PV, onshore wind and offshore wind. The reported CAPEX and OPEX costs refer exclusively to electrolyser costs.

Low-emission hydrogen could become cost competitive with unabated natural-gas based production by 2030 in Northwest Europe

LCOH for selected technologies in Northwest Europe in the APS Scenario, 2021-2030



Notes: APS = Announced Pledges Scenario; LCOH = levelised cost of hydrogen; NG = Natural gas; NG w/o CCUS = natural gas-based hydrogen production without CCUS; NG w/CCUS = natural gas-based hydrogen production with CCUS. Ranges of production cost estimates reflect regional variations in costs and renewable resource conditions.

Assumptions: discount rate = 5%; system lifetime = 25 years; natural gas price = USD 30-38/MWh (2021) and 27-35/MWh (2030); solar PV electricity cost = USD 44-59/MWh (2021) and USD 30-39/MWh (2030); onshore wind electricity cost = USD 41-44/MWh (2021) and USD 39-41/MWh (2030); offshore wind electricity cost = USD 79-89/MWh (2021) and USD 48-55/MWh (2030); CO_2 price = USD 0-46/t CO2 (2021) and USD 135/t CO_2 (2030).

NG w/o CCUS: CAPEX = USD 780/kW H_2; OPEX = 4.7% of CAPEX; LHV efficiency = 76%; load factor = 95%.

NG w/CCUS: CAPEX = USD 1 470/kW H_2 (2021) and USD 1 460/kW H_2 (2030); OPEX = 4% of CAPEX; LHV efficiency = 69%; load factor = 95%; capture rate = 95%.

Electrolysis: CAPEX = USD 1 500/kWe (2021) and USD 390/kWe (2030); OPEX = 3% of CAPEX; LHV efficiency = 65% (2021) and 69% (2030); solar PV load factor = 12-16% (2021) and 13-17% (2030); onshore wind load factor = 37-42% (2021) and 37-42% (2030); offshore wind load factor = 51% (2021) and 55% (2030).

Annex

Summary table: key low-emission hydrogen projects in Northwest Europe

Expected capacity of the ten largest low-emission hydrogen projects in Northwest Europe by country and status (GW)

Name	Country	Project start year	Production capacity (kt H_2/year)	Type	Status
Lacq Hydrogen	France, Spain	2030	1000	Electrolysis	Concept phase
BrintØ - Hydrogen Island	Denmark	2030	1000	Electrolysis	Concept phase
HyNet Northwest	United Kingdom	2026 – 2030	900	Natural gas with CCUS	Feasibility study
AquaVentus	Netherlands	2025 – 2030	870	Electrolysis	Feasibility study
NortH2	Netherlands	2027 – 2030	700	Electrolysis	Feasibility study
DelpHYnus	United Kingdom	2027	450	Natural gas with CCUS	Feasibility study
Mitsubishi and Shell project	Netherlands	2030	400	Electrolysis	Concept phase
Get H2 Lingen	Germany	2023 – 2030	340	Electrolysis	Concept phase
H-Vision	Netherlands	2030	300	Natural gas with CCUS	Feasibility study
Keadby Hydrogen	United Kingdom	2030	300	Natural gas with CCUS	Feasibility study

Source: IEA (2022), Hydrogen Projects Database.

Regional and country groupings

Africa – Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of the Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe and other countries and territories.[1]

Asia Pacific – Australia, Bangladesh, Brunei Darussalam, Cambodia, Chinese Taipei, India, Indonesia, Japan, Korea, the Democratic People's Republic of Korea, Malaysia, Mongolia, Myanmar, Nepal, New Zealand, Pakistan, the People's Republic of China,[2] the Philippines, Singapore, Sri Lanka, Thailand, Viet Nam and other countries and territories.[3]

Central and South America – Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, the Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela and other countries and territories.[4]

Eurasia – Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan and Uzbekistan.

Europe – Albania, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus,[5,6] Czech Republic, Denmark, Estonia, Finland, the Former Yugoslav Republic of North Macedonia, France, Germany, Gibraltar, Greece, Hungary, Iceland, Ireland, Italy, Kosovo,[7] Latvia, Lithuania, Luxembourg, Malta, the Republic of Moldova, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine and United Kingdom.

European Union – Austria, Belgium, Bulgaria, Croatia, Cyprus,[5,6] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, the Slovak Republic, Slovenia, Spain and Sweden.

Middle East – Bahrain, the Islamic Republic of Iran, Iraq, Israel,[8] Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, the Syrian Arab Republic, the United Arab Emirates and Yemen.

North Africa – Algeria, Egypt, Libya, Morocco and Tunisia.

North America – Canada, Mexico and the United States.

[1] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cape Verde, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Niger, Reunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia, Swaziland and Uganda.

[2] Including Hong Kong.

[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, the Lao People's Democratic Republic, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guyana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, St. Kitts and Nevis, St Lucia, St. Vincent and the Grenadines, Suriname and Turks and Caicos Islands.

[5] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[6] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[7] The designation is without prejudice to positions on status, and is in line with the United Nations Security Council Resolution 1244/99 and the Advisory Opinion of the International Court of Justice on Kosovo's declaration of Independence.

[8] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Abbreviations and acronyms

AEM	anion exchange membrane
AFC	alkaline fuel cells
ALK	alkaline electrolyser
ATR	autothermal reforming
CAPEX	capital expenditure
CCfD	carbon contract for differences
CCGT	combined-cycle gas turbine
CCS	carbon capture and storage
CCU	carbon capture and use
CCOS	carbon capture and offshore storage
CCUS	carbon capture, utilisation and storage
CHP	combined heat and power
CfD	contract for differences
CO_2	carbon dioxide
CSA	Central and South America
EC	European Commission
EHB	European Hydrogen Backbone
EIB	European Investment Bank
EU	European Union
EU ETS	EU Emissions Trading System
EUR	Euros
EV	electric vehicle
FC	fuel cell
FCEV	fuel cell electric vehicle
FID	final investment decision
FT	Fischer-Tropsch
GBP	British pounds
GHG	greenhouse gas
GoOs	guarantees of origin
H_2	hydrogen
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
LH_2	liquid hydrogen
LHV	lower heating value
LNG	liquefied natural gas
LOHC	liquid organic hydrogen carrier
LOI	letter of intent
LPG	liquefied petroleum gas
MeOH	methanol
MOC	memorandum of collaboration
MOU	memorandum of understanding
NH_3	ammonia
NOK	Norwegian kroner
NO_x	nitrogen oxides
OPEX	operating expenditure
PEM	proton exchange membrane
PV	photovoltaics
RED	Renewable Energy Directive (EU)
R&D	research and development
RD&D	research, development and demonstration
RNFBO	renewable fuels of non-biological origin
SMR	steam methane reforming
SOEC	solid oxide electrolysis cell
TSO	transmission system operator
UK	United Kingdom
UN	United Nations
US	United States
USD	United States dollars

Units of measure

bcm	billion cubic metres
Gt	gigatonnes
GW	gigawatt
GWh	gigawatt-hour
kg	kilogramme
kg H2	kilogramme of hydrogen
km	kilometres
kt	kilotonnes
kt H2	kilotonnes of hydrogen
kW	kilowatt
kWh	kilowatt-hour
MBtu	million British thermal units
MJ	megajoule
Mt	million tonnes
Mt CO_2	million tonnes of carbon dioxide
Mt H_2	million tonnes of hydrogen
Mtpa	million tonnes per year
MW	megawatt
MWh	megawatt-hour
PJ	petajoule
t CO2	tonnes of carbon dioxide
tpa	tonnes per year
TWh	terawatt-hour
vol%	volume percentage

Acknowledgments, contributors and credits

This Northwest European Hydrogen Monitor was prepared by the Gas, Coal and Power Markets Division (GCP) of the Energy Markets and Security Directorate (EMS). This Monitor is the result of a collaboration of the countries involved in the Hydrogen Initiative of the Clean Energy Ministerial (CEM-H2I) workstream entitled "Roundtable on the North-West European Region" and the hydrogen working group of the Pentalateral Forum.

The analysis was led and coordinated by Gergely Molnár, Gas Analyst. The principal IEA authors and contributors were (in alphabetical order): Jose Miguel Bermudez Menendez, Javier Jorquera, Megumi Kotani, Gergely Molnár, Francesco Pavan, Amalia Pizarro Alonso, Javier Sesma Montolar. Carlos Fernandez Alvarez and Uwe Remme provided valuable comments and expert advice.

Special thanks to Peter Fraser (former head of GCP) for his support and guidance on the Monitor.

The Northwest European Hydrogen Monitor extensively benefited from the feedback and guidance provided by IEA's senior leadership, in particular Keisuke Sadamori, Director of the IEA Energy Markets and Security Directorate.

Members of the Northwest European Hydrogen Monitor Expert Panel provided essential data and information on hydrogen market developments in their respective countries. The members of the Expert Panel are:

Austria: Sarah Neumann (Federal Ministry for Climate Action and Energy)

Belgium: Pieter Deleu and Frederik Vanhuysse (Federal Public Service Economy)

Denmark: Søren Lyng Ebbehøj (PtX secretariat)

France: Tudor Florea (Ministry of Ecological Transition)

Germany: Michael Bakman (Geman Energy Agency), Michael Leibrandt (Federal Ministry for Economic Affairs and Energy), Kim Malin Lakeit (Geman Energy Agency)

Luxembourg: Pit Losch (Ministry of Energy and Spatial Planning), Jean-François Schneiders (Creos)

Netherlands: Carla Robledo and Rodrigo Pinto Scholtbach (Ministry of Economic Affairs and Climate Policy), Maartje Hofker (Gasunie)

Norway: Martine-Sorlie Espeland (Minister of Petroleum and Energy)

Switzerland: Markus Bareit and Melanie Ridoli (Swiss Federal Office of Energy)

United Kingdom: Jasmina Bide (BEIS), Simone Cooper-Searle (BEIS), Anthony Green (National Grid), Lara Hirschhausen (BEIS), Fintan O'Brien (BEIS), Ellie Sykes (BEIS), James Walker (Ofgem).

Many thanks to the IEA Communications and Digital Office for their help in producing the report, particularly to Astrid Dumond, Tanya Dyhin, Merve Erdil, Grace Gordon, Jethro Mullen, Isabelle Nonain-Semelin, Julie Puech, Lucile Wall, Therese Walsh and Wonjik Yang. Elspeth Thomson edited the manuscript.

The work could not have been achieved without the financial support provided by the Governments of Germany, Luxembourg, the Netherlands, Norway, Switzerland and the United Kingdom.

For any questions and comments, please contact: Gergely.Molnar@iea.org

IEA Publications
International Energy Agency
Website: www.iea.org
Contact information: www.iea.org/contact

Typeset in France by IEA - November 2022
Cover design: IEA
Photo credits: © Shutterstock