Northwest European Hydrogen Monitor 2024

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Abstract

Northwest Europe is at the forefront of low-emissions hydrogen[1] development. This region accounts for around half of Europe's total hydrogen demand, and it has vast and untapped renewable energy and carbon storage 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 low-emissions hydrogen from production sites to demand centres.

The development of low-emissions hydrogen in Northwest Europe could gradually scale up in the short- to medium-term. Northwest European countries now have the ambition to develop up to 30 to 40 gigawatts (GW) of electrolyser capacity by 2030. However, most low-emissions hydrogen projects are currently in the early stages of development. Their success will depend to a large extent on supporting policies and regulatory frameworks, with continuous monitoring of progress. The cost-efficient development of low-emissions hydrogen markets will also necessitate a regional approach that maximises existing synergies among national markets.

This is the second edition of the Northwest European Hydrogen Monitor. It provides an annual update of low-emissions hydrogen market developments in Northwest Europe, and is the result of 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 regular dialogues with key stakeholders to facilitate the exchange of information and data collection.

[1] When the term "low-emissions 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.

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Executive summary

Low-emissions hydrogen can play a significant role in decarbonising existing gas and energy systems and will be critical to the countries' efforts to meet their energy and climate targets. In addition to its environmental benefits, low-emissions hydrogen can help reduce reliance on fossil fuel imports in the medium-term, bolstering energy security.

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

Low-emissions hydrogen is defined here as hydrogen produced via electrolysis where the electricity is generated from a low-emissions source (renewables or nuclear), biomass, or fossil fuels with carbon capture, utilisation and storage (CCUS). A detailed overview of the terminology is provided in the Annex.

Northwest European countries are raising their low-emissions hydrogen targets

Adopting and implementing clear hydrogen strategies, including medium- and long-term targets, is considered essential to provide the necessary impetus and guidance for the development of hydrogen markets.

Since Russia's invasion of Ukraine, several Northwest European countries have doubled their hydrogen production targets, and others are considering increases. The majority of the countries in the region adopted production targets for electrolytic hydrogen, while Norway opted for a technology-neutral approach. Altogether, Northwest European countries now have ambition to develop as much as 30 to 40 gigawatts (GW) of electrolyser capacity by 2030. Nonetheless, recent market developments, inflation and cost increases might drive countries to revise their targets. In general, the focus has been on upscaling hydrogen production in many countries, though the attention is also rapidly shifting to stimulating demand.

The regulatory framework for low-emissions hydrogen continued to shape up in 2023

In addition to strong policy support, regulatory certainty is essential to unlock the investment necessary to scale up a low-emissions hydrogen market and facilitate cross-border trade.

Northwest European countries and the European Union continued to advance regulatory frameworks for low-emissions hydrogen in 2023. The delegated acts outlining detailed rules on the EU definition of renewable hydrogen were formally published in June 2023. In the United Kingdom, the Energy Act 2023 received Royal Assent in

October 2023. It creates a new comprehensive legislative regime for the energy system, with key provisions related to hydrogen business models and the regulation of hydrogen pipelines, as well as carbon dioxide (CO_2) transport and storage. And at the end of 2023, the European Union reached a formal agreement on the Hydrogen and Decarbonised Gas Markets Package, laying the foundations for the future European low-emissions hydrogen market.

Northwest European hydrogen production could reach 7 Mt by 2030…

Based on the IEA's [Hydrogen Production Projects Database](), Northwest Europe's production of low-emissions hydrogen (and derivatives) could reach just above 7 million tonnes (Mt) per year by 2030 if all planned projects become commercially operational (and taking into account assumptions on efficiency and utilisation factors). This would equate to approximately 2% of the region's total primary energy demand. Electrolytic hydrogen supply would contribute 55% of total low-emissions hydrogen production, while fossil fuel-based hydrogen projects equipped with CCUS would account for 45%. Based on announced projects, the United Kingdom, the Netherlands, Denmark and Germany are expected to account for three-quarters of Northwest Europe's low-emissions hydrogen production by 2030.

… however, less than 4% of low-emissions hydrogen projects are in advanced stage of development

According to the IEA's Hydrogen Production Projects Database, less than 4% of the projects that could provide low-emissions hydrogen supply by 2030 have been committed, meaning they are either in operation, have reached a final investment decision (FID) or are under construction. More than 95% are currently undergoing feasibility studies or are in the concept phase.

In contrast, in North America, 14% of potential low-emissions hydrogen supply by 2030 is supported by projects which are either operational, have reached FID, or are under construction. In China, projects which are either operational or are in a mature phase of development (FID and/or under construction) account for more than half of expected low-emissions hydrogen supply by 2030.

Scaling up of low-emissions hydrogen requires greater policy attention on demand creation

Creating demand for low-emissions hydrogen is a key instrument to stimulate investment in low-emissions hydrogen supply including via quotas, fuel standards and public procurement rules. Demand security is essential for the conclusion of long-term offtake agreements, which in turn can help to de-risk investment and improve the economic feasibility of low-emissions hydrogen projects.

Hydrogen demand in Northwest European currently stands at around 4.5 Mt per year, making up about 55% of OECD Europe's total demand and nearly 5% of total global demand for hydrogen. In line with the overall global trend, virtually all hydrogen consumption in Northwest Europe is concentrated in the refining and chemicals subsectors.

In the European Union, the revised EU Renewable Energy Directive (RED III) sets legally binding targets for renewable hydrogen use in industry and transport by 2030. The implied renewable hydrogen demand in Northwest Europe under RED III would be approximately 1.6 Mt by 2030, rising to 2.3 Mt by 2035. This is well below announced low-emissions hydrogen ambitions from Northwest European countries. Combined with the absence of economic incentives to bridge the cost gap between renewable and fossil fuel hydrogen, this helps explain the difficulty many projects developers currently face in securing offtake contracts.

Steep cost reductions are needed to make renewable electrolytic hydrogen competitive with unabated gas-based hydrogen

Initial price discovery suggests that renewable hydrogen prices stood almost three times of the assessed levelised cost of hydrogen (LCOH) from unabated gas in 2023. This highlights the need to improve the cost-competitiveness of low-emissions and renewable hydrogen. Under the IEA's Announced Pledges Scenario (APS), which assumes countries implement national targets in full and on time, the decline in renewable electrolytic hydrogen production costs, together with a carbon price of over USD 135 per tonne of CO_2-equivalent, could ensure that the levelised cost of hydrogen from renewable electrolysis is comparable with the LCOH from unabated gas in the region – and in certain cases, it would be lower.

Support measures should take a holistic approach and span the entire value chain

The relatively low share of committed projects highlights the need for a holistic approach to support the nascent low-emissions hydrogen sector. Scaling it up will require an effective, interlocking framework of subsidy schemes and support mechanisms along the entire value chain – including research and development, production, transportation and, in particular, 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-emissions hydrogen projects. Demand creation should be a key instrument to stimulate investment, including via quotas and public procurement rules. The European Union has launched the Hydrogen Bank, a key financial instrument which aims to de-risk investment in renewable hydrogen projects. Under the auctions carried out through the Hydrogen Bank, renewable hydrogen producers bid for a fixed premium to bridge the gap between their production costs and the price consumers are currently willing to pay. The first auction round, totalling EUR 800 million, attracted 132 project bids and accounted for 85 GW of electrolyser capacity, though only a small fraction of them were funded in the first round.

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

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

Based on announced projects that aim to trade hydrogen or hydrogen-based fuels, 16 Mt of hydrogen equivalent (H_2-eq) could be moved around the globe by 2030. However, three-quarters of export-oriented projects are in early stages of development. Less than one-third in terms of volume by 2030 have identified a potential offtaker. Countries in the Northwest European region account for three-quarters of global import volume by 2030 for which a final destination has been identified.

Instruments such as auctions can be used to create a bidding competition for contracts and help close the gap between production costs and the prices consumers are willing to pay. For example, Germany's H2Global auction-based mechanism will facilitate the conclusion of long-term import contracts for low-emissions hydrogen and hydrogen derivatives. The scale-up of international trade in hydrogen and hydrogen derivatives will also require building up transport infrastructure, including ports. Northwest Europe hosts 13 ammonia-handling facilities and 16 facilities that handle methanol, mainly concentrated in Germany, France and the Netherlands.

Northwest Europe's hydrogen network could increase tenfold by early 2030s, though firm investment commitments are lacking

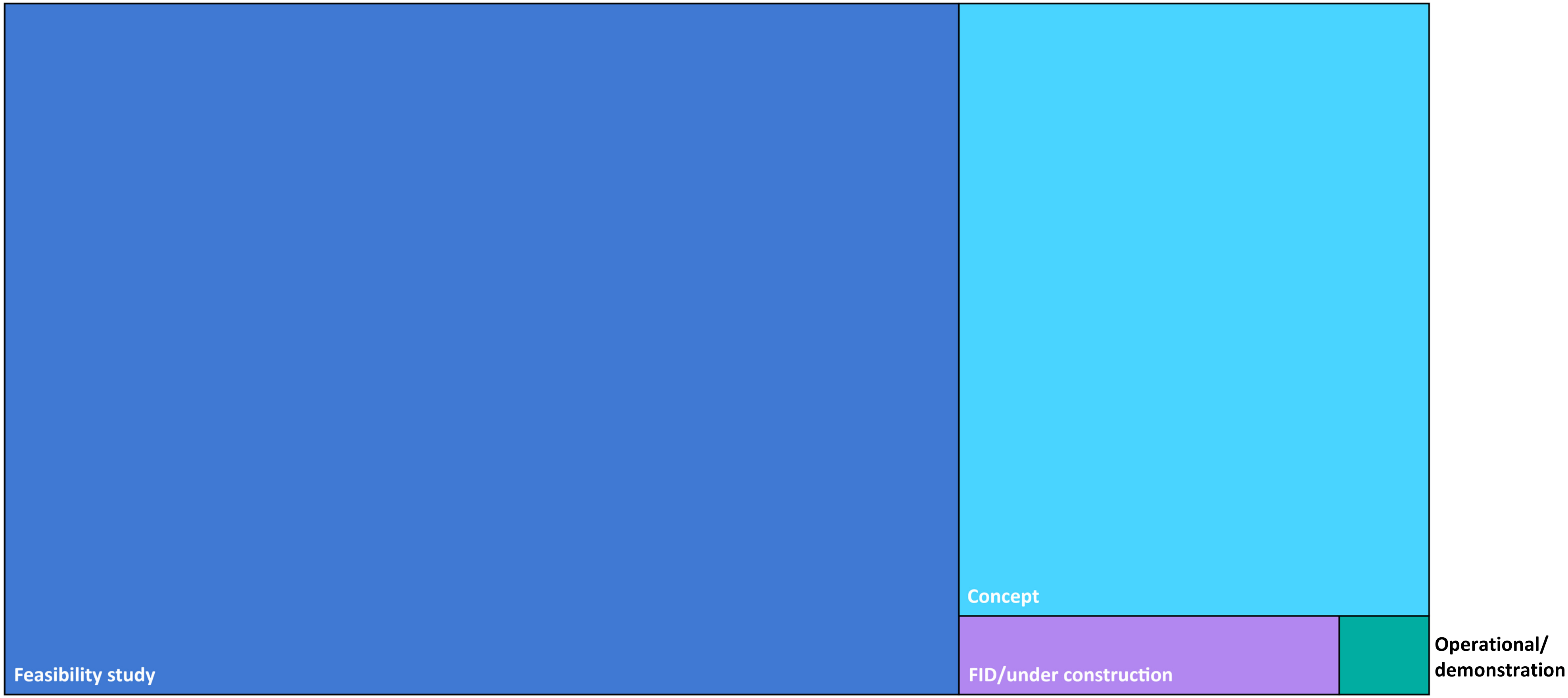
Achieving ambitious targets for low-emissions hydrogen deployment will require accelerating the development of hydrogen infrastructure for transport and storage. Based on pipeline project announcements, the length of the region's hydrogen network could increase tenfold to over 18 000 kilometres (km) by early 2030. However, the majority of announced projects lack firm investment commitments, which also reflects current uncertainty in demand. Close to two-thirds of the hydrogen pipelines that could be operational by 2030 would be repurposed natural gas pipelines. Repurposing existing natural gas pipelines to serve hydrogen can result in substantial cost savings and shorter lead times when compared with new-build hydrogen networks. This, in turn, could translate into lower transmission tariffs and improve the cost-competitiveness of low-emissions hydrogen.

Underground storage is essential to unleash the full potential of low-emissions hydrogen as an energy carrier

Developing underground storage capacity for hydrogen will be crucial for it to reach its full potential as an energy carrier and respond to the evolving flexibility requirements of a more complex energy system. Based on the IEA's [Hydrogen Infrastructure Projects Database](), Northwest Europe could develop over 3 terawatt-hours (TWh) of hydrogen storage capacity by 2030. However, just 10% of the expected capacity by 2030 has reached FID and/or is under construction. Considering the relatively long lead times of new-build hydrogen pipelines and hydrogen storage projects, concentrated and immediate action by all stakeholders would be required to meet the targets set for 2030.

Less than 4% of projects underpinning the expected low-emissions hydrogen production by 2030 have already reached a final investment decision or are under construction

Potential low-emissions hydrogen production in Northwest Europe in 2030 by status



Source: IEA (2024), Hydrogen Projects Database.

Hydrogen policies and regulation

Northwest European countries strengthened their hydrogen policies and regulations in 2023

Strong policy support and a clear regulatory framework are essential for the development of hydrogen markets. In policy terms, hydrogen strategies are crucial to set out the role of low-emissions hydrogen in the broader energy system and setting medium- and long-term targets. And besides strong policy support, regulatory certainty is essential to unlock the investment necessary to scale up a low-emissions hydrogen market and facilitate cross-border trade.

The European Union's Hydrogen Strategy, published in July 2020, sets out a vision to create a European hydrogen ecosystem and scale up production and infrastructure to an international dimension. It sets a target for 40 GW of renewable hydrogen electrolyser capacity by 2030. 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 of between 30 GW and 40 GW by 2030.

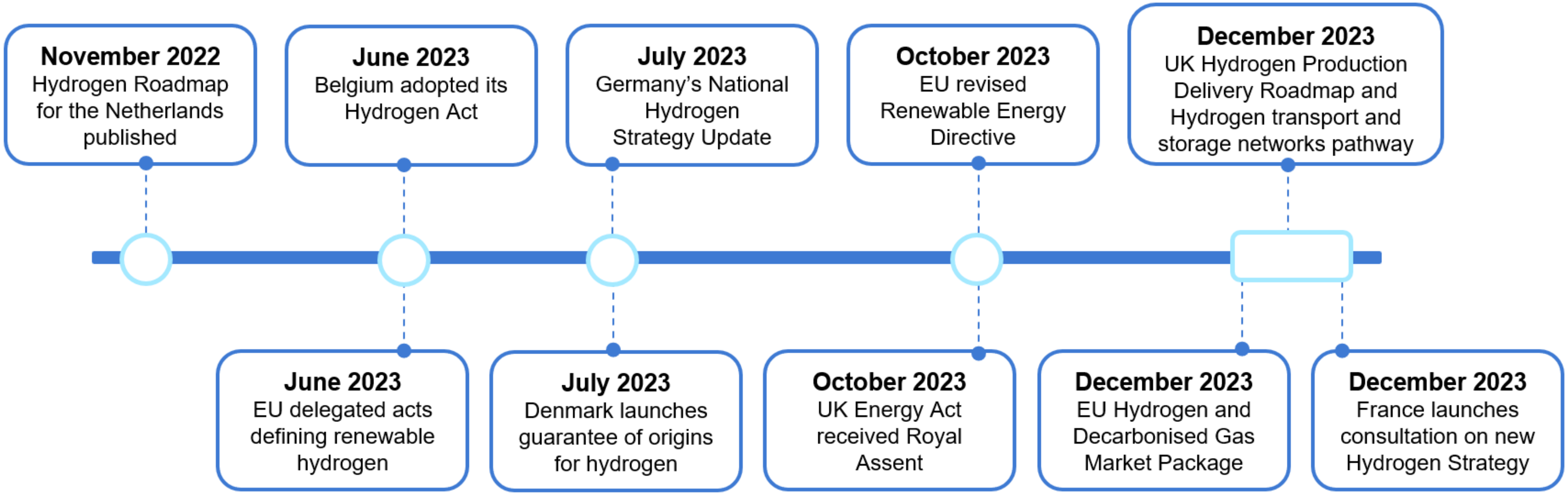
Since Russia's invasion of Ukraine, the European Union has raised its target for hydrogen production from 5.6 Mt to 10 Mt by 2030, complemented by 10 Mt of imports. Similarly, several Northwest European countries have doubled, or are considering increasing, their production targets. They include Germany, which doubled its electrolyser capacity target from 5 GW to at least 10 GW by 2030. The Netherlands is aiming for 3-4 GW of installed electrolyser capacity by 2030, while the Dutch parliament recently called upon the government to set a target of 8 GW installed capacity by 2032. In April 2022 the United Kingdom doubled its ambition for low-carbon hydrogen production capacity from 5 GW to up to 10 GW by 2030. In its Hydrogen Production Delivery Roadmap, published in December 2023, the United Kingdom set targets for 6 GW of electrolytic and 4 GW of CCUS-enabled hydrogen by 2030.

Northwest European countries and the European Union continued to advance the regulatory framework for low-emissions hydrogen in 2023. The delegated acts outlining detailed rules on the EU definition of renewable hydrogen were formally published in the EU Official Journal in June 2023. Belgium adopted its Hydrogen Act in July 2023, establishing a regulatory framework for the transport of hydrogen via pipeline. At the end of 2023 the European Union reached a formal agreement on the Hydrogen and Decarbonised Gas Markets Package, which lays the foundations for the future European low-emissions hydrogen market. In the United Kingdom, the Energy Act 2023 creates a new comprehensive legislative regime for the energy system, with key provisions related to hydrogen business models and the regulation of hydrogen pipelines, as well as CO_2 transport and storage.

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

Europe's regulatory framework for low-emissions hydrogen is shaping up

Key hydrogen policies and regulations enacted in the European Union and Northwest Europe since November 2022



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

EU regulation paves the way for an open and competitive low-emissions hydrogen market

The European Union has continued to advance the regulatory framework necessary for the scale-up of a low-emissions hydrogen market. This included the publication of detailed rules on the definition of renewable hydrogen and establishing a regulatory framework underpinning the operation of future hydrogen networks.

Delegated acts on the definition of renewable hydrogen

As foreseen under Articles 27(3) and 28(5) of the Renewable Energy Directive, in June 2023 the European Commission formally published two delegated acts outlining detailed rules on the EU definition of renewable hydrogen:

- The first act defines the conditions under which hydrogen, hydrogen-based fuels and other energy carriers can be considered as renewable fuels of non-biological origin (RFNBOs).
- The second act provides a methodology for calculating life-cycle greenhouse gas (GHG) emissions for RFNBOs to ensure a 70% reduction in CO_2-equivalent compared to the nearest comparable fuel.

The delegated acts provide regulatory certainty both to suppliers and consumers on the definition of renewable hydrogen, which is expected to help channel EU funds towards renewable hydrogen projects as well as guide the approval of national state aid schemes.

Certain industrial players have raised concerns on the complexity of the delegated acts, claiming that it could put at risk certain projects under development. The new rules apply to both domestic hydrogen producers and imports.

Three main criteria define what can be considered as renewable hydrogen:

- **Additionality:** Starting from 1 January 2028, renewable hydrogen producers will be required to ensure that electricity fed into their electrolysers is sourced from renewable energy installations no older than three years. Project developers are exempted from additionality until 2038 if their hydrogen installation is commissioned before 2028.
- **Temporal correlation:** Hydrogen production has to be matched to renewable electricity production on a monthly basis up until the start of 2030, when it will have to be matched within the same one-hour period.
- **Geographical correlation:** The renewable energy assets that feed the electrolysers producing hydrogen have to be located either: (1) in the same bidding zone as the electrolyser; (2) in an interconnected bidding zone, provided that electricity prices in the relevant time period on the day-ahead market in such interconnected bidding zone are equal to or higher than in the bidding zone where the hydrogen is

produced; or (3) in an offshore bidding zone interconnected with the electrolyser's bidding zone.

When electricity is sourced from the grid, hydrogen producers may count electricity taken from the grid as fully renewable in the following cases:

- If their installations are located in a bidding zone where the average proportion of renewable electricity exceeded 90% in the previous calendar year and the production of RFNBOs does not exceed a maximum number of hours set in relation to the proportion of renewable electricity in the bidding zone.
- If the installation producing the renewable liquid and gaseous transport fuel of non-biological origin is located in a bidding zone where the emissions intensity of the electricity is lower than 18 gCO_2-eq/MJ and the following criteria are met: (1) power purchase agreements with renewable electricity producers are concluded for an amount that is at least equivalent to the amount of electricity that is claimed as fully renewable; (2) the conditions of geographical and temporal correlation are met.
- If the electricity used to produce renewable hydrogen is consumed during an imbalance settlement period during which the hydrogen producer can demonstrate, that: (1) power-generating installations using renewable energy sources were redispatched downwards; and (2) the electricity consumed for the production of hydrogen reduced the need for redispatching by a corresponding amount.
- If the electricity is sourced by meeting the conditions on additionality, temporal correlation and geographic correlation.

The Renewable Energy Directive III sets hydrogen use targets

The revised EU Renewable Energy Directive (published in October 2023) sets legally binding targets for renewable hydrogen use in industry and transport by 2030. A detailed overview of the directive is provided under the Demand section of the Monitor.

Hydrogen and Decarbonised Gas Market Package

In December 2021 the European Commission proposed a hydrogen and decarbonised gas market package to establish common market rules for renewable and natural gases as well as hydrogen. This includes the review and revision of Gas Directive 2009/73/EC and Gas Regulation (EC) No. 715/2009. The Council and the European Parliament reached a provisional agreement on the proposal in December 2023, which is expected to be formally adopted in 2024.

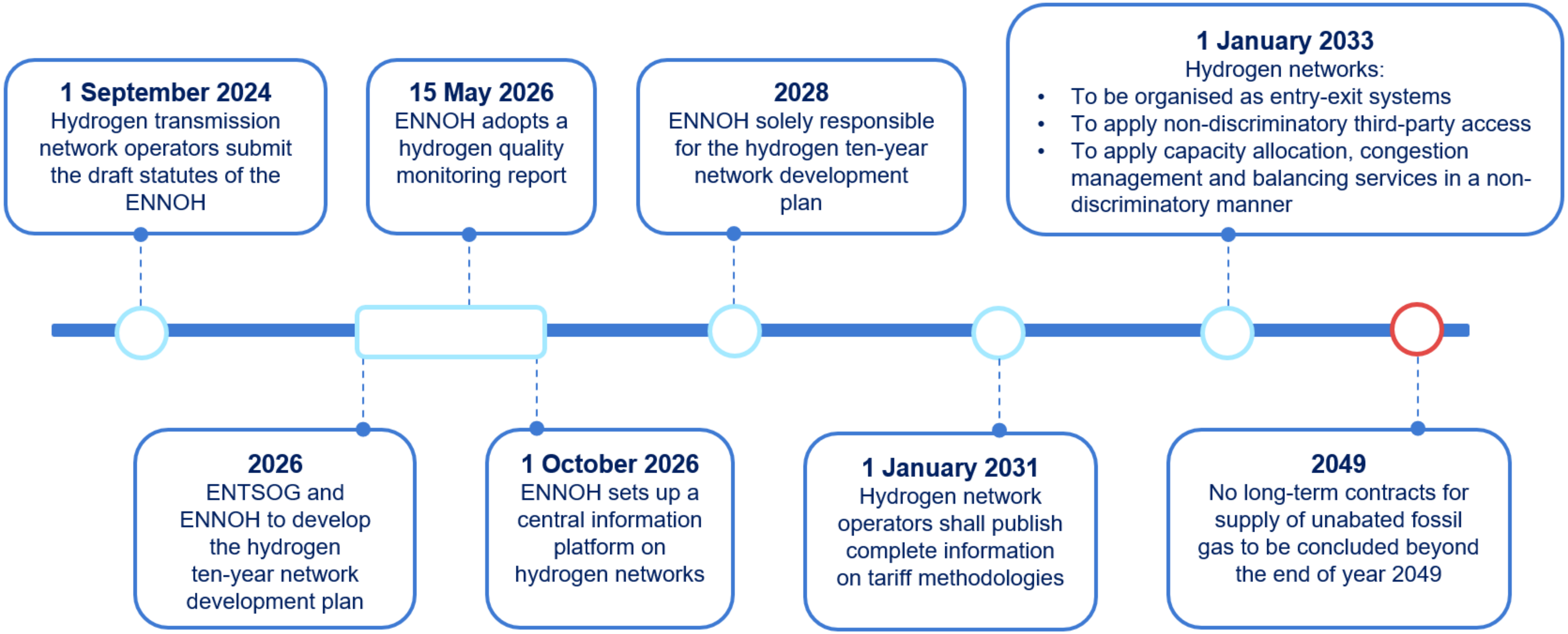
The Gas Directive **defines "low-carbon hydrogen"** as hydrogen derived from non-renewable sources, which meets the GHG emission reduction threshold of 70% compared to the fossil fuel comparator for RFNBOs. The Commission is to adopt delegated acts to specify the methodology for assessing GHG emissions savings from "low-carbon hydrogen".

In line with the current EU natural gas regulation, the new regulatory framework sets guidelines for the gradual implementation of non-discriminatory third-party **access to future hydrogen networks**, blending limits, unbundling, tariffs, network codes and operational transparency. The key provisions related to hydrogen include:

- **Unbundling:** The operation of hydrogen networks should be separated from activities of energy production and supply in order to avoid the risk of conflicts of interest on behalf of the network operators. Hydrogen transmission network operators should be unbundled two years after the entry into force of the directive. Besides ownership unbundling, the independent transmission system operator (ITO) model, which is used in natural gas legislation, is included as a possible unbundling model. Member states have the possibility of granting a derogation to the legal unbundling provisions, while existing hydrogen networks may be granted derogations to these requirements.
- **Non-discrimination:** As of 1 January 2033 hydrogen networks will be organised **as an entry-exit system** and apply rules on third-party access, capacity allocation, congestion management and balancing in a non-discriminatory manner.
- **Tariffs:** The national energy regulator will fix or approve tariffs for hydrogen network access in accordance with transparent criteria or their methodologies, or both. Tariffs should include remuneration for the network owner, which provides for adequate remuneration of the network assets and of any new investments made therein, provided they are economically and efficiently incurred.
- **Hydrogen network development:** Hydrogen transmission network operators are to submit to the relevant regulatory authority every two years a ten-year network development plan (while hydrogen distribution network operators are to submit such plan every four years). The regulatory authority will consult all actual or potential system users on the ten-year network development plan in an open and transparent manner. The regulatory authority will publish the result of the consultation process, including possible needs for investment, decommissioning of assets and demand-side solutions not requiring new infrastructure investment.
- **Blending:** The upper percentage limit of blending hydrogen into natural gas networks is set at 2% at cross-border interconnection points. Notably, such blending should be a last resort solution, as it is less efficient compared to using hydrogen in its pure form and diminishes the value of hydrogen.

The new regulation lays down the legal foundation for the establishment of the **European Network of Network Operators for Hydrogen** (ENNOH). ENNOH will consist of certified hydrogen transmission network operators in member states. By 1 September 2024 hydrogen network operators are required to submit to the European Commission and the EU Agency for the Cooperation of Energy Regulators (ACER) the draft statutes and procedural rules of ENNOH that have yet to be established. From 1 October 2026 ENNOH will operate a **central web-based platform** to provide market participants with all the relevant information necessary to access the hydrogen network. In addition, ENNOH will be responsible for developing ten-year hydrogen network development plans starting from 2028.

The European Union's Hydrogen and Decarbonised Gas Markets Package lays the foundations for the future European low-emissions hydrogen market



Notes:

ENTSOG = European Network of Transmission System Operators for Gas.
ENNOH = European Network of Network Operators for Hydrogen.

Sources: IEA analysis based on European Council (2023), Proposal for a Regulation of the European Parliament and of the Council on the internal markets for renewable and natural gases and for hydrogen (recast); European Council (2023), Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen (recast).

Northwest European countries continued to strengthen their policy and regulatory frameworks for low-emissions hydrogen

Austria set a target for 1 GW electrolyser capacity by 2030

Austria published its National Hydrogen Strategy in June 2022. The clear focus of the strategy is on the deployment of renewable hydrogen. However, apart from renewable hydrogen, it also includes climate-neutral hydrogen in its proposals – especially for use in industry – which encompasses hydrogen produced from fossil natural gas with complete CO_2 separation or pyrolysis. When using hydrogen from fossil natural gas, it has to be ensured that CO_2 separation occurs without the emission of GHGs, and that there are no GHG emissions along the entire value chain (life cycle).

Austria's Hydrogen Strategy has a target of **1 GW electrolyser capacity** for the production of renewable hydrogen by 2030 and aims **to replace 80% of current consumption of fossil-based hydrogen** with climate-neutral hydrogen in energy-intensive industries by 2030. The strategy foresees the creation of a supporting framework for the production of renewable hydrogen, the development of a targeted hydrogen infrastructure and the enhancement of international partnerships for climate-neutral hydrogen. In addition, it aims to the strengthen Austria's innovation and technology potential through the focused development of hydrogen technologies.

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; and (8) setting priorities at the European and international level.

Furthermore, the government adopted a draft **Renewable Gas Act** and submitted it to parliament in March 2024 for approval. The act foresees a rising renewable gas quota for biomethane and renewable hydrogen. Up to the end of 2030 gas providers will be legally bound to substitute 7.5 TWh of natural gas sold to customers with renewable gas. Details regarding these regulations are currently under discussion.

Belgium adopted its Hydrogen Act in 2023

The Belgian **Federal Hydrogen Strategy** was approved by the Council of Ministers in October 2021 and was updated in October 2022. According to the Federal Hydrogen Vision and Strategy, the total domestic demand for both H_2 molecules and H_2 derivatives will increase to between 125 TWh and 200 TWh per year by 2050 (bunkering fuels included). In its National Recovery and Resilience Plan, Belgium set a target to have at least 0.15 GW of electrolysis capacity in operation by 2026.

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 use to decarbonise industry and transport. More specifically, **the strategy is based on four pillars:**

- Positioning Belgium as a hub for the import of renewable molecules for Europe.
- Consolidating Belgium's leadership in hydrogen technologies.
- Organising a robust hydrogen market.
- Focusing on co-operation.

In July 2023 Belgium's parliament adopted the **Hydrogen Act**, which establishes a regulatory framework for the transport of hydrogen via pipeline and aims to promote the optimal development of the Belgian hydrogen market.

Among its key provisions, the Hydrogen Act:

- Guarantees non-discriminatory access to the hydrogen transport network for all interested parties.
- Defines the rules and procedures for preparing the network development plan and for setting regulated network tariffs.
- Regulates the designation of the hydrogen network operator.
- Designates the Commission for Electricity and Gas Regulation (CREG) as the regulator for hydrogen transmission.

In line with the procedure laid down in the Hydrogen Act, companies may until 30 November 2030 apply to be certified as the hydrogen transport network operator (HNO). Applications are assessed by the Directorate-General for Energy of the Federal Ministry of Economy, SMEs, Self-employed and Energy and the energy regulator CREG. The HNO will thereafter be designated by the federal Minister of Energy by way of ministerial decree. The HNO is expected to be designated and certified by March/April 2024.

The HNO's key responsibilities will include:

- Managing, developing and operating the hydrogen transport network in a safe, reliable, efficient and economically responsible manner.
- Preparing, every two years, a network development plan.
- Providing non-discriminatory access to the hydrogen transport network on the basis of the conditions set out in the code of conduct with respect to access to the hydrogen transport network.

Under the Hydrogen Act, CREG will establish a tariff methodology and publish it on its website. The HNO will thereafter propose tariffs in accordance with that tariff methodology, which must be approved by CREG before they can become effective.

Denmark sets a 4-6 GW target for electrolyser capacity by 2030 and launched guarantees of origin for hydrogen in 2023

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. Under its strategy, Denmark aims to build between 4 GW and 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. Reaching the electrolysis capacity target by 2030 is expected to entail CO_2 emission reductions of between 2.5 Mt and 4.0 Mt.

In July 2023 Denmark launched **a guarantee of origin (GO) scheme** for hydrogen and derivatives such as ammonia and methanol. The GO will certify the amount of hydrogen that has been produced with renewable energy sources. The scheme is expected to facilitate the development of hydrogen trading in the future.

In 2023 Denmark decided to allocate responsibility for hydrogen transmission networks to **Energinet** and the task of hydrogen distribution to Evida, the gas distribution company.

France launched a consultation process on its new Hydrogen Strategy at the end 2023

The National Strategy for the Development of Decarbonised and Renewable Hydrogen was published in September 2020. The 2030 targets for the decarbonised hydrogen development in France include:

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

At the end of 2023 France launched a consultation process on its **new Hydrogen Strategy**. The government identified the following strategic guidelines:

- **Production capacity targets:** Install 6.5 GW of electrolytic hydrogen production capacity by 2030 and 10 GW by 2035.
- **The scale-up of hydrogen transport infrastructure:** Give priority to the development of a network of hydrogen hubs, in particular the hubs of Fos-sur-Mer, Dunkirk, Havre-Estuaire de la Seine, and Vallée de la Chimie, and their connection to storage infrastructure.

- **Unequivocal support from the government:** Create a support mechanism worth EUR 4 billion for the deployment of decarbonised hydrogen production over 10 years.
- **A strategy open to the world:** Provide support to the French hydrogen sector in its international development, and support the emergence of a global market for hydrogen and its derivatives.
- **Focus on hydrogen-related technologies:** Strengthen the integration of the hydrogen ecosystem around French flagship projects and ensure coverage of all key products and technologies in the value chain.
- **Ensure that hydrogen can contribute to power system flexibility**, including through the development of hydrogen storage.
- **Guarantee the framework conditions necessary for the development of the French hydrogen sector:** Develop the regulatory framework, access to skills and land, and connection to the electricity network.

Germany adopted its National Hydrogen Strategy Update in 2023, targeting at least 10 GW of electrolytic hydrogen capacity by 2030

Germany published its National Hydrogen Strategy (NHS) in June 2020. The NHS laid down a coherent framework for the future production, transport and use of hydrogen and its derivatives, as well as setting a target for 5 GW of electrolytic hydrogen capacity by 2030. In July 2023 the German government published the National Hydrogen Strategy Update (NHS 2023) in order to meet higher climate protection targets and new challenges relating to the energy market after Russia's invasion of Ukraine.

NHS 2023 expects that around **95-130 TWh** of hydrogen will be needed by 2030 (up from 90-110 TWh in the previous NHS). To cover part of this demand, Germany plans to establish up to **at least 10 GW of generation capacity by 2030** (doubling the previous target of 5 GW). According to the federal government's assessment based on analysis of the current scenarios, around 50-70% (45-90 TWh) of the 95-130 TWh demand forecast for 2030 will be covered by imports from abroad (in the form of hydrogen and hydrogen derivatives).

NHS 2023 sets out the following work programme and targets until 2030:

- **Accelerated market ramp-up of hydrogen:** The market ramp-up of hydrogen, its derivatives and hydrogen application technologies will be significantly accelerated.
- **Domestic hydrogen production:** The target for domestic electrolyser capacity in 2030 will be increased from 5 GW to at least 10 GW. The remaining demand will be covered by imports.

- **Development of an efficient hydrogen infrastructure:** By 2027/28 a hydrogen start-up grid with more than 1 800 km of repurposed and newly built hydrogen pipelines will be established in Germany. With the continued expansion of the hydrogen grid, all major production, import and storage centres will be connected to the relevant consumers by 2030.[2]

- **Implementation of hydrogen applications in the sectors:** By 2030 hydrogen and its derivatives will be used in industrial applications, heavy-duty commercial vehicles in particular, and increasingly in aviation and shipping. In the power sector, hydrogen will contribute to the security of energy supply.

- **Technology leadership:** German suppliers are increasing their technology leadership and now offer the entire value-added chain of hydrogen technologies from production (e.g. electrolysers) to a variety of applications (e.g. fuel cell technology).

- **Creation of appropriate framework conditions:** Coherent regulatory conditions at national, European and, if possible, international level will support the market ramp-up.

An **import strategy** is planned as a follow-up to the NHS 2023. It is expected to cover topics such as technology imports, infrastructure, energy security and supply diversification. Furthermore, a **system development strategy** (SDS) is being developed. The SDS should provide a framework that guides subsequent processes, such as grid development plans for electricity and gas, as well as hydrogen.

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 has annual consumption of fossil hydrogen of about 450 tonnes. The immediate objective is to substitute fossil hydrogen with renewable hydrogen to cut GHG emissions by over 5 kt per year.

The Netherlands' Hydrogen Roadmap calls for higher hydrogen production targets

The Netherlands' strong hydrogen ambitions were initially stated back in 2019 in the National Climate Agreement and reinforced in 2020 with its Hydrogen Strategy. They continue to receive supportive legislation and funding. The Hydrogen Strategy focuses on scaling up hydrogen production by means of electrolysis and setting up a nationwide hydrogen transport infrastructure.

[2] Since the publication of the NHS, German gas transmission system operators have submitted a draft application for a "core hydrogen grid" to the national grid regulating authority. The draft foresees approximately 9 700 km of new and repurposed pipelines to be operational by 2032.

In the meantime, the current government allocated up to EUR 10 billion in funds for the support of hydrogen projects along the entire value chain, with more than half of the budget aimed at supporting electrolysis projects.

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

- 500 MW of electrolyser capacity in 2025 and at least **3-4 GW of electrolyser capacity in 2030**.
- Targets for the use of renewable hydrogen in industry that align with the European Union's Fit for 55 target.
- For mobility, 50 hydrogen refuelling stations in 2030, supplying renewable hydrogen (including use in refineries) in line with the European Union's Fit for 55 target.
- Home heating pilot schemes for approximately 1 000 homes by 2030.
- Development of a national hydrogen backbone of approximately 750-1 000 km of pipelines and approximately four salt caverns for hydrogen storage to be available by 2030.

In November 2022 the Dutch National Hydrogen Programme [3] published the Hydrogen Roadmap for the Netherlands, commissioned by the Ministry of Economic Affairs and Climate Policy. The roadmap suggests the **scaling up of production targets**: 600 MW of electrolyser capacity by 2025 and 6-8 GW of installed capacity by 2030, based on two conditions: (1) development of the offshore wind roadmap as planned; and (2) expanded government budgets to counter increasing costs. This would enable the production of around 80 PJ/yr of hydrogen by 2030 (equating to approximately 44% of the Netherlands' current industrial hydrogen consumption). The roadmap foresees **potential demand for renewable and low-carbon hydrogen** rising to 40-80 PJ in the industrial sector and to 18-58 PJ in the transport sector by 2030. It also expects **hydrogen imports** to scale up post-2025 and the development of a **hydrogen network** that provides access to storage facilities and connects all the large industrial clusters to one another and the Netherlands to its neighbours in about 2027-2030. As regards **storage**, the roadmap foresees the development of three or four salt caverns with a total volume of 750-1 000 GWh by 2030.

The **hydrogen market will be regulated** as of 2033 following the regulations established in the EU Hydrogen and Decarbonised Gas Markets Package. This will include regulations on tariffs, third-party access and the roles of private and public sector parties in transport, storage and import infrastructure. Until then, the transport of hydrogen has been declared a Service of General Economic Interest

[3] The Dutch National Hydrogen Programme is a public-private partnership for the joint realisation of ambitions and agreements in the field of hydrogen. It consists of representatives from the entire hydrogen sector, and relevant officials.

and a **Hydrogen Network Operator** (HyNetwork Services or HNS, state-owned and a subsidiary of Gasunie) has been appointed to operate it. A subsidy grant of EUR 750 million is to be provided to HyNetwork Services to cover its losses during the start-up phase.

The government also provided a policy framework for the import of hydrogen and hydrogen carriers in its letter to parliament, **Energy Diplomacy and Hydrogen Imports** (June 2023), stressing the importance of active energy diplomacy aimed at future security of supply of (renewable) hydrogen. The framework expresses a commitment to developing an integrated EU hydrogen market and the creation of a Northwest European onshore and offshore hydrogen backbone. Close co-operation with neighbouring countries will be crucial in this respect. The Netherlands is committed to developing bilateral strategic partnerships for the development of "**hydrogen corridors**" for trade within the European Union and for imports from beyond. The diversification of imports from a broad group of countries is important to reduce risks caused by strategic dependency.

To achieve this, the Dutch government:

- Has signed bilateral agreements on hydrogen and energy with strategic partners such as Australia, Canada, Chile, Denmark, Indonesia, Japan, Morocco, Namibia, Norway, Oman, Portugal, Saudi Arabia, Spain, Uruguay, the United Arab Emirates, the United States and South Africa.
- Is deploying the expertise and resources of state-owned entities (Invest International, Port of Rotterdam Authority, Gasunie) to develop hydrogen corridors and other necessary infrastructure.
- Is working closely with Germany through participation in H2Global (joint tender worth EUR 600 million to be launched by the end of 2024) and by working with Germany trilaterally with future exporting countries to develop corridors towards Northwest Europe.
- Is participating in the EU Hydrogen Bank.
- Is playing an active role in international organisations with the aim of creating a transparent and stable international hydrogen market, including through the International Partnership for Hydrogen & Fuel Cells in the Economy (IPHE), the Clean Energy Ministerial Hydrogen Initiative (CEM-H2I), the IEA Technology Collaboration Programme and the CEM International Hydrogen Trade Forum.

The government is currently working on policies for **hydrogen safety**. These policies are intended to provide guidance for projects and initiatives that fall outside the scope of current regulations. Several government bodies are working together to develop the policies, both to identify the most pressing subjects and projects, and to discuss and specify the policies themselves.

Several sections from the Hazardous Substances Publication Series (or PGS from the Dutch acronym) are also important for hydrogen roll-out. The PGS guidelines contain requirements and criteria that can be used in environmental licensing, drafting general rules and supervising companies for occupational safety, environmental safety and fire safety.

Norway adopted its 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.

The Hydrogen Roadmap sets several 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.
- Create five to ten pilot projects for the development and demonstration of new, more cost-effective hydrogen solutions and technologies.

Switzerland is set to publish its Hydrogen Strategy in 2024

Switzerland's **National Hydrogen Strategy** is currently under development and is expected to be published in 2024. Hydrogen is expected to contribute to the decarbonisation of the energy system, which is why the Hydrogen Strategy is expected to focus on the production of hydrogen from CO_2-neutral production processes.

The **Pipelines Ordinance** was revised as of 1 July 2023. This regulates supervisory responsibility and the division of competences between the federal government and the cantons and extends the area of application of the Pipelines Act to hydrogen.

The United Kingdom sets out production vision and a new Energy Act lays the foundation of hydrogen regulation

In its Hydrogen Strategy, published in August 2021, the United Kingdom set an ambition for 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 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:

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

- **CCUS** deployed in at least two industrial clusters by the mid-2020s, identified through the CCUS Cluster Sequencing Process, and two additional 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 Hydrogen Production Delivery Roadmap (published in December 2023) sets targets for 6 GW of electrolytic and 4 GW of CCUS-enabled hydrogen by 2030.

At the end of 2023 the United Kingdom announced the outcome of its first hydrogen allocation round, totalling 125 MW of electrolytic production capacity across 11 projects and backed by over GBP 2 billion in revenue support over 15-year contracts. It also opened a second hydrogen allocation round, with a target of up to 875 MW capacity.

The UK Low Carbon Hydrogen Standard sets out a methodology for calculating the GHG emissions from hydrogen production, and sets a threshold of 20 g CO_2-eq/MJ LHV and other compliance criteria for hydrogen to be considered "low-carbon". The United Kingdom is committed to setting up a certification scheme from 2025, to demonstrate compliance with the Low-Carbon Hydrogen Standard.

The Energy Act 2023 (EA 2023) received Royal Assent in October 2023. It creates a new comprehensive legislative regime for energy production, energy security and the regulation of the energy sector in the United Kingdom. The key provisions relating to hydrogen include:

- The introduction of **business models** given effect through revenue support contracts for the production, transport and storage of hydrogen. A more detailed overview of the business models and funding available to low-emissions hydrogen is provided under the "Support mechanism and subsidy schemes" section of this report.
- Powers providing robust and reliable **options for funding** these business models: levy funding and exchequer funding. The Hydrogen Production Business Model will initially be exchequer funded, with the intention to transition to levy funding in 2026, subject to consultation and legislation being in place. No decision has yet been taken with regard to how the hydrogen transport and storage business models will be funded.
- The establishment of a **regulatory framework for CO_2 transport and storage**. The EA 2023 gives legal powers to Ofgem as the economic regulator of CO_2 transport and storage.
- The foundation for the **establishment of the independent system operator** ("national energy system operator" or NESO).

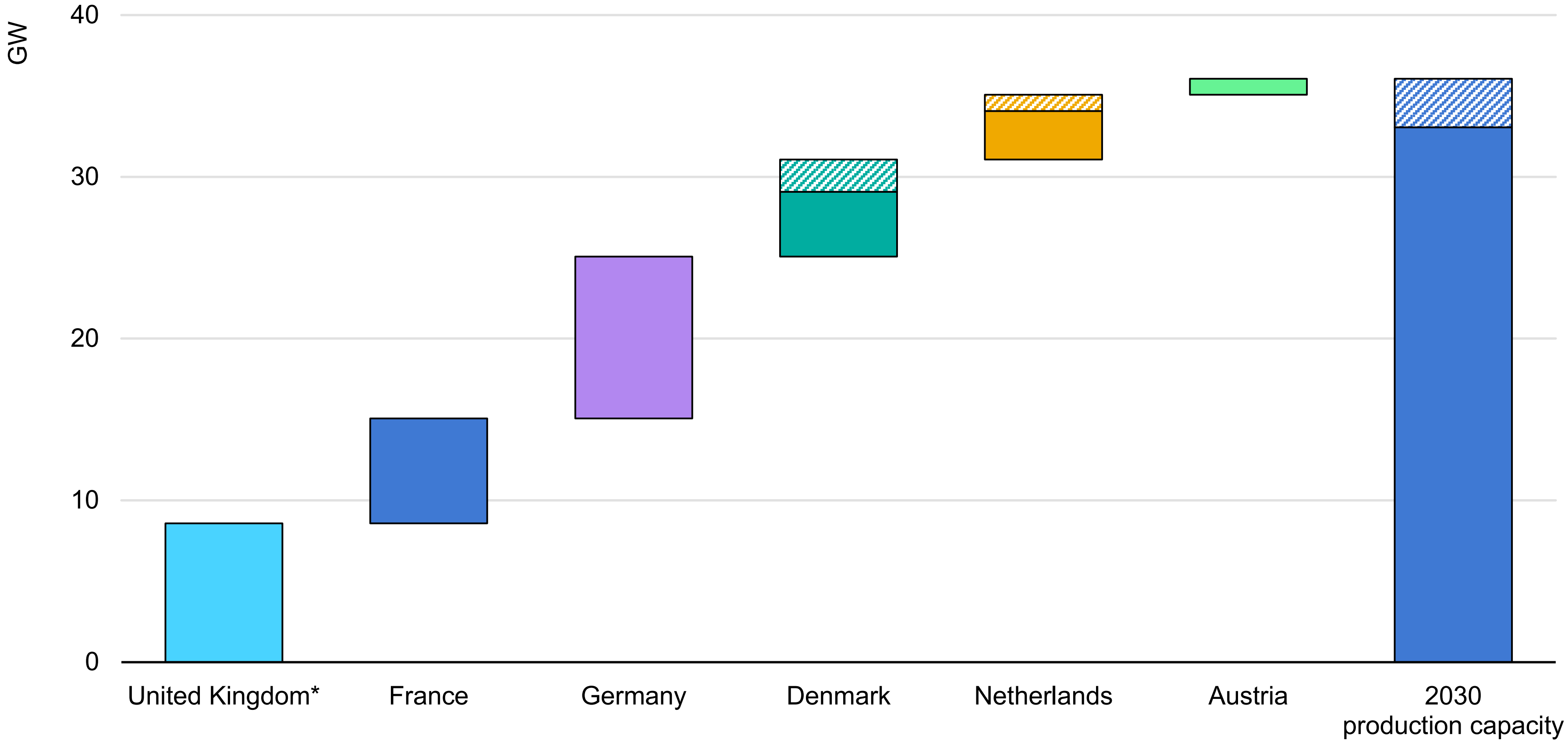
In addition, the Hydrogen Transport and Storage Networks Pathway sets out the intention to launch the first allocation rounds for government support for hydrogen infrastructure, with the ambition to support up to two storage projects at scale and associated pipelines, to be under construction or operational by 2030. The pathway sets the ambition that the NESO takes on strategic planning activities for hydrogen transport and storage infrastructure from 2026.

In December 2023 the United Kingdom stated that it sees potential strategic and economic value in supporting the blending of up to 20% hydrogen by volume into the GB gas distribution networks in certain circumstances that align with the strategic role of blending. When deciding whether to enable blending in the GB gas distribution networks, the government will consider safety evidence from industry trials and tests, as well as any implications on the economic case.

In the absence of an overarching consenting framework for offshore hydrogen pipelines and storage, in September 2023 the UK government introduced secondary legislation to extend existing offshore oil and gas pipeline and storage regulatory frameworks to cover offshore hydrogen pipelines and storage.

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

Electrolysis capacity targets in Northwest Europe by 2030



* The values for the United Kingdom have been estimated assuming 70% efficiency.
Note: The shaded areas represent targets under discussion and/or the higher range of announced targets.
Sources: IEA analysis based on various policy documents (hydrogen strategies, roadmaps and papers).

Subsidy schemes and support mechanisms

Subsidy schemes and support mechanisms play a crucial role in unlocking the full potential of low-emissions hydrogen in Northwest Europe

Support mechanisms and subsidy frameworks remain a key piece of the puzzle in developing markets for hydrogen. Early-stage state aid across various segments of the hydrogen value chain can help reduce risk, from R&D to the production stages, enabling projects to surmount uncertainty linked to the relatively nascent nature of the low-emissions hydrogen market. This section provides an overview of principal recent evolutions in subsidy and support mechanisms at both the EU and national levels in Northwest Europe.

European Union

Key among the EU funding programmes for hydrogen is the **European Hydrogen Bank**, announced in the September 2022 EU State of the Union speech and for which high-level details were communicated throughout 2023. In August 2023 the European Commission published the final terms and conditions surrounding the funding attribution mechanism and rules for participation, both central elements in stimulating European domestic production of hydrogen.

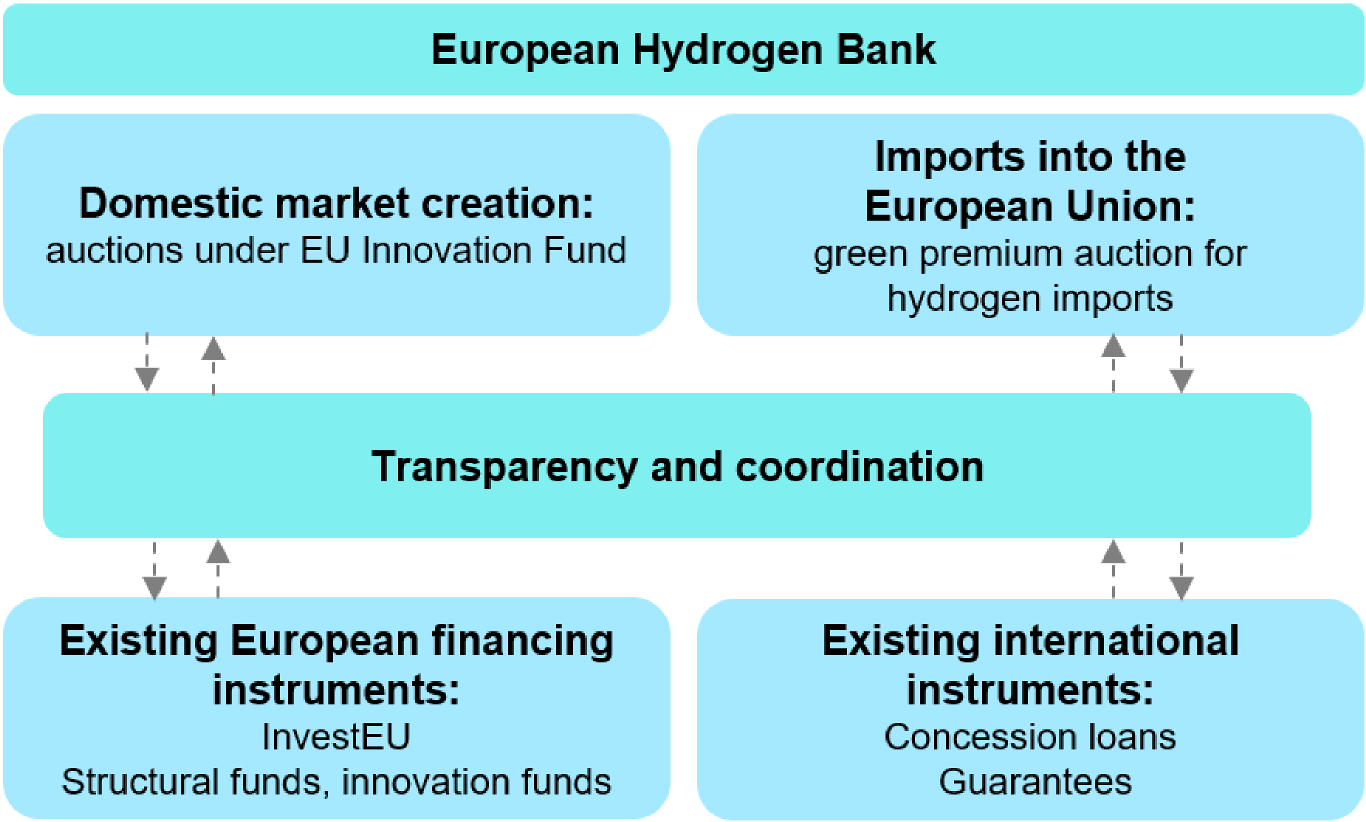
Hydrogen production subsidies, in the form of a fixed premium per kilogramme of low-emissions hydrogen produced, are set to be funded from the EU Innovation Fund, itself financed from EU Emissions Trading System (ETS) revenues. Funds will be attributed through an auction system — a system successfully tested in renewable power capacity deployment — allowing participants to submit bids for the lowest fixed premium they would be ready to accept in order to reduce the gap between their production costs and those of fossil-based hydrogen. Cost discovery through the auction system is expected to be a key benefit of the mechanism, providing transparency in the early steps of a budding hydrogen market. The first auction round, totalling EUR 800 million, was launched on 23 November 2023 and was finalised in early February 2024, attracting 132 project bids and accounting for 85 GW of electrolyser capacity.

Some of the rules on funding attribution and participation in the mechanism leave more leeway to project promoters than previously expected. Notably, the maximum available premium a participant can bid for is set at EUR 4.5/kg (up from a previously suggested EUR 4/kg) and the maximum delay allowed from the time of award to project commissioning increased to 5 years from 3.5.

The terms and conditions also allow a degree of flexibility regarding project promoters' electricity sourcing strategies, requiring "demonstration that [a] project has a credible plan… towards securing renewable electricity" through reporting requirements covering at least 60% of total electricity requirements. Importantly, the published terms and conditions also outline the rules for the cumulation of auction support with other public support mechanisms.

The European Hydrogen Bank aims to unlock private investment in renewable hydrogen

European Hydrogen Bank: Proposed activities



Sources: IEA analysis based European Commission (2022), Communication from the European Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Hydrogen Bank.

The **Important Projects of Common European Interest** (IPCEI) scheme at the European Union level is also a key vehicle to channel EU member state funding to the development of the hydrogen value chain. Since 2022, three individual IPCEIs pertaining to hydrogen have been approved:

- **Hy2Tech** (July 2022), covering a wide part of the hydrogen technology value chain, from generation to end-user applications, with 15 member states providing up to EUR 5.4 billion of public funding.
- **Hy2Use** (September 2022), focusing on hydrogen production (electrolysers) and transport infrastructure, as well as on the integration of hydrogen into industrial processes, with 13 member states providing up to EUR 5.2 billion of public funding.
- **Hy2Infra** (February 2024), targeting the deployment of (1) large-scale electrolysers, (2) new and repurposed hydrogen transmission and distribution pipelines, (3) large-scale hydrogen storage facilities, and (4) port infrastructure for liquid organic hydrogen carriers. In total, seven member states are set to provide up to EUR 6.9 billion of public funding.

Austria

Austria has continued its progress in implementing hydrogen support mechanisms, building on existing subsidy programmes spanning the industrial and transport sectors on the demand side, as well as programmes aimed at supporting renewable hydrogen production (see 2022 Northwest European Hydrogen Monitor).

The publication of the National Hydrogen Strategy in June 2022 took an important step in setting targets and guiding principles to frame the direction of domestic hydrogen developments, providing a base on which to implement further subsidy programmes.

As part of the Climate and Energy Fund (*Klima- und Energiefonds*), the Energy Research Programme 2023 included hydrogen technologies as a sub-topic, directing up to EUR 10 million toward specific electrolysis and fuel cell concepts.

Additionally, Austria announced in February 2024 that it would dedicate a further EUR 400 million, potentially through the European Hydrogen Bank's second auction round in 2024, to support renewable hydrogen projects.

Previously announced or existing programmes include:

- The Hydrogen Production Support Act (WFöG) foresees the participation of Austria in the European Hydrogen Bank, through the “auction as a service” mechanism. At least EUR 400 million is to be made available to fund renewable hydrogen production projects through this mechanism, with a fixed premium per produced unit of renewable hydrogen over a timespan of ten years. The act is currently under public consultation.

- The **Renewable Expansion Act (EAG)** earmarked EUR 40 million per year through to 2030 to support investment costs relating to electrolysis projects of 1 MW or higher, and exempts them from certain grid-related fees.
- The **Transformation of Industry** funding programme makes EUR 2.975 billion available through to 2030 for the decarbonisation of energy-intensive and hard-to-abate industries, a portion of which is targeted at hydrogen applications, notably in industrial segments such as iron and steel, chemicals and cement. A first call was launched in 2023, with a budget of EUR 175 million.
- The **Domestic Environmental Support (UFI)** programme funds climate protection measures taken by companies, municipalities and associations with a focus on the use of renewable heat, waste heat utilisation, energy efficiency measures and resource efficiency, as well as pilot and demonstration facilities in production processes, providing EUR 150 million per year until 2026.
- The **Transformation of Economy** funding programme totals EUR 100 million until 2026 under the Recovery and Resilience Facility framework.
- ***Vorzeigeregion Energie*** (Model Energy Region) targets analysis, realisation, development and demonstration along the entire hydrogen value chain with EUR 40 million of funding.
- **The Emission-free Buses & Infrastructure (EBIN) and Emission-free Commercial Vehicles & Infrastructure (ENIN)** programmes are transport-oriented, designed to promote zero-emission vehicle fleets, whereby hydrogen-powered solutions are eligible for funding among other zero-emission solutions. A total of EUR 256 million is available under EBIN between 2022 and 2026 and a total of EUR 365 million under ENIN.
- The **Zero Emission Mobility** programme supports innovative research and development projects with EUR 8 million yearly, to make emission-free mobility more accessible to the general public.
- **COMET Centre** on “Hydrogen Research Centre Austria,” providing nearly €10 million over the 2023-26 period to R&D in hydrogen.

Belgium

In 2023 Belgium held two important tenders providing financial support to R&D and development-phase projects in the hydrogen space, spanning both the supply side and demand side.

The **Clean Hydrogen for Industry** project call awarded a total of EUR 30 million to six projects in its first tender in 2022, and aims to award a further EUR 19 million in its 2023 call, which was open from October 2023 to the end of January 2024. The call aims to promote various project phases (R&D, demonstration) and, by doing so, help shape the federal Hydrogen Strategy.

A more general call, **Clean Hydrogen for Belgium**, held its second tender simultaneously, aiming to award EUR 10 million to hydrogen projects, with no more than EUR 8 million going to any single project and with requested support representing no more than 70% of any project's budget. Both calls are financed under the **federal Recovery and Transition Plan**.

In addition to these financing initiatives, a EUR 250 million budget has been earmarked to award a subsidy to the hydrogen network operator (HNO) in the context of work being undertaken on the first phase of a hydrogen network. This amount, which supplements the initial EUR 95 million set aside to kickstart construction, will help facilitate HNO investment in expanding the grid and ensuring interconnections with neighbouring markets.

Further support mechanisms include a EUR 6 million subsidy for the **development of green steel**, as well as ongoing negotiations for the **easing of the tax burden** on green investments, also applicable to hydrogen technologies.

Denmark

Following Denmark's Climate Act of 2020, further emphasis has been given to hydrogen through specific funding programmes. In 2022 the Danish government agreed to earmark DKR 1.25 billion (EUR 167 million) to support the production of green hydrogen to feed into derivative fuels (Power-to-X [PtX]) for use in hard-to-abate sectors. In 2023 the government concluded its first PtX tender, selecting six winning projects for a total electrolysis capacity of 280 MW. The financial support is set to be paid as a fixed price premium over a ten-year period.

Further funds have been earmarked or allocated to hydrogen projects, including DKK 850 million (~EUR 110 million) in funding to Danish IPCEI participation, DKK 500 million (~EUR 67 million) for innovative green technologies via funds from the REACT-EU initiative and the Just Transition Fund, and DKK 400 million (~EUR 53 million) from the Energy Technology Development and Demonstration Programme (EUDP) for the development of PtX solutions.

France

France announced a significant financing package for hydrogen projects in its September 2020 Hydrogen Strategy, earmarking EUR 7.2 billion through to 2030, up from an initial EUR 100 million sum announced in a 2018 hydrogen deployment plan for the year 2019. Coupled with additional financing commitments made in 2021, total announced funding reached approximately EUR 9 billion.

In May 2023 an additional EUR 175 million of financing from the "France 2030" investment plan was announced, targeting the development of hydrogen ecosystems that combine different segments of the hydrogen value chain, from production to distribution and end use.

In September 2023 the French government announced details of the allocation of the first tranche of funding from these commitments, totalling EUR 4 billion to support 1 GW of electrolyser capacity. The money is set to be allocated through three rounds of auctions scheduled for 2024, 2025 and 2026, with the first-round envelope of EUR 700 million in 2024 targeting a total capacity of 150 MW. The two subsequent annual rounds would aim to select projects totalling 250 MW and 600 MW, respectively.

The tenders will be open to both renewable and low-carbon hydrogen projects, although eligibility conditions disqualify projects relying on carbon capture from receiving aid. Furthermore, rules would set limits on the end-use segments benefiting from this production and would limit the export of subsidised hydrogen volumes.

Germany

In Germany around 45 funding measures and schemes are at least partially dedicated to hydrogen and its derivatives, with over 25 measures directly aimed at hydrogen projects. Total announced funding dedicated solely to hydrogen and its derivatives amounts to over EUR 10 billion.

The **H2 Global** scheme, a private initiative that receives government funds, is the largest such programme with EUR 4.4 billion earmarked over the 2022-2036 period to facilitate the ramp-up of hydrogen demand in Germany. Through the programme, renewable hydrogen is set to be purchased abroad and resold domestically through an auction system, with the price premium compensated by federal government grants over a maximum period of ten years. Over time, the losses are expected to be reduced, as the willingness to pay for sustainable energy sources increases. The investment and planning security provided by H2Global enables companies on the supply side to set up production facilities on an industrial scale. On the user side, companies will be able to purchase renewable energy sources at economic prices for the first time and thus drive forward their decarbonisation. H2Global thus enables production, the establishment of international supply chains and the application of renewable hydrogen and its derivatives ahead of time – before the market emerges – and gives the economy the associated competitive advantage.

The hydrogen core network is not directly subsidised, but the state provides subsidiary financial protection against unforeseeable events in the development and use of the network by a so-called **"amortisation account"**. The core network is to be financed via grid fees. In the initial years of operation of the core grid, a difference between the high investment costs and the scarce income from grid fees is to be expected, given the small number of initial users. This difference is to be financed temporarily from the amortisation account.

The **Carbon Contracts for Difference** (CCfD) programme is set to run over the 2024-2045 period with a total budget in the mid-double digit billion euro range. It aims to support industrial companies (steel, ammonia, cement and lime) by compensating for the cost premium of transitioning to low-carbon and carbon-free processes. Through cost compensation, the programme aims to drive early demand for both electrolytic hydrogen produced with renewable electricity and hydrogen produced through steam methane reforming with carbon capture and storage. A first funding round of EUR 4 billion was allowed under EU state aid rules as of February 2024.

The **German Power Plant Strategy** includes tenders for up to four 2.5 GW hydrogen-ready gas-fired power plants, allowing the use of both electrolytic and fossil-based hydrogen, as well as in-situ CCS. The plants are eligible for public funding from the Climate and Transformation fund, up to a total of approximately EUR 15-20 billion.

In December 2023 Germany announced that it would allocate EUR 350 million to the domestic arm of the European Hydrogen Bank pilot auction through its “auctions as a service” scheme.

Germany has made a total of EUR 1.5 billion available for **overall support of renewable fuels** through the production and market ramp-up stages. 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.

The **Decarbonisation in Industry Funding Programme** supports energy-intensive industry, from the R&D phase to the large-scale application of emissions-reducing processes. The programme runs from 2021 to 2024 with a budget of approximately EUR 3 billion.

Living Laboratories of the Energy Transition (a funding format within the 7th Energy Research Programme) intends to close the technological development gap for innovations between application-oriented research and broad implementation.

Funding through the **Hydrogen Innovation and Technology Centre (ITZ)** is intended to create joint development environments for nascent hydrogen-focused projects and companies, reducing the need for investment by individual players and facilitating co-operation in product development. ITZ funding runs from 2021 to 2024 with a budget of up to EUR 290 million.

Further subsidies exist that support co-operation in the field of hydrogen with third countries. These include HySupply, a German-Australian feasibility study on hydrogen from renewable energy 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.

In addition, the Federal Ministry of Economic Affairs and Climate Action (BMWK) finances programmes such as the **PtX-Hub** and the

H2Uppp (International Hydrogen Ramp-up Programme), which support investment in hydrogen and its derivatives primarily in developing and emerging countries.

Luxembourg

The Luxembourg government is developing a subsidy scheme for the production of renewable hydrogen. A final concept paper was published in 2023. With a view to launching an initial tender for both CAPEX and OPEX aid, the Ministry of the Economy held a public consultation between December 2023 and 29 February 2024. Luxembourg is also in contact with H2Global and is awaiting further details on the European Hydrogen Bank domestic and international Global European Hydrogen Facility (REPowerEU). Luxembourg is working on implementing the General Block Exemption Regulation, which will also entail possible subsidies along the hydrogen value chain, including infrastructure.

Netherlands

Approximately EUR 60 million was awarded to hydrogen projects through subsidy schemes in 2020 and 2021 in the Netherlands. Building on these allocations, 2022 and 2023 marked two equally important years with the development of specific instruments to mobilise previously earmarked funding, supplementing existing funding mechanisms. In total for the period to 2030, over EUR 10 billion in hydrogen subsidies is expected to be allocated using specific instruments, with further subsidies potentially available from more general funding programmes.

Programmes range from R&D to the promotion of hydrogen in different end-use sectors, and include:

- The **OWE scheme** (Ramping up Hydrogen Production Through Electrolysis) supports electrolysis projects ranked on subsidy intensity per MW of installed capacity. EUR 250 million was allocated in 2023 and up to EUR 1 billion is allocated for 2024, with around EUR 3.9 billion still available for future tenders.
- Along with Germany, the Netherlands has pledged EUR 300 million through the **H2 Global** scheme (see Germany above) towards a joint tender for the import of renewable hydrogen starting in 2027.
- The **MOOI scheme** (Mission-Driven Research, Development and Innovation) supports industrial research and experimental development. It is targeted at integrated solutions that contribute to climate goals.
- The **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.

- The **DEI+ scheme** (Demonstration of Energy and Climate Innovation) supports practical experiments, pilots and demonstrations. In June 2022 there was a specific call for hydrogen and low-carbon chemistry via DEI+, with a budget of EUR 30 million.
- The **TSE Scheme** (Top Sector Energy Scheme) supports projects at the feasibility study stage relating to innovative pilot or demonstration projects. The TSE Scheme was established specifically for R&D and supports projects that can reduce CO_2 emissions from industry cost-effectively by 2030.
- The **SDE++ scheme** (Sustainable Energy Transition Subsidy) supports the deployment of renewable energy generation technologies and other CO_2-reducing techniques.
- The **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 subsidy expenditure in accordance with the SDE++ scheme.
- The **MIT scheme** (Innovation Stimulation Region and Top Sectors) is available for small and medium-sized enterprises.
- ***GroenvermogenNL*** (Green PowerNL) is a programme that focuses on accelerating the scaling up of hydrogen and low-carbon chemistry, with a maximum budget of EUR 838 million between 2021 and 2028. It focuses on R&D, pilots, demonstration projects and human capital development, including training. The aforementioned EUR 30 million DEI+ scheme is part of this programme.

Norway

Over recent years, Norway has provided public funding for hydrogen projects through various public bodies and schemes, including Enova, Innovation Norway, *Forskningsrådet* (Research Council of Norway), PILOT-E, and *Grønn Plattform*. Funding announcements totalled NOK 1.757 billion (~EUR 153 million) in 2021, NOK 2.315 billion (~EUR 201 million) in 2022, and NOK 861 million (~EUR 75 million) in 2023.

Switzerland

The Swiss government plans to publish a National Hydrogen Strategy in 2024 and, as such, does not currently have specific hydrogen targets in place. Furthermore, there are as yet no direct subsidy schemes in place to support the production and development of low-carbon hydrogen. Nevertheless, public funding opportunities exist in application-oriented R&D for hydrogen and fuel cell technologies through the Swiss Federal Office of Energy.

In Switzerland, certain standards and tax exemptions provide indirect support for hydrogen in certain end-use sectors, notably transport. For example, fuel cell trucks are exempt from both the heavy vehicle tax and the mineral oil tax, while emissions standards for passenger and light-duty vehicles provide support for fuel cell electric vehicles.

Looking ahead, revisions of various laws are underway, which could include further support mechanisms for hydrogen production in the future. Entry into force of these laws is planned for 2025.

United Kingdom

In October 2023 the Energy Act, the largest piece of energy legislation in the country's history, received Royal Assent, setting out policy and governance foundations for the future UK energy system, including hydrogen. Among the key measures, the act provides a framework for various business models to support hydrogen production (see the Hydrogen Production Business Model below), hydrogen transport and hydrogen storage.

Although funding details are set to come from future complementary legislation, the Energy Act confirms the statutory footing for revenue support contracts in developing a hydrogen market.

A regulated asset base will form the basis of the hydrogen transport business model. An external subsidy mechanism will be created alongside a regulated asset base to ensure that charges to users of the pipelines and/or networks are not prohibitive, while allowing hydrogen transport providers to make a reasonable return on their investment.

The hydrogen storage business model is set to be centred primarily around support for geological storage, putting in place a minimum revenue floor so as to mitigate both price and volume risk. As revenues from activity increase, the subsidy is set to decrease while ensuring an incentive to maximise facility usage. However, the support mechanism is not set to erase all risks, such as development, technology or decommissioning risks. Over time, as with the hydrogen transport business model, the objective is for subsidies to give way to a self-sustaining industry segment.

The **Hydrogen Production Business Model** (HPBM) has been established to provide revenue support for producers to overcome the operating cost gap between low-emissions hydrogen and alternative high-carbon fuels. Following the first joint Net Zero Hydrogen Fund/HBPM electrolytic hydrogen allocation round (HAR1) in 2022, the UK government announced the successful projects to be offered contracts in December 2023, totalling 125 MW and backed by over GBP 2 billion in revenue support. HAR 2 was launched in late 2023 with a capacity target of up to 875 MW and is set to close for applications around mid-April 2024.

In addition, the **Net Zero Hydrogen Fund** (NZHF) is set to provide GBP 240 million of funding to support the development of new low-carbon hydrogen production plants through the 2020s, working toward the 10 GW low-carbon hydrogen target by 2030.

The NZHF 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.

The first 15 winning projects from round 1 of strands 1 and 2 were selected in 2023, for total support of GBP 37.9 million. Seven successful applicants from the NZHF strands 1 and 2 round 2 competition were announced in March 2024, which were allocated GBP 21 million.

Multiple smaller-scale financing schemes and competitions have been set up to provide direct funding to low-carbon solutions, including to hydrogen-oriented projects. These funding streams target various end uses, notably transport and industry. The table below provides a summary of the government funding available for low-emissions hydrogen in the United Kingdom.

Summary of UK government funding for hydrogen since the publication of the Hydrogen Strategy

Fund or competition	CAPEX	DEVEX	OPEX	Available or allocated funding	Status
Production					
Net Zero Hydrogen Fund (NZHF)	X	X		GBP 240 million total funding delivered across 4 NZHF strands. GBP 58.9 million allocated across rounds 1 and 2 of NZHF strands 1 and 2.	Ongoing, running to March 2025.
Hydrogen Allocation Rounds: NZHF/Hydrogen Production Business Model (HPBM)			X	Funding available across lifetime of contracts dependent on negotiations with individual projects. Over GBP 2 billion revenue support from HPBM and over GBP 90 million for construction from NZHF.	Successful HAR1 projects announced. See Hydrogen Economy Roadmap for timelines of future HARs and cluster sequencing process.
Net Zero Innovation Portfolio (NZIP) Low-Carbon Hydrogen Supply 2 competition	X	X		GBP 62 million allocated.	Ongoing, running to March 2025.
NZIP Direct Air Capture and Greenhouse Gas removal programme	X	X		GBP 10 million; hydrogen spend only.	Ongoing, running to March 2025.
NZIP Hydrogen BECCS Innovation Programme	X	X		GBP 31 million allocated.	Ongoing, running to March 2025.

Fund or competition	CAPEX	DEVEX	OPEX	Available or allocated funding	Status
Networks and storage					
NZIP Longer Duration Energy Storage competition	X	X		GBP 9 million; hydrogen spend only.	Ongoing, running to March 2025.
Hydrogen Transport Business Model	X	TBD	X	TBD	Intention for first allocation round to open end of 2024.
Hydrogen Storage Business Model	X	X	X	TBD	Intention for first allocation round to open end of 2024.
Use of hydrogen					
Industrial Energy Transformation Fund	X	X		GBP 289 million available across all technologies, plus a further GBP 185 million.	Ongoing, Phase 3 running to 2028 subject to business case approval.
NZIP Red Diesel Replacement Competition		X		GBP 26 million for 6 projects, 5 of which are hydrogen-focused.	Ongoing, running to March 2025.
NZIP Industrial Hydrogen Accelerator	X	X		GBP 13 million allocated.	Ongoing, running to March 2025.
NZIP Industrial Fuel Switching 2 Competition	X	X		GBP 23 million; hydrogen spend only.	Ongoing, running to March 2025.
NZIP Green Distilleries Competition	X	X		GBP 6 million; hydrogen spend only.	Ongoing, running to September 2024.

Fund or competition	CAPEX	DEVEX	OPEX	Available or allocated funding	Status
Local Industrial Decarbonisation Plans Competition		X		GBP 5 million available.	Ongoing, completing in December 2024.
Clean Maritime Demonstration Competition rounds 1-4		X		Rounds 1-4: GBP 128 million allocated.	Rounds 1 and 2 completed, rounds 3 and 4 running to March 2025.
Zero Emission HGV and Infrastructure Demonstrators	X	X		GBP 200 million available.	Ongoing, running to 2030.
Advanced Fuels Fund		X		GBP 135 million allocated.	Ongoing, running to March 2025.
APC's Collaborative R&D Competition – round 22		X		GBP 77.1 million joint government and industry funding allocated.	Ongoing, running to late 2026.
Zero Emission Vessels and Infrastructure Competition	X	X		GBP 80 million available.	Ongoing, running to March 2028.
Tees Valley Hydrogen Transport Hub Fund		X		Phase 1: GBP 2.6 million allocated. Phase 2: GBP 13 million allocated.	Ongoing, running to March 2025.
Zero Emission Flight Infrastructure Project	X			GBP 4.2 million allocated.	Completed March 2023.

Notes: CAPEX = capital expenditure; DEVEX = development expenditure; OPEX = operating expenditure.
Source: UK Department for Energy Security and Net Zero (2023), Hydrogen Strategy Delivery Update

Hydrogen demand

The European Union and Northwest European countries have set out demand targets for low-emissions hydrogen

The willingness of end users to opt for low-emissions hydrogen will be key in the development of this market. The uptake of low-emissions hydrogen will be a gradual process and necessitate the support of governments to incentivise demand creation at the early stages of market development.

Recent hydrogen demand trends in the European Union and Northwest Europe

The European Union's current hydrogen consumption totals approximately 7.5 Mt (250 TWh) per year, almost all of which is fossil-based and whose use is concentrated in refining and in the production of ammonia, methanol and other chemicals. According to data from the European Hydrogen Observatory, Northwest European hydrogen demand currently stands at around 4.5 Mt (150 TWh) per year, making up about 55% of total European demand and nearly 5% of total global demand for hydrogen. In line with the overall European trend, virtually all Northwest European consumption is concentrated in the refining and chemicals subsectors. Within chemicals, ammonia production is by far the largest application, followed by methanol.

Germany and the Netherlands together account for approximately 60% of Northwest European hydrogen demand. The United Kingdom, France and Belgium make up a further third of the Northwest European market.

The European Union has set out hydrogen use targets in industry and the transport sector

By 2030 the European Union is aiming for a market total of 20 Mt (660 TWh) of renewable hydrogen, half of which would be domestically produced and half imported.

In 2023 EU policy continued to highlight the key role for hydrogen in decarbonising the bloc's energy consumption over the coming decades. The revised Renewable Energy Directive (RED III) entered into force in November 2023, setting out requirements for the origin of hydrogen use across certain sectors, notably in industry and transport. As in prior EU discussions, these are the two sectors where low-emissions hydrogen is seen as playing an immediate and significant role. EU member states have agreed that renewable fuels of non-biological origin (RFNBOs) should account for at least 42% of hydrogen use (for final energy and non-energy uses) in industry by 2030. By 2035 the share of renewable hydrogen rises to 60%. In transport, RED III establishes that 1% of all fuel supplied to the sector by 2025 must either fall under the advanced biofuel or biogas classification, or comply with RFNBO rules. This share rises to 5.5% by 2030, with a minimum contribution of 1% from RFNBOs.

However, particularities and exemptions feature in reaching these targets. In industry, an exemption to the RFNBO rule is possible if

(1) a member state is on track to meet its renewable energy targets, and (2) 23% or less of its hydrogen consumption comes from fossil fuels by 2030, and 20% or less by 2035. Meeting these two requirements effectively allows for a share of non-renewable hydrogen – including nuclear-derived hydrogen, for example – to count in meeting the RFNBO targets. In transport, EU rules allow for every unit of RFNBO consumed to account for more than one unit toward the RFNBO target, a measure put in place to partly compensate for the high relative cost of these fuels. RED III establishes an additional multiplier effect for the shipping and aviation sectors, set to steer more RFNBO use in these particularly cost-sensitive segments. In practice, this will lead to a reduction in the actual amount of renewable hydrogen required to attain the objectives set out in the directive.[4] The ReFuelEU Aviation initiative, also adopted in late 2023, extends renewable hydrogen objectives to air transport specifically. Concretely, the directive requires 1.2% of all aviation fuel to be of green hydrogen-derived synthetic origin by 2030. This share would then progressively rise to 35% by 2050.

Industry could drive more than 7 Mt of low-emissions hydrogen demand by 2030 across all of Europe

Industry is expected to continue to account for the vast majority of low-emissions hydrogen consumption in the short to medium term. According to the Clean Hydrogen Monitor, in 2030 industrial low-emissions hydrogen demand across Europe could reach between 7.1 Mt and 7.4 Mt (230 TWh to 245 TWh) based on the announced project pipeline. By then, ammonia and steel production are expected to be the two largest consuming subsectors of low-emissions hydrogen, compared to refining activities making up the largest share of current – largely fossil-based – hydrogen consumption in the region. Based on this project pipeline, Northwest European demand could reach around 3.5 Mt (115 TWh) per year by 2030, making up just about half of total European industrial demand for low-emissions hydrogen. This would account for virtually all European hydrogen demand in the steel sector, just over half of ammonia-driven demand, and about a quarter of refining sector demand.

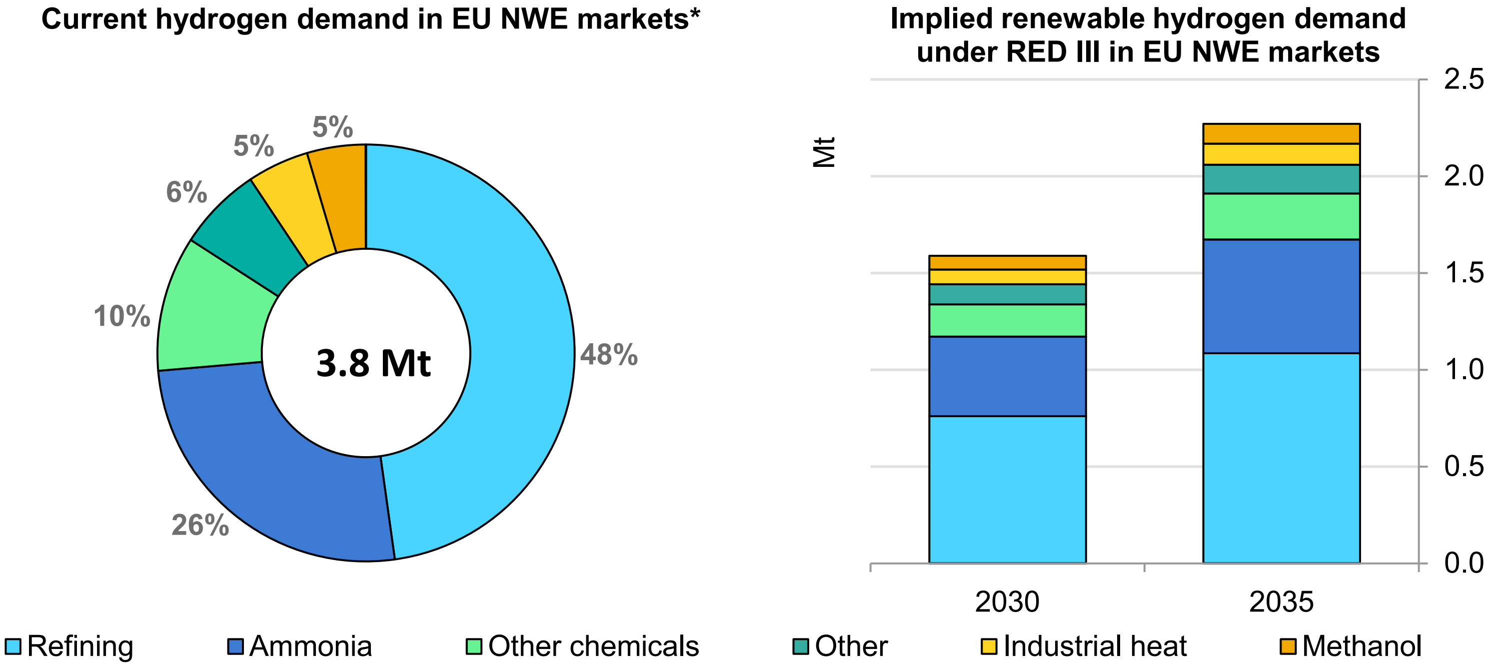
Northwest European countries are setting hydrogen use targets

Several – though not all – Northwest European countries have set demand targets or put forward potential ranges for low-emissions hydrogen in their strategies, roadmaps and policy papers. Based on these announcements, Northwest Europe's low-emissions hydrogen consumption could reach above 6 Mt (200 TWh) per year by 2030, with demand concentrated mostly in industry. These countries are aiming, in the first stage, to replace current consumption of hydrogen from fossil fuels with low-emissions hydrogen. The following section provides an overview of current hydrogen consumption and the prospects for low-emissions hydrogen demand in Northwest Europe.

[4] See the amendment to Article 27 in Directive (EU) 2023/2413.

Industry is set to drive initial demand creation for low-emissions hydrogen

RED III implications for current hydrogen consumption in industry



* “EU NWE markets” comprise the EU markets covered in this report: Austria, Belgium, Denmark, France, Germany and the Netherlands.

Notes: The RED III directive states that 42% of industrial hydrogen use must comply with RFNBO rules by 2030, and 60% by 2035. If applied to current hydrogen consumption in EU NWE markets, this would imply approximately 1.6 Mt and 2.3 Mt of renewable hydrogen consumption in 2030 and 2035, respectively.

Source: IEA analysis based on European Hydrogen Observatory (2024), Datasets.

Austria

Hydrogen consumption in Austria is approximately 120 kt/year, largely natural gas-based and concentrated in ammonia production and refining. By 2030 Austria aims to progressively replace 80% of current fossil-based hydrogen consumption with climate-neutral hydrogen. Among the driving measures in this respect is the Transformation of Industry programme, supporting hydrogen demand in difficult-to-decarbonise industrial sectors, where a majority of the country's current hydrogen demand resides.

Further demand stimulation comes through programmes supporting zero-emissions mobility (including hydrogen solutions) in buses, trucks and aviation.

Belgium

One of the four pillars around which the Belgian Federal Hydrogen Strategy is centred is the positioning of the country as a European import and transit hub for hydrogen. By 2030 domestic demand for renewable hydrogen is estimated to reach between 2 TWh and 6 TWh. This compares to current total annual hydrogen consumption of around 12.5 TWh (0.4 Mt).

The federal strategy identifies a key role for hydrogen and hydrogen derivatives in various applications, including in industry, transport and buildings, as well as in providing flexibility for the grid.

Denmark

The Danish Hydrogen Strategy is centred on developing PtX solutions to decarbonise hard-to-abate sectors, tying into the country's electrification strategy. The country's ambitions are not only to reduce its domestic emissions through these developments, but also to contribute to decarbonisation beyond its borders. As such, Denmark is positioning itself as a green hydrogen exporter to neighbouring markets, including Germany, Sweden, the Netherlands and Belgium.

Despite an export-driven strategy, Denmark considers that hydrogen also has emissions reduction potential domestically. Although hydrogen demand is likely to remain relatively limited before 2030, total potential CO_2 emissions reductions could range from 1.3 Mt CO_2 to 5.1 Mt CO_2 annually by then, with the largest potential being in heavy transport such as shipping and aviation.

France

French hydrogen consumption is estimated at around 0.9 Mt (30 TWh) per year in recent years, although it is likely to have fallen in 2022 as overall industrial energy demand fell year-on-year. In contrast to certain neighbouring EU member states, the French Hydrogen Strategy prioritises domestic hydrogen production to fulfil domestic demand needs. The strategy focuses foremost on decarbonising existing hydrogen uses, particularly in refining and ammonia production, giving other applications such as transport secondary priority.

Under existing plans, including the Plan France 2030 and the National Low-Carbon Strategy (SNBC), France could aim for domestic electrolytic hydrogen production of around 23 TWh (0.7 Mt) by 2030, growing to around 40 TWh (1.2 Mt) by 2050. Of the 2050 total, 20 TWh (0.6 Mt) would go to industry, 15 TWh (0.5 Mt) to the power sector and the rest to other sectors.

Germany

Germany is the largest hydrogen market in Europe, currently consuming around 57 TWh/year. As per the July 2023 update to the German National Hydrogen Strategy, consumption is expected to reach 95-130 TWh by 2030, growing to 290-440 TWh by 2050.

Industry remains the priority sector for hydrogen use, particularly in those subsectors most difficult to decarbonise through alternative options (e.g. electrification). In this sector, Germany has put forward Carbon Contracts for Difference (CCfD), a financial mechanism aiming to compensate companies for the additional costs associated with switching industrial processes to lower-emission methods and fuels.

The transposition of EU measures has partly driven German policy support for hydrogen demand, particularly in the transport sector. Further domestic initiatives have also added to the support for this sector, notably through a March 2023 funding call for publicly accessible hydrogen refuelling stations for heavy-duty vehicles.

In February, Germany laid out the essential elements of a new Power Plant Strategy. The strategy foresees tenders for up to 10 GW of hydrogen-ready gas-fired power plants, in which all types of hydrogen would be allowed. The first tender rounds are expected in Q4 2024 and are aimed at projects that contribute to decarbonising the electricity system. The tenders are to be supported with public funding of approximately EUR 15-20 billion. The strategy foresees a shift from natural gas to hydrogen use in 2035-2040, the exact date to be determined in 2032.

Developing hydrogen and hydrogen-ready infrastructure is also a central element in Germany's approach. In a first instance, this applies to gas importing infrastructure through the LNG Acceleration Act, by requiring hydrogen readiness to ensure the operation of assets beyond 2044.

Finally, the National Hydrogen Strategy Update sidelines hydrogen use in heating, restricting it to limited applications, judging that sufficient viable alternatives can be deployed to decarbonise the sector.

Luxembourg

Luxembourg's industrial hydrogen consumption is around 19 GWh/year (or 0.6 kt H_2/year). According to its Hydrogen Strategy, the country aims to switch 100% of its fossil-based hydrogen consumption to renewable hydrogen by 2030. This would cause GHG emissions to drop by over 5 kt/year. In the ramp-up phase of increasing hydrogen demand in industry, the government will allow for the use of low-emissions hydrogen as long as renewable hydrogen is not available in sufficient quantities and at competitive cost.

Netherlands

The Netherlands' current hydrogen use totals approximately 50 TWh/year, essentially as a feedstock for industry, including in refining and chemical processes (e.g. ammonia production). The goal is to substitute these volumes with clean hydrogen and to generate additional demand for hydrogen as an energy carrier or feedstock in other (industrial) sectors over time.

Targets are put forward for hydrogen use in other sectors, including the objective of rolling out a network of 50 hydrogen filling stations by 2025 for road transport. In shipping, the target is for 150 zero-emission inland vessels by 2030, encompassing hydrogen and hydrogen-based options such as ammonia and synthetic fuels. In aviation, the national target is for the sector to use 14% renewable fuels by 2030, based on renewable hydrogen supply.

In the built environment, the objective is for pilot projects to cover 1 000 homes heated by hydrogen by 2030, although a definitive role for the energy carrier in this sector is uncertain and will depend on multiple factors.

Clean hydrogen will also play a role in the energy system, to balance supply and demand through underground storage. In addition, the intent is to have a CO_2-neutral power sector by 2035 in which renewable and low-carbon hydrogen will replace natural gas in gas-fired power plants.

Norway

Norway's hydrogen strategy, published in 2020, gives particular attention to hydrogen's potential role in decarbonising segments of the transport sector. Key among these is maritime bunkering, notably targeting ferry routes. The Norwegian government's action plan for green shipping also outlines hydrogen's potential role in this sector, particularly where pure electrification would be less feasible due to scheduling, distance or speed constraints.

While pilot projects for hydrogen use have been put forward in other sectors, Norway could position itself as a hydrogen exporter under the right policy and market conditions.

Switzerland

Switzerland's current use of hydrogen stands at around 430 GWh/year (13 kt), essentially as a feedstock in industry. Swiss policy around hydrogen consumption is primarily centred on the transport sector, with fuel cell trucks exempt from both heavy-duty vehicle taxes and the mineral oil tax. Additionally, emissions standards exist for passenger and light-duty vehicles. According to the roadmap, domestic low-emissions hydrogen production should be able to cover Swiss hydrogen demand until 2035.

United Kingdom

The United Kingdom sees low-carbon hydrogen playing a key role in decarbonising energy consumption across industry, power, transport and potentially home heating. The December 2023 Hydrogen Production Delivery Roadmap sets out potential demand ranges across each of these sectors, leading to a total potential range of 18-41 TWh of hydrogen demand by 2030, and a range of 50-175 TWh by 2035.

UK policy support for hydrogen use in industry reaches across multiple applications via a number of individual schemes, including the Industrial Fuel Switching Competition, the Industrial Hydrogen Accelerator Programme and the Industrial Energy Transformation Fund. The Local Industrial Decarbonisation Plans Competition, for example, aims to support the development of area-based, collaborative "local clusters" to explore technological solutions and identify localised hydrogen options.

UK industry could consume an additional 12-19 TWh by 2030 and the ambition is for 50 TWh of fuel switching from fossil fuels to electricity and hydrogen by 2035.

Hydrogen is seen as a significant opportunity for the United Kingdom and is likely to play a key role in supporting the decarbonisation of parts of the transport sector, such as maritime and aviation (direct use or via sustainable aviation fuels). Within maritime, R&D schemes include the Zero Emissions Vessels and Infrastructure scheme, and the Clean Maritime Demonstration Competition. These are run by the UK Shipping Office for Reducing Emissions and focus on accelerating the technology necessary to decarbonise the domestic maritime sector, including via hydrogen and hydrogen-derived fuels.

The government expects battery electrification to remain the dominant zero-emission technology for passenger cars and vans, and to increasingly dominate new heavy-goods vehicles, buses and coaches. There may be some specific use cases where hydrogen offers advantages, such as where longer ranges are needed in rural or remote locations (e.g. non-road mobile machinery and construction vehicles).

Hydrogen is considered a key component of the UK government's commitment to decarbonise the country's power system by 2035.

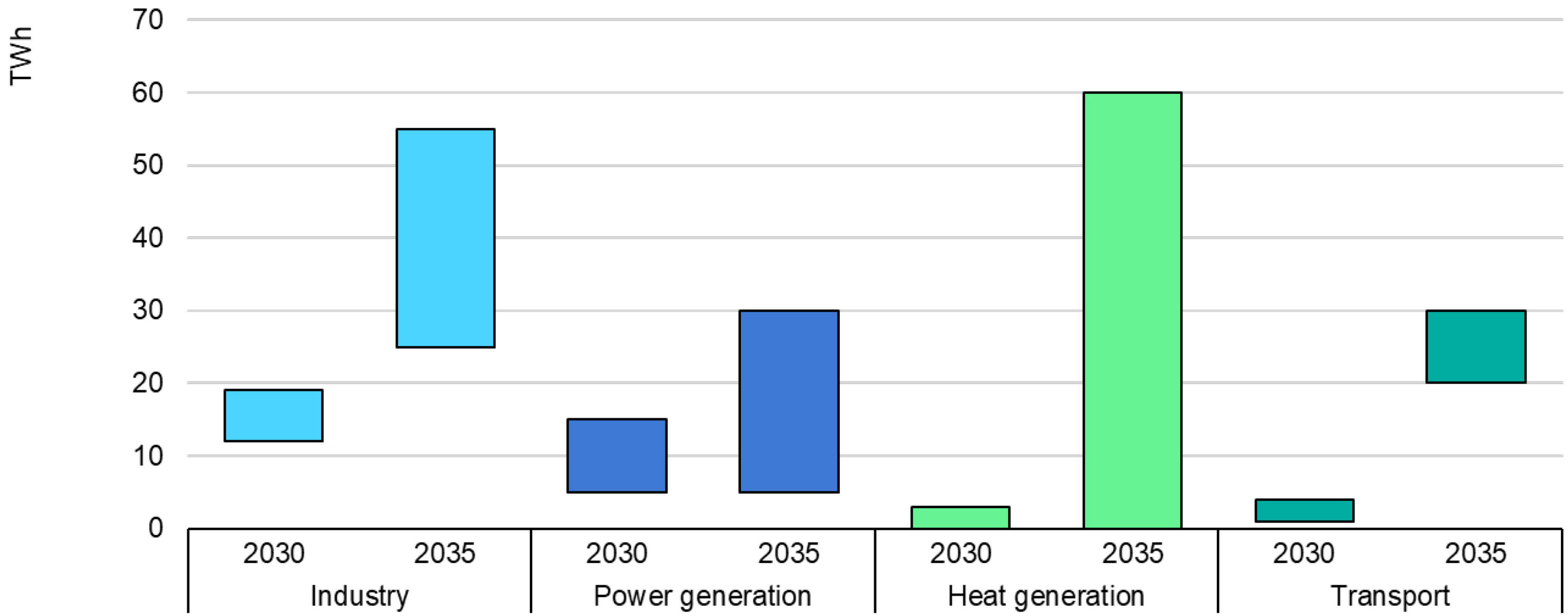
Hydrogen to power (H2P) solutions are seen as offering a flexibility option for the power grid as well as a decarbonisation outlet for existing unabated gas power plants. As outlined in the recent UK government consultation on hydrogen to power, analysis indicates that H2P could facilitate between 5 GW and 12 GW of low-carbon electricity generation by 2035, rising to between 20 GW and 90 GW by 2050. In March 2023 the UK government consulted on its decarbonisation readiness requirements, proposing to require that new-build and substantially refurbished power plants are built in a way that enables them to easily decarbonise by conversion to either 100% hydrogen-firing or retrofitting CCS technology within the lifetime of the plant.

The United Kingdom has provided further clarity on this through the publication of the second consultation on the Review of Electricity Market Arrangements in March 2024.

The UK government has committed to making strategic decisions on hydrogen-based heating in 2026, highlighting the less certain nature of the potential role for the fuel in this sector. Until then, co-ordination with industry, regulators and other entities is contributing to development and testing projects, such as SGN's H100 hydrogen home heating trial in Fife, where green hydrogen is set to be delivered to homes through a dedicated distribution network. The UK government decided in December 2023 not to proceed with a hydrogen village trial in Redcar as it became clear that the main source of hydrogen supply would not be available in time.

United Kingdom's hydrogen demand ambitions are expanding, but significant uncertainty remains

United Kingdom's potential hydrogen demand ranges by sector, 2030 and 2035



Note: Data do not necessarily represent targets, but potential demand ranges.
Source: UK Department for Energy Security and Net Zero (2023), Hydrogen Production Delivery Roadmap.

Hydrogen supply

Northwest Europe is at the forefront of low-emissions hydrogen development

The ten countries considered in the Hydrogen Monitor produced just over 4 Mt of hydrogen in 2022, according to European Hydrogen Observatory. Unabated fossil fuels accounted for 99% of the inputs, and Germany, the Netherlands and the United Kingdom were responsible for over 70% of total hydrogen production. An additional 0.5 Mt of hydrogen is produced as a by-product.

As per the IEA Hydrogen Projects Database, Northwest Europe's electrolytic hydrogen production capacity stood at over 220 MW in 2023. Most of the operating capacity is located in Germany, accounting for around 40% of the total. Two gas-based hydrogen production projects capture CO_2 for use in industrial or agricultural applications in the Netherlands and in France. For the purposes of this Monitor, these projects are not classified as low-emissions hydrogen.

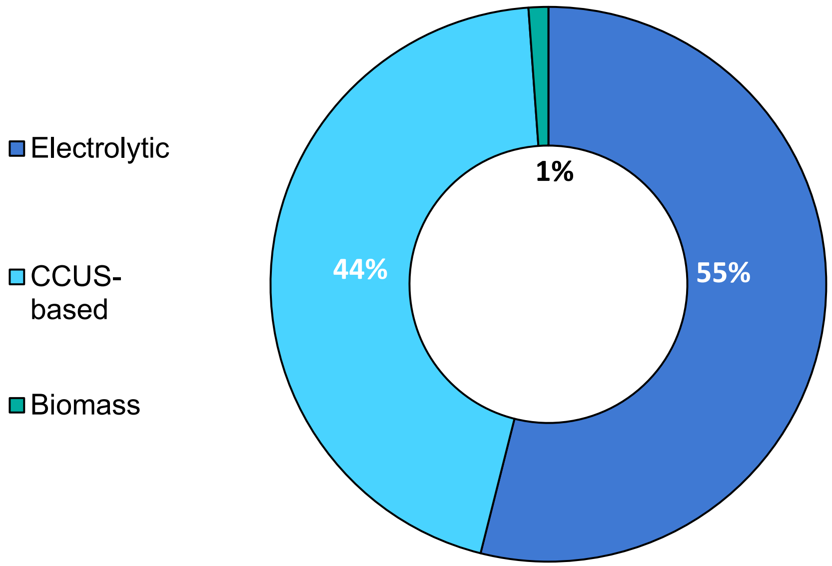
Northwest European countries are at the forefront of low-emissions hydrogen production development. Based on projects under development, the region is expected to account for about two-thirds of the total low-emissions hydrogen supply added in OECD Europe by 2030. If all planned projects become commercially operational, and taking the assumptions on efficiency and utilisation factors into account, Northwest Europe's production of low-emissions hydrogen (and derivatives) could reach just above 7 Mt/yr by 2030. Fossil fuel-based hydrogen projects equipped with CCUS would account for 45% of total low-emissions hydrogen production, while electrolytic hydrogen supply would contribute 55%.

Notably, less than 4% of the projects underpinning the expected low-emissions hydrogen supply by 2030 have already reached FID or are under construction. Over 95% are currently undergoing feasibility studies or are in the concept phase. This highlights the importance of policies and support mechanisms unlocking the investment necessary for the scale-up of low-emissions hydrogen. State-backed risk-sharing mechanisms can help to de-risk investment and improve the economic feasibility of low-emissions hydrogen projects. Demand creation should be a key instrument to stimulate investment, including via quotas and public procurement rules.

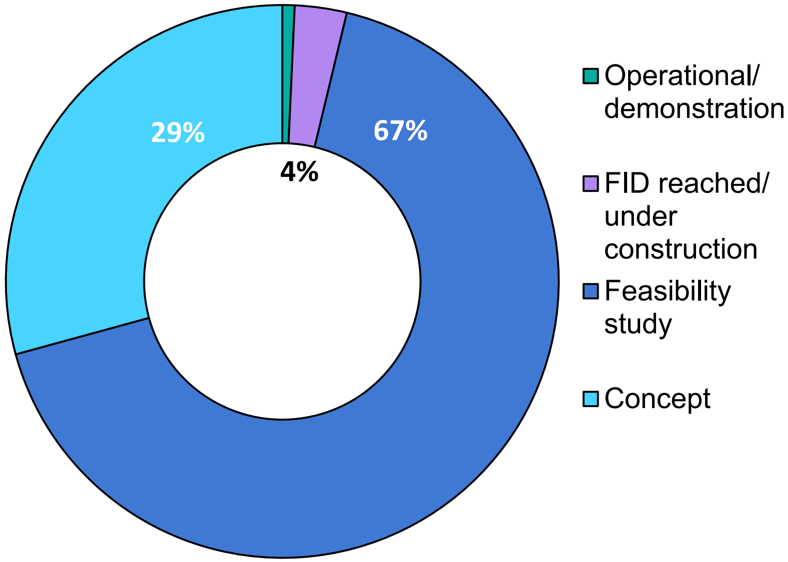
This section provides an overview of the expected low-emissions hydrogen supply in Northwest Europe, by technology route and by project status.

Electrolytic hydrogen is expected to account for 55% of Northwest Europe's low-emissions hydrogen supply by 2030

Potential low-emissions hydrogen supply in Northwest Europe by type, 2030



Potential low-emissions hydrogen supply in Northwest Europe by project status, 2030



Source: IEA (2024), Hydrogen Projects Database.

The United Kingdom, the Netherlands, Denmark and Germany are leading low-emissions hydrogen project announcements in Northwest Europe

The scale and the speed of low-emissions hydrogen development is expected to vary across Northwest European countries, depending on their policy choices, regulatory frameworks and resource endowment. In this regard, several of them have included electrolyser capacity deployment targets in their national hydrogen strategies, reflecting their strong potential for wind power generation, while Norway has chosen a technology-neutral approach. Based on announced projects, the United Kingdom, the Netherlands, Denmark and Germany are expected to account for three-quarters of Northwest Europe's low-emissions hydrogen production by 2030.

The following section provides an overview of projects relating to low-emissions hydrogen and its derivatives 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 had 15.2 MW of installed electrolyser capacity at the end of December 2023. The largest project is H2FUTURE, equipped with a 6 MW proton exchange membrane electrolyser (PEM) electrolyser and operational near Linz (Upper Austria) since 2019. The DEMO4GRID project was commissioned in 2022 and is supported by a 3.2 MW alkaline electrolyser. The project is intended to supply green hydrogen for the food retailing company, MPREIS, to replace fossil-based natural gas for heating.

The total capacity of electrolytic renewable hydrogen projects that have reached FID and/or are under construction is around 143 MW. They include the WIVA P&G Hydrogen Region project, which will be supported by 20 MW of electrolyser capacity (using both PEM and solid oxide electrolyser cell [SOEC] technology) and is expected to start operations in 2025. The majority of electrolytic hydrogen projects are either undergoing feasibility studies or are in the conceptual phase.

If all planned projects start commercial operations by 2030, the combined capacity of Austria's renewable hydrogen projects would stand at around 600 MW, falling short of the government's 1 GW target. On this basis, it is estimated that Austria could produce approximately 30 kt of renewable hydrogen by 2030.

Belgium

The Belgian Federal Hydrogen Strategy does not specify a low-emissions 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 Hydrogen Projects Database, the country has four operational low-emissions hydrogen production facilities, with a combined capacity of 1.3 MW. Projects that have reached FID and/or are under construction have a total capacity of 2.5 MW. In addition, the Hydrogen Offshore Production Europe (HOPE) demonstration project is expected to start operations in 2025. The project will be supported by a 10 MW PEM electrolyser. The project will support businesses in Ostend and throughout the North Sea coast region to operate in a cleaner, more carbon-neutral way.

Several projects are either in the midst of feasibility studies or are in their conceptual phase. They could add 0.8 GW and 0.5 GW of low-emissions hydrogen production capacity, respectively, by 2030. Together, all of the low-emission hydrogen projects under development in Belgium could produce close to 0.3 Mt by 2030.

Denmark

Denmark adopted its Power-to-X Strategy in March 2022, setting a target for 4-6 GW of electrolyser capacity by 2030.

Denmark has several operational electrolytic hydrogen projects. The majority are small-scale with a combined installed electrolysis capacity of approximately 16 MW. The capacity of projects that have reached FID and/or are under construction is 250 MW. They include the Port of Aabenraa Methanol project, which is supported by a 60 MW PEM electrolyser and is expected to ramp up operations in 2024. The project will supply low-emissions methanol to shipping companies and fuel retailers.

Projects that are in the midst of feasibility studies or are in their concept phase could add 3.3 GW and 14 GW of low-emissions hydrogen production capacity, respectively, by 2030. They include the BrintØ Hydrogen Island project, which is expected to have 10 GW of installed electrolyser capacity. Together, all of the low-emissions hydrogen projects currently under development in Denmark could produce close to 1 Mt by 2030.

France

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

France has several small-scale low-emissions hydrogen production projects. In all, the country has around 28 MW of electrolytic hydrogen production 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-emissions hydrogen project. Projects that have reached FID and/or are under construction could add 250 MW of low-emissions hydrogen production capacity by 2030. This includes the Normand'Hy – Air

Liquide project, which will have an electrolyser capacity of at least 200 MW and is expected to start operations in 2025. Air Liquide announced an investment of over EUR 400 million for the construction of this project in September 2023.

Projects undergoing feasibility studies or that are in their concept phase could add 4 GW and 3.2 GW of low-emissions hydrogen capacity, respectively, by 2030. This does not include the giant Lacq Hydrogen Project, which is located outside the geographical scope of Northwest Europe and is developed by the gas transmission system operators of France and Spain, Enagás and Terḗga.

In addition to electrolytic hydrogen, several gas-based low-emissions hydrogen projects are under consideration in France. According to the IEA Hydrogen Projects Database, they could add 0.1 Mt of low-emissions hydrogen production by 2030. Together, all of the low-emissions hydrogen projects currently under development in France could produce close to 0.7 Mt by 2030.

Germany

Under its National Hydrogen Strategy Update, Germany doubled its target for domestic electrolyser capacity in 2030 from 5 GW to at least 10 GW.

Germany currently accounts for about 40% of Northwest Europe's operational electrolytic hydrogen production capacity. Distributed among several small-scale projects, the country has approximately 90 MW of electrolyser capacity.

The projects that have reached FID and/or are under construction could add close to 650 MW of low-emissions electrolytic hydrogen capacity by 2030. This includes the SALCOS project, which is expected to start operations in the second half of the decade and will initially be supported by a 100 MW electrolyser.

Projects that are in the midst of feasibility studies or are in their concept phase could add 5 GW and 6 GW of electrolytic hydrogen production 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-emissions hydrogen projects in the conceptual phase of project development. They include the H2GE Rostock project, which is being developed by VNG and Norway's Equinor. Under the project scheme, Norwegian gas would be converted into low-emissions hydrogen in Germany via carbon, capture and offshore storage (CCOS). The CO_2 emissions would be stored in the Norwegian continental shelf.

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

Luxembourg

At the time of writing, although Luxembourg had not set quantified targets for low-emissions hydrogen production, the government had stated its aim of replacing fossil-based hydrogen with low-emissions hydrogen to reduce GHG emissions by more than 5 kt CO_2/year.

Netherlands

The Netherlands has set a target of 3-4 GW of electrolyser capacity by 2030, with an intermediate target of 0.5 GW by 2025. The Hydrogen Roadmap for the Netherlands, commissioned by the Ministry of Economic Affairs and Climate Policy, suggests the scaling up of production targets: 600 MW of electrolyser capacity by 2025 and 6-8 GW of installed capacity by 2030.

At present, the Netherlands has close to 10 MW of electrolytic low-emissions hydrogen production capacity in operation. In addition, Shell's Pernis refinery in the Rotterdam area captures carbon emissions from hydrogen production as part of the OPAC project. For the purposes of this Monitor, this project is not classified as low-emissions hydrogen.

Projects that have reached FID and/or are under construction could add around 210 MW of electrolyser capacity by 2030. This includes the Holland Hydrogen I project, which will be supported by 200 MW of electrolyser capacity and is expected to be operational by 2025. The project will supply low-emissions hydrogen to Shell's Pernis refinery, with the electricity sourced from the future Hollandse Kust North offshore wind farm.

Projects that are currently subject to feasibility studies could add 8.5 GW of electrolytic low-emissions hydrogen production capacity, while those currently in the conceptual phase could add a further 4.3 GW by 2030. They include the giant NorthH2 (4 GW) and HyNetherlands Phase 2 Projects (0.9 GW). In addition, several gas- and oil-based low-emissions hydrogen projects are in the early phases of development. If they reach commercial maturity, they could add around 0.65 Mt of low-emissions hydrogen production by 2030.

Together, all of the low-emissions hydrogen projects currently under development in the Netherlands could produce close to 1.4 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-emissions hydrogen production.

As at March 2023 Norway had 4 MW of electrolytic hydrogen production capacity. Projects for electrolytic and low-emissions hydrogen production that have reached FID amount to 78 MW. They include an industrial pilot for a 24 MW electrolysis plant developed by Linde for Yara as part of the SKREI project to produce green ammonia at their Herøya-Porsgrunn plant, as well as the world's first production plant for clean hydrogen with integrated carbon capture, opened by H2 Production AS and Zeg Power AS at Kollsnes in Bergen.

Based on the IEA Hydrogen Projects Database, projects that are subject to feasibility studies could add 2 GW of electrolytic low-emissions hydrogen production capacity, while those currently in the conceptual phase could add 0.9 GW by 2030. In addition, several gas-based low-emissions hydrogen projects are undergoing feasibility studies or are in the conceptual phase. They could supply 0.4 Mt of low-emissions hydrogen by 2030.

Together, all of the low-emissions hydrogen projects currently under development in Norway could produce over 0.7 Mt by 2030.

Switzerland

Switzerland has not yet set any low-emissions hydrogen production targets. The country's Hydrogen Strategy is currently in preparation and is expected to be published in the second half of 2024.

Switzerland has several small-scale, low-emissions hydrogen production projects in operation, with a total capacity of 10.5 MW. Several electrolytic projects are close to FID and could add around 50 MW in the coming years. Electricity is mainly sourced from hydropower.

Projects that are currently in the midst of feasibility studies could add 100 MW of electrolytic, low-emissions hydrogen production capacity by 2030.

Together, all of the low-emissions hydrogen projects currently under development in Switzerland could produce over 20 kt by 2030.

United Kingdom

In the British Energy Security Strategy, the United Kingdom doubled its low-emissions hydrogen production ambition to up to 10 GW by 2030, with electrolytic hydrogen accounting for at least half of it. The Hydrogen Production Delivery Roadmap (published in December 2023) sets a target of up to 6 GW of electrolytic and up to 4 GW of CCUS-enabled hydrogen by 2030. The strategy sets intermediate targets of up to 1 GW of electrolytic hydrogen capacity in construction or operational by 2025, and similarly up to 1 GW of CCUS-enabled hydrogen capacity in construction or operational by 2025.

The United Kingdom currently has close to 10 MW of electrolytic, low-emissions hydrogen production capacity, mostly in the form of small-scale pilot projects. Projects that have reached FID and/or are under construction could add 55 MW of electrolytic hydrogen production capacity by 2030. The gap between capacity under construction or with FID and capacity in the early stages of development indicates that policy support, including funding, will be important for the United Kingdom to deliver its hydrogen production ambitions. The various support mechanisms, including the Hydrogen Production Business Model (HPBM) scheme and the Net Zero Hydrogen Fund, are expected to accelerate project development in the near term, facilitating FIDs.

Projects in the midst of feasibility studies could add 1.4 GW of electrolytic hydrogen production capacity by 2030, while those in the conceptual phase could add 0.5 GW. They include giant projects such as the Kintore Scotland Hydrogen project (with a capacity of over 3 GW) and the Gigastack-Hornsea 2 project (1 GW). In addition, several gas-based low-emissions hydrogen projects are being considered. Although most of them are currently either undergoing feasibility studies or are in the conceptual phase, they could add close to 1.8 Mt of low-emissions hydrogen supply by 2030.

The United Kingdom is progressing negotiations for the capital and revenue funding needed for the country's first commercial-scale CCUS-enabled hydrogen production plants. The UK government has previously announced the HyNet and East Coast clusters as the Track 1 clusters. Eight potential CCUS projects, including two CCUS-enabled hydrogen projects, were selected to enter into negotiations with the UK government for potential financial support. Negotiations with these projects are progressing at pace across both CCUS Track-1 Clusters and we are continuing to work collaboratively to maintain our ambitious timetable to take FID and begin construction of the UK's first of a kind carbon capture and storage network in 2024.

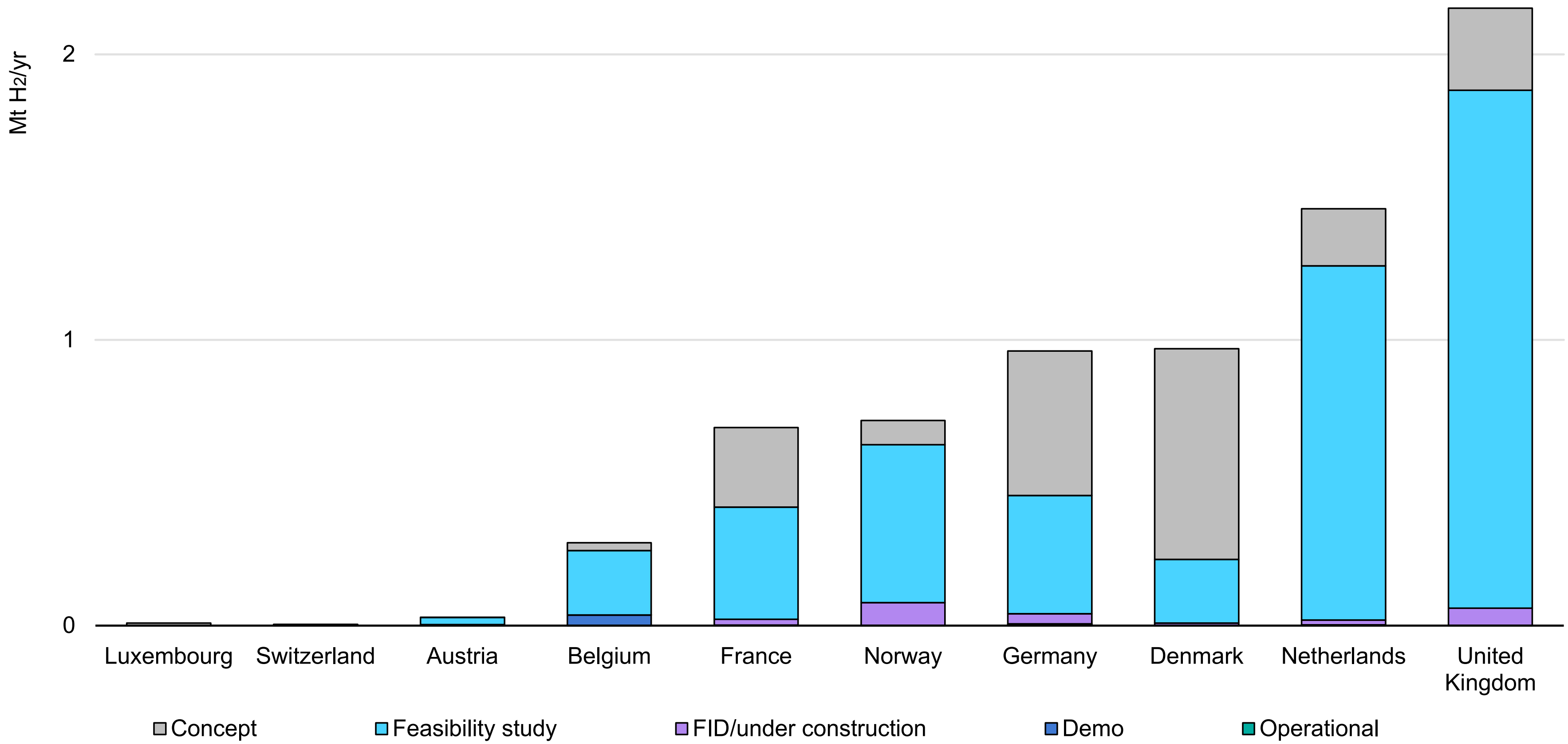
The HyNet North West Project alone could account for around half of the country's gas-based low-emissions hydrogen supply by 2030.

This project aims to decarbonise the industries located in Northwest England and North Wales by providing low-emissions hydrogen produced from natural gas via autothermal reforming subject to CCS. According to the project developers, HyNet North West could reduce carbon emissions by 10 Mt/year by 2030.

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

Less than 4% of the announced production due online by 2030 has reached FID or is under construction

Potential low-emissions hydrogen production by 2030 based on current project status by Northwest European country



Source: IEA (2024), Hydrogen Projects Database.

Production costs and price discovery

Fossil-based hydrogen production costs significantly moderated in 2023

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

Recent production cost dynamics

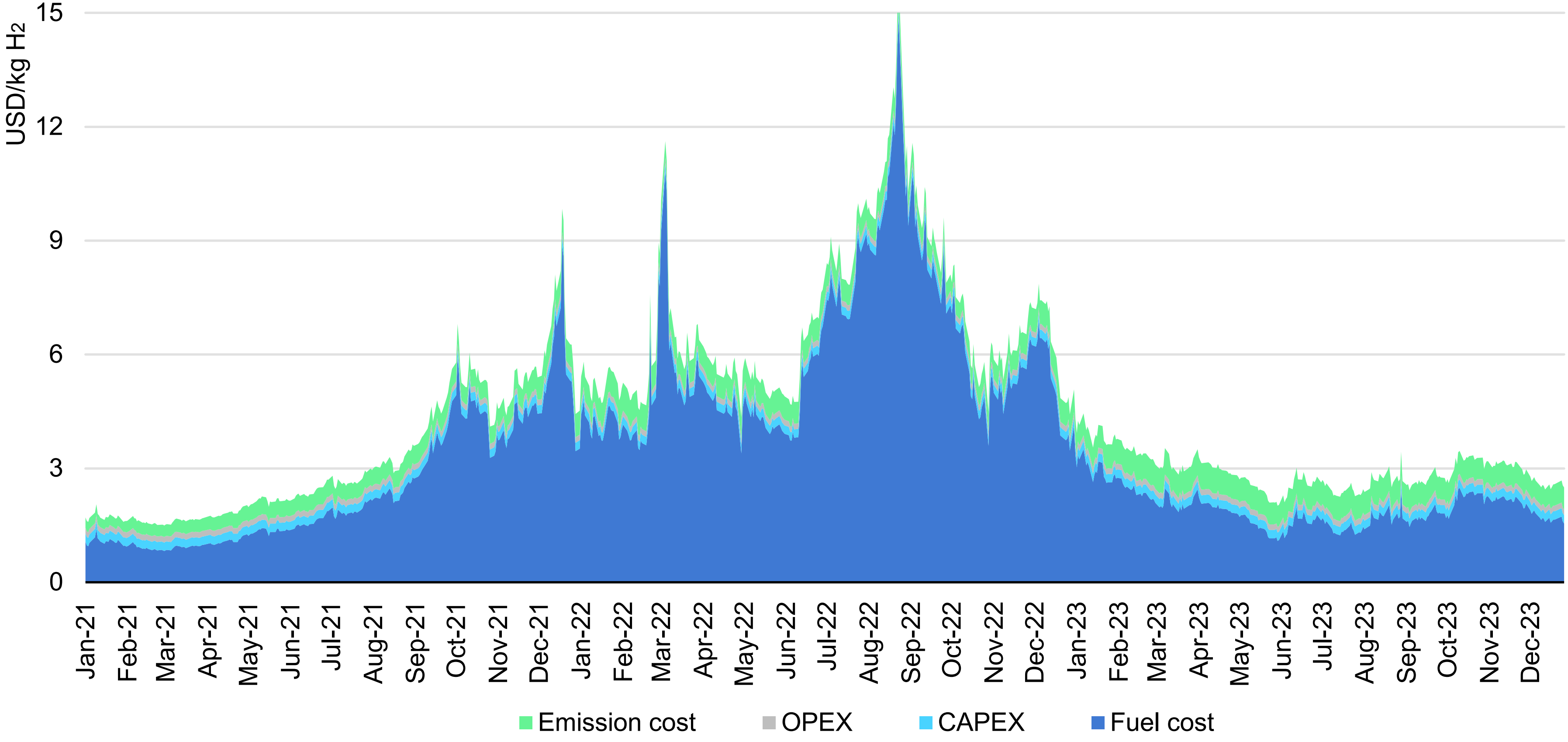
The majority of hydrogen in Northwest Europe is currently produced via steam methane reforming (SMR). Natural gas typically accounts for 70% of the levelised cost of hydrogen production (LCOH) and for about 80% of the operating expenses. The steep decline in Russia's piped gas deliveries to Europe drove up natural gas prices to all-time highs in 2022. Gas prices on TTF – Europe's most liquid and widely traded hub – rose from an average USD 5.5/MBtu (EUR 4.5/MBtu) between 2016 and 2020 to USD 40/MBtu (EUR 39/MBtu) in 2022. This had profound implications for hydrogen production costs. In addition, carbon prices rose significantly in the region, driving up production costs of unabated gas-based hydrogen further. Consequently, the assessed LCOH from gas via SMR rose from a below USD 2.5/kg H_2 (EUR 2.1/kg H_2) in 2021 to around USD 6/kg H_2 (EUR 5.7/kg H_2) in 2022. The surge in gas prices contributed 90% of the increase in estimated hydrogen production costs. The strong increase in the LCOH from unabated gas tested its competitiveness. The estimated LCOH from wind-powered electrolysis stood at USD 1/kg H_2 (EUR 0.95/kg H_2) below the unabated SMR production route in 2022, when gas prices rose to exceptionally high levels.

In 2023 natural gas moved towards a gradual rebalancing. In Europe, TTF prices fell by almost 70% compared with 2022 to average USD 13/MBtu (EUR 12/MBtu) in 2023. Steep demand reductions, together with lower gas storage injection needs and healthy LNG inflows, softened natural gas prices despite the continued decline in Russian piped gas deliveries to the European Union (down by 60% in 2023 y-o-y). Consequently, the assessed LCOH from unabated gas more than halved and averaged just above USD 2.5/kg H_2 (USD 2.3/kg H_2).

Hence, low-emissions hydrogen production routes were not competitive with unabated production in Northwest Europe in 2023. The estimated LCOH from solar PV-powered electrolysis in 2023 was about USD 6-8/kg H_2 (EUR 5.5-7.5/kg H_2). Leveraging the wind power potential of this group of countries, the estimated LCOH from wind power-based electrolysis was below USD 6/kg H_2 (USD 5.5/kg H_2) both for onshore wind and offshore wind. The estimated LCOH from gas with CCUS was at just above USD 3/kg H_2 (EUR 2.7/kg H_2) in 2023.

Lower natural gas prices weighed on hydrogen production costs in 2023

LCOH from gas via SMR without CCUS, 2021-2023



Initial price discovery takes off for renewable hydrogen in Germany

Low-emissions and renewable hydrogen is not currently traded on exchanges or over the counter. Nevertheless, initial price discovery can play an important role in the scale-up of the market and support investment decisions. In Germany, the European Energy Exchange launched HYDRIX – a price index for renewable hydrogen – in May 2023. The index is published on a weekly basis based on the lower heating value of hydrogen. HYDRIX is quoted in EUR/MWh to facilitate price comparison with natural gas and electricity. Given that hydrogen is not currently traded on exchanges, HYDRIX is based on actual price indications from renowned and established market participants from industry. Renewable hydrogen prices on HYDRIX averaged EUR 230/MWh (or USD 7.5/kg H_2) between May 2023 and February 2024. Hence, according to industry actors, renewable hydrogen prices stood almost three times the assessed LCOH from unabated gas during this period. This highlights the need to improve the cost-competitiveness of low-emissions and renewable hydrogen.

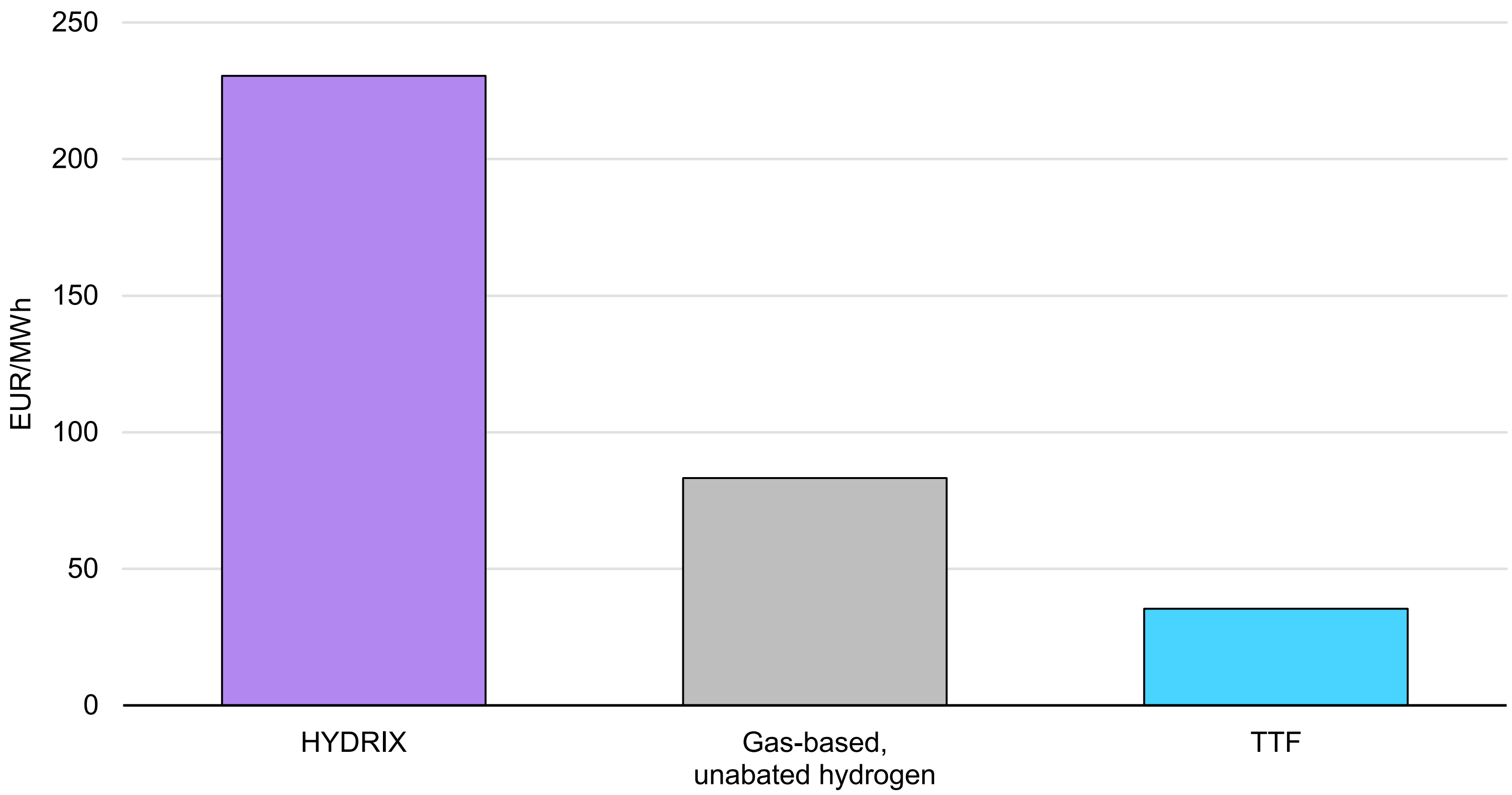
Hydrogen production cost outlook in Northwest Europe

Hydrogen produced via renewable electrolysis and gas-based supply with CCUS could become cost-competitive with unabated gas-based hydrogen in Northwest Europe by 2030. Under the IEA Announced Pledges Scenario (APS), renewable electrolytic hydrogen production costs are in the range of USD 2.4-4/kg H_2 (EUR 2.3-3.8/kg H_2).[5] Natural gas with CCUS could be the cheapest production alternative at USD 1.9-2.3/kg H_2 (EUR 1.8-2.2 kg/H_2), lower than natural gas without CCUS (which we estimate at around USD 2.7/kg H_2 or EUR 2.55 kg H_2), assuming that CO_2 prices reach USD 135/t CO_2 (EUR 127/t CO_2). The decline in electrolysis and renewable technology costs is the key driver behind the steep decline expected in low-emissions hydrogen production costs. Moreover, expectations of higher carbon prices benefit the prospective competitiveness of low-emissions hydrogen. For example, the total cost of installing an electrolyser manufactured in Europe or the United States could decline by 60% over the outlook period, from USD 1 700-2 000/kW in 2023 (or EUR 1 570-1 850/kW) to USD 700-800/kW (or EUR 650-750/kW) by 2030 in the APS. However, the rising cost of capital and the volatility of raw material prices present a risk to the cost evolution of these technologies. In the APS, the share of CAPEX in the LCOH from offshore wind declines from approximately one-third in 2023 to around 20% in 2030 – as electrolyser capital costs decrease. In contrast the share of CAPEX in the total LCOH from natural gas (both unabated and with CCUS) stays in the range of 10-20%. In the case of gas-based hydrogen production, the higher CAPEX and OPEX costs associated with CCUS systems can be more than offset by higher carbon prices. The cost reductions in the APS together with a carbon price of over USD 135/t CO_2-eq (EUR 127/t CO_2) could ensure that the LCOH from renewable electrolysis is comparable with the LCOH from unabated gas in the region – and in certain cases lower.

[5] Exchange rate used as of 12 April 2024.

Initial price discovery highlights the significant price premium of renewable hydrogen compared to alternative energy carriers

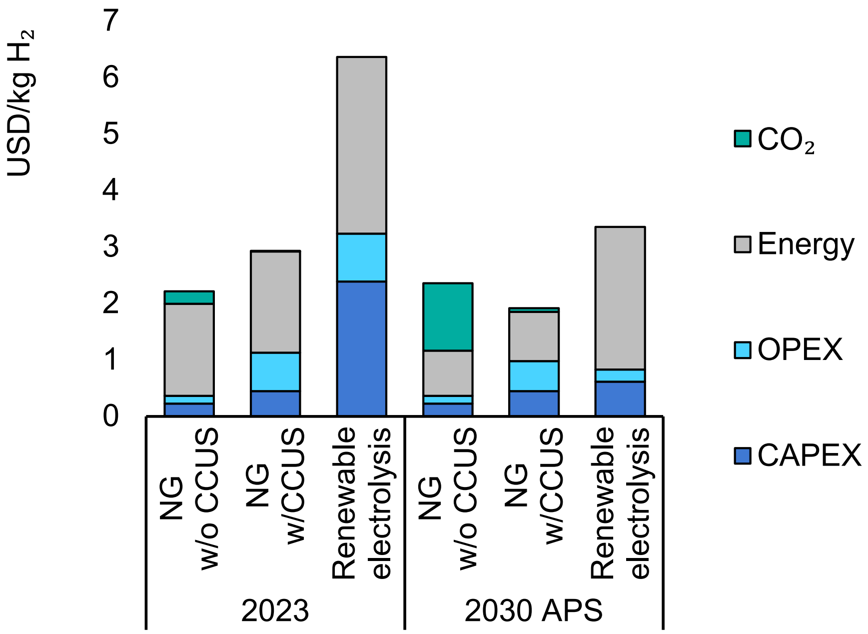
Renewable hydrogen prices on HYDRIX, the assessed LCOH from unabated gas and TTF month-ahead gas prices, May 2023-February 2024



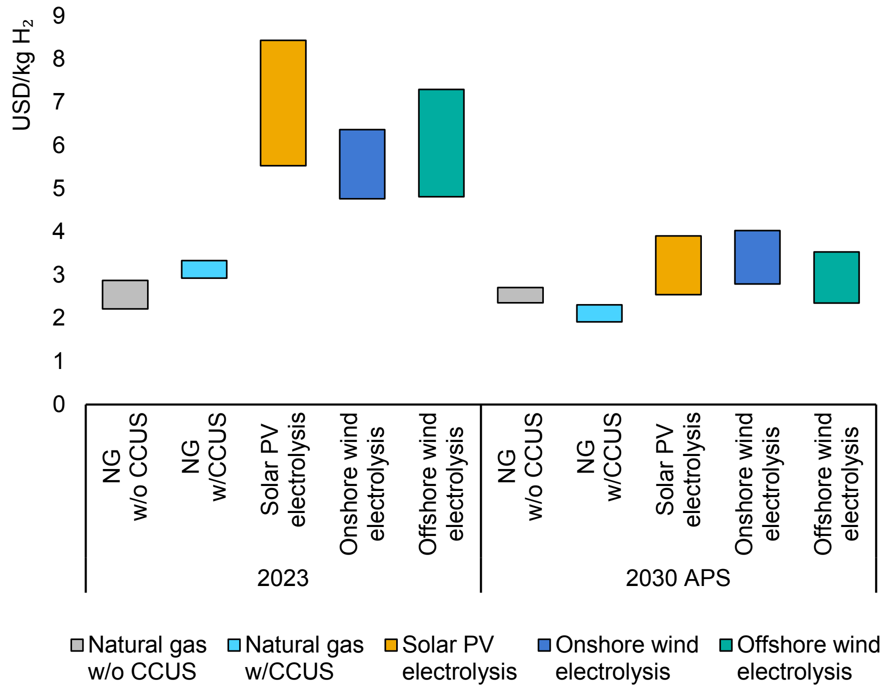
Source: IEA analysis based on EEX (2024), Hydrix; Powernext (2024), Spot Market Data.

Low-emissions hydrogen production costs could steeply decline by 2030 under the APS

Cost-component breakdown for selected technologies, Northwest Europe, 2023-2030



LCOH via selected technologies in Northwest Europe in the APS, 2023-2030



Notes: NG = natural gas; CCUS = carbon capture, utilisation and storage; w/ = with; w/o = without. Renewable technologies considered include onshore and offshore wind. For electrolysis, CAPEX refers to the installed electrolyser system, while the renewable system cost is factored into the energy cost component.

For the techno-economic assumptions please refer to the Annex of the Global Hydrogen Review 2023.

Hydrogen trade

A nascent market for low-emissions hydrogen trade

Hydrogen trade flows are currently limited to a few existing hydrogen pipelines connecting industrial areas in France, Belgium and the Netherlands, and to a few pilot projects to demonstrate hydrogen trade by ship. The only exceptions are ammonia and methanol, which are already globally traded as feedstocks for the chemical industry.

In the case of Northwest Europe, the Antwerp-Rotterdam-Rhine-Ruhr area accounts for about 40% of the European Union's chemical production, for which hydrogen is an important feedstock. The region is a centre of hydrogen production and demand today, but it is also well placed to be a hub for trade in clean molecules thanks to the excellent port infrastructure with access to international routes. The ports of Rotterdam, Antwerp and Hamburg, among others, have worked on strategic plans to position themselves as key import hubs for hydrogen and its derivatives. In addition, several memorandums of understanding (MoUs) have been signed with counterparts in prospective exporting countries.

Pilot shipments of low-emissions hydrogen-based fuels take off in 2023

Over the course of 2023 several pilot projects have completed initial shipments of low-emissions hydrogen-based fuels, mainly from the Middle East to destinations in the Asia Pacific region. This is the case with the 5 kt of low-emissions ammonia (NH_3) shipped from Saudi Arabia to India by SABIC Agri-Nutrients Company, to be used in the fertiliser industry. Another cargo of ammonia was shipped from Saudi Arabia's Ma'aden mining company to Bulgaria in the summer of 2023, containing 25 kt NH_3 for the fertiliser industry. Ammonia is already traded at scale today, with about 20 Mt NH_3 per year (or 10% of global production) shipped internationally and used mainly as a feedstock in the chemical industry. However, almost all the ammonia is produced from unabated fossil fuels.

Earlier in 2023 the first shipment of 2 600 litres of synthetic gasoline produced from the Haru Oni pilot plant in southern Chile was shipped to the United Kingdom for testing in the automotive sector. While this is a small amount of synthetic fuel, the Haru Oni project plans to scale up annual production to 55 million litres by 2025 (equivalent to the annual consumption of about 83 000 passenger cars) and to 550 million litres by 2027 (about 830 000 passenger cars).

Based on the announced projects that aim to trade hydrogen or hydrogen-based fuels, 16 Mt of hydrogen equivalent (H_2-eq) could be moved around the globe by 2030, and this could grow to 25 Mt H_2-eq by 2040. Export-oriented projects represent more than 40% of the low-emissions hydrogen that could be produced by all the announced production projects by 2030 (38 Mt), indicating that the potential export market is a strong driver in the development of projects. But only a small number of projects are at advanced stages of development (i.e. having at least reached FID), all for the trade of ammonia and accounting for less than 0.4 Mt H_2-eq by 2030.

Three-quarters of the export-oriented projects are still at the early stages of development by 2030 and less than 25% of them are undergoing a feasibility study. Moreover, less than one-third of the projects, in terms of volume by 2030, have identified a potential offtaker, and only a few have signed a binding offtake agreement. The NEOM Green Hydrogen Company, developer of the eponymous project in Saudi Arabia, has signed a 30-year offtake agreement with Air Products for the supply of low-emissions ammonia from 2026 onwards. Securing offtakers for the long run is a necessary condition for the projects to move ahead and to guarantee economic sustainability.

Northwest European countries are carving out a central role

Countries of the Northwest European region account for three-quarters of global import volume by 2030 for which a final destination has been identified. The Netherlands, Germany and Belgium, with their industrial activity and developed port infrastructure, are the preferred destinations for trade-oriented projects, and account for the majority of the 5 Mt H_2-eq that Northwest Europe could receive by 2030 according to announced projects.

Australia and Central and South America could be the main exporting regions to supply low-emissions hydrogen and hydrogen-based fuels to Northwest Europe. A large amount of the announced trade flows result from an MoU between Fortescue and E.ON for the export of up to 5 Mt of hydrogen to Europe by 2030, although the details of this agreement are still subject to finalisation and the final volume will depend on the demand in Europe. Intra-European trade could also emerge in the future, connecting locations with favourable renewable resources – such as the Iberian peninsula, Denmark and Norway – and demand hubs mainly in the Netherlands and Germany. This is the case of the Norwegian Barents Blue project, for the export of ammonia to the Port of Rotterdam, and the agreement between Equinor and the German energy company RWE for hydrogen trade via pipeline to Germany. But around 60% of the announced projects due by 2030 have yet to identify a destination. The high share of projects at the early stage of development, without a defined destination or offtake agreements, leaves uncertainty about the full development of the trade market by 2030.

In order for the European target to be reached by 2030, not only do the current projects in the pipeline with Europe as the destination have to move forward to FID in the next few years, but they also have to double in terms of volume to reach the 10 Mt of renewable hydrogen as stated in the REPowerEU plan – although this is non-binding.

Northwest European countries are actively investigating low-emissions hydrogen import opportunities

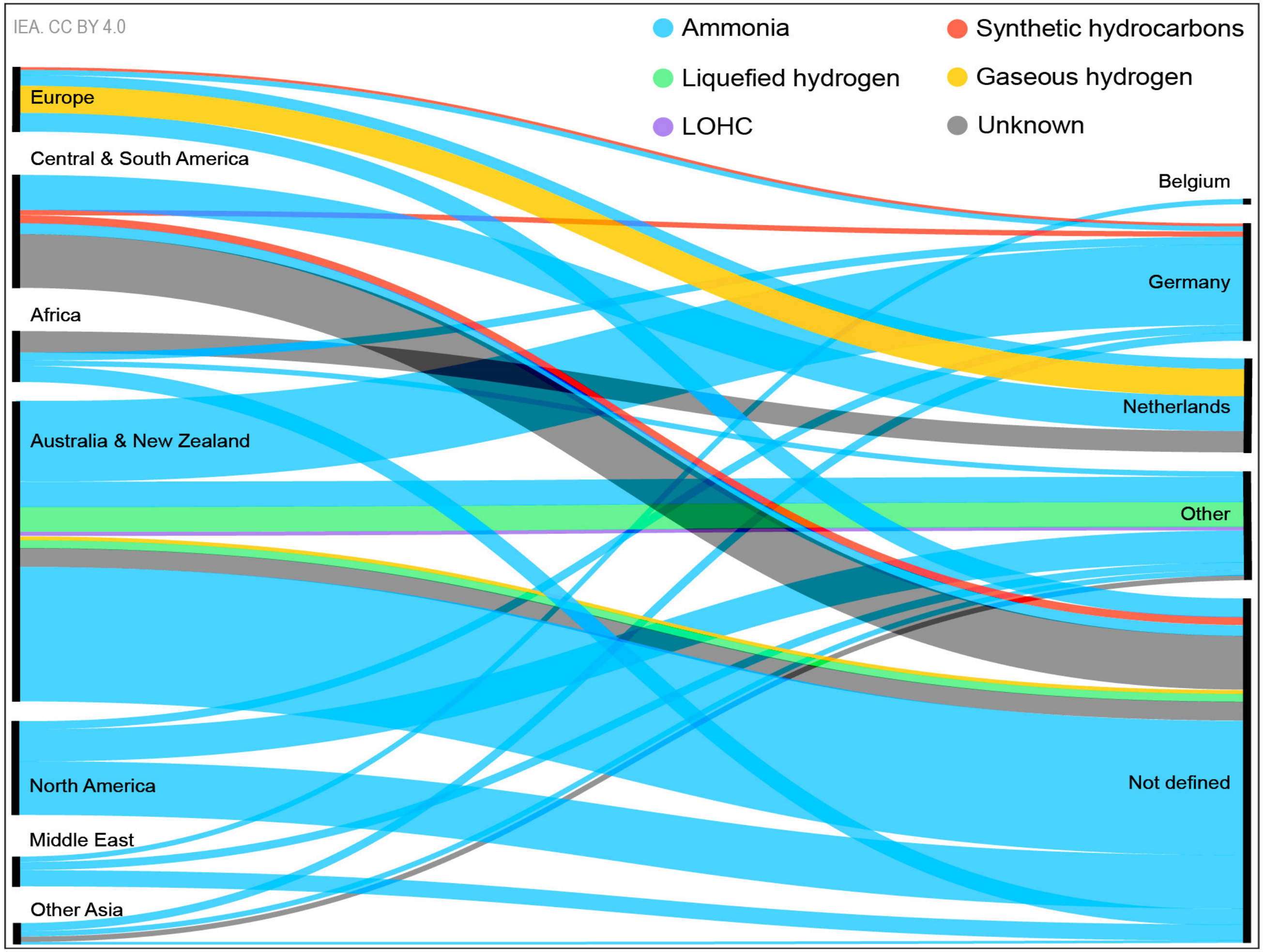
List of selected agreements signed by Northwest European countries in 2023

Parties	Year	Description
Australia–Netherlands	2023	MoU to support the development of a renewable hydrogen supply chain from Australia to Europe.
Chile–France	2023	Joint declaration to create a bilateral working group on low-carbon hydrogen, reinforcing technical and political co-operation between the two countries.
Chile–Netherlands	2023	Renewal of the MoU with the Port of Rotterdam, and a new agreement focused on the construction of a strategic co-operation agenda in green hydrogen for the period 2023-2025.
Germany–Denmark	2023	Joint declaration of intent for the ramp-up of a German-Danish hydrogen infrastructure, with the aim of importing hydrogen to Germany.
Germany-Netherlands	2023	Joint Declaration of Intent on a common H2Global call for fostering imports, and a Joint Declaration of Intent on further energy cooperation regarding hydrogen infrastructure, including import infrastructure.
Spain–Netherlands	2023	Memorandum of collaboration to promote the renewable hydrogen industry.
Morocco–Netherlands	2023	MoU between Morocco and the Netherlands on co-operation in the field of renewable energy, including hydrogen.
Saudi Arabia–Netherlands	2023	MoU between Saudi Arabia and the Netherlands on co-operation in the field of (renewable) energy (including hydrogen), energy efficiency and energy security.
United Kingdom–Germany	2023	Joint declaration of intent on establishing a hydrogen partnership to strengthen strategic and technical collaboration on hydrogen.
United Kingdom–Norway	2023	Updated existing MoU on CCUS to include a specific annex on hydrogen collaboration.
South Africa–Denmark **South Africa–Netherlands**	2023	In the framework of a joint visit of Danish and Dutch ministries to South Africa, MoUs were signed on green hydrogen and an energy partnership programme.

Source: IEA analysis based on government and company announcements.

Northwest Europe is set to lead the development of low-emissions hydrogen trade

Potential low-emissions hydrogen trade flows based on announced projects, 2030



Notes: LOHC = liquid organic hydrogen carrier. In million tonnes of hydrogen equivalent. Only flows larger than 150 kt H_2 equivalent per year are shown.
Source: IEA Global Hydrogen Review 2023.

Offtake agreements and government support will be key to scaling up low-emissions hydrogen trade

Securing long-term offtake is fundamental for trade projects to move ahead – and also for their respective production stage. Bilateral trade contracts with a clear pricing mechanism, often between companies, provide investment security to developers, particularly given the highly capital-intensive nature of hydrogen production and infrastructure projects. But, while future cost reduction for low-emissions hydrogen production is expected by the end of the decade, the offtaker may initially face a cost disadvantage compared to traditional unabated fossil hydrogen supply; here is where government action can support the deployment of the low-emissions hydrogen trade.

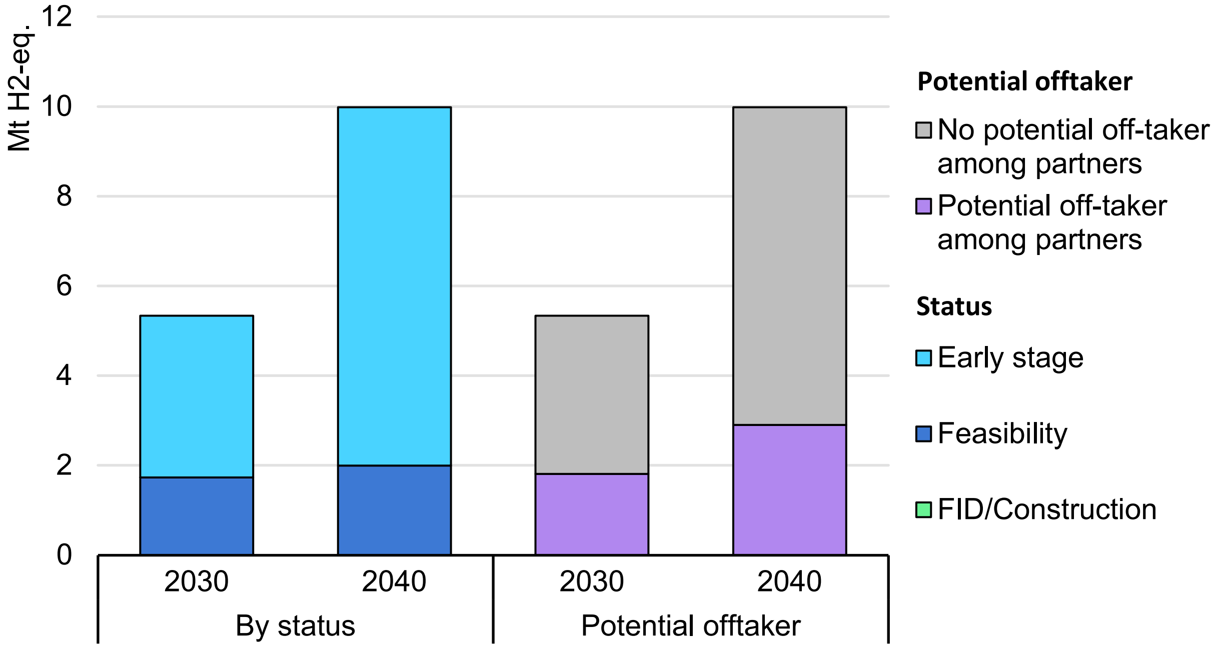
Instruments such as auctions can be used to create a bidding competition for contracts and help to close the gap between demand and supply price levels. The most developed support programme for hydrogen trade is the German H2Global double auction system. Through a market intermediary, HINT.CO, an auction will be held for the purchase of hydrogen via fixed-price 10-year contracts, from suppliers outside the European Union. In parallel, on the demand side, a separate auction will be held to sell the hydrogen to buyers with shorter contracts of about one year. The first tender was launched at the end of 2022 and closed in May 2023, with deliveries planned to begin in 2024. The initial budget was EUR 900 million, but the German government has allocated a further EUR 3.5 billion for tenders up to 2036, and the Dutch government announced in 2023 that it would join the auction mechanism, allocating a further EUR 300 million.

In March 2023 the European Commission established the European Hydrogen Bank with the aim of supporting and boosting renewable hydrogen production and use. With an initial budget of EUR 800 million funded through the ETS Innovation Fund, the European Hydrogen Bank launched its first auction in November 2023: producers of renewable hydrogen (as defined in the Renewable Energy Directive and in the Delegated Acts) can bid for support in the form of a fixed premium per kg of hydrogen, with a ceiling at EUR 4.5/kg, for a duration of 10 years. Recently, the European Commission has announced the second auction of the European Hydrogen Bank for the spring of 2024.

A similar support mechanism was launched by Denmark in April 2023, and the six project winners were selected in October. From a total budget of DKK 1.25 billion (about EUR 170 million), selected projects bid for a fixed premium per kg of renewable hydrogen produced for 10 years. Almost 280 MW of electrolysis capacity has been initially covered by this PtX tender, but one project has been excluded from the subsidy after it was unable to meet the requirements.

The majority of low-emissions hydrogen import projects are at early stages of development

Low-emissions hydrogen imports into EU NWE by status, based on announced projects, 2030-2040



Notes: "Potential offtaker" refers to projects that have identified a potential buyer or end user, even if a binding offtake agreement has not been signed yet. The amount of hydrogen equivalent traded is computed from the capacity of each plant, considering average capacity factors (reported in the technical documentation of the IEA Hydrogen Projects Database) and assuming that a certain share of production will be available for trade, in the case of projects aiming for multiple end uses. For each project, a 50% availability factor is assumed for the first year of operation. Only projects with a disclosed start year are included.
Source: IEA Global Hydrogen Review 2023.

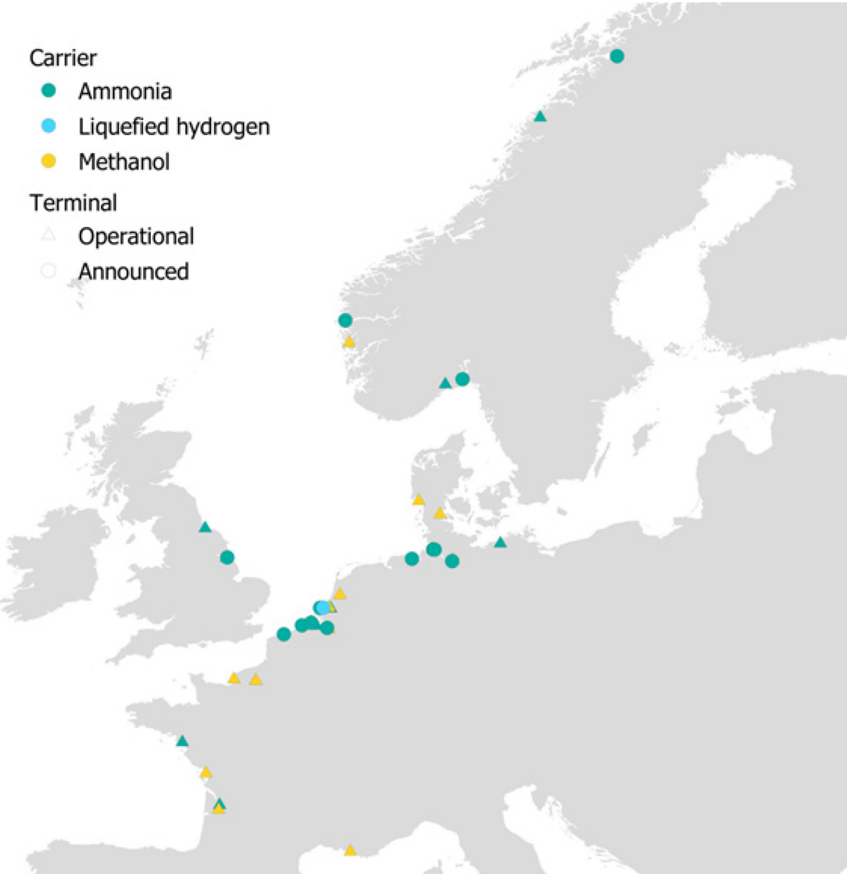
Ports will play a crucial role in enabling low-emissions hydrogen trade

Port infrastructure is set to play an important role in the future trade in low-emissions hydrogen and hydrogen-based fuels. Globally, approximately 150 terminals and ports can handle ammonia, and more than 110 have facilities to handle methanol. Northwest Europe hosts 13 ammonia-handling facilities and 16 that handle methanol, mainly concentrated in Germany, France and the Netherlands. Existing facilities are used for the current trade in ammonia (about 20 Mt per year, or 10% of global production) and methanol (about 35 Mt per year, or one-third of global production), while hydrogen trade via shipping today is essentially non-existent. Meeting the future demand for trade in hydrogen-based fuels will require both higher utilisation of existing plants and an expansion of port infrastructure.

Based on announced projects, around 50 terminals with port infrastructure for the trade in hydrogen and ammonia could be realised worldwide by the end of the decade. In June 2022 OCI reached FID for the expansion of the existing ammonia terminal in the Port of Rotterdam, and it is assessing the feasibility of expanding the storage capacity. In the same port, new ammonia import terminals are planned by Gunvor, ACE and Koole. Together with plans for new import terminals, announcements have been made for large-scale ammonia cracking facilities in port areas such as Wilhelmshaven, Rostock and Brunsbuttel (Germany), Antwerp (Belgium), Liverpool and Immingham (United Kingdom), and two in the Port of Rotterdam (Netherlands). The latter two, in particular, with an announced capacity of more than 1 Mt of hydrogen output combined, could be a focal point for the trade in ammonia trade in the Northwest European region.

Port infrastructure can solidify Northwest Europe's leading position in hydrogen trade development

Existing and announced port infrastructure for hydrogen and hydrogen-based fuels in Northwest Europe



Sources: IEA Global Hydrogen Review 2023 and IEA Infrastructure Projects Database.

Infrastructure

Dedicated infrastructure will be key to the large-scale deployment of low-emissions hydrogen

The large-scale deployment of low-emissions hydrogen will need to be underpinned by an effective and cost-efficient transmission and distribution system, strategically designed to connect supply sources to demand centres. In addition, the deployment of low-emissions hydrogen will need to be coupled with the development of cost-effective, large-scale and long-term storage solutions. Storage will play a key role in enabling low-emissions hydrogen to reach its full potential as an energy carrier and respond to the evolving flexibility requirements of a more complex energy system.

The following section provide a thorough review of the current state of and prospects for hydrogen infrastructure in Northwest Europe, with a particular focus on transmission systems and underground storage facilities. For further details on hydrogen infrastructure developments, refer to the IEA Hydrogen Infrastructure Projects Database.

The current state of hydrogen infrastructure in Northwest Europe

Transmitting hydrogen by onshore pipeline 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 ten countries considered in the Hydrogen Monitor have approximately 1 600 km of hydrogen pipelines in operation, with over 95% of them located in Belgium, France, Germany and the Netherlands. Most are closed systems owned by large merchant hydrogen producers and are concentrated near industrial consumer centres (such as petroleum refineries and chemical plants). The majority of these pipelines were built as dedicated infrastructure for the transport of hydrogen. In addition, several projects repurposing natural gas pipelines to serve hydrogen are being considered. The first gas pipeline repurposing project was undertaken by the Netherlands, with the 12 km Yara-Dow pipeline, put into commercial hydrogen service in November 2018.

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 is only one operational hydrogen salt cavern facility, located in the United Kingdom and commissioned in 1972. In addition, several pilot and demonstration projects are under development, including the repurposing of natural gas caverns to serve hydrogen and the assessment of fast-cycling capabilities. To date, experience of storing pure hydrogen in porous reservoirs such as depleted fields or aquifers is limited.

Northwest Europe has set ambitious targets for hydrogen network development by 2030

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 33 European gas infrastructure companies launched the European Hydrogen Backbone initiative, with the aim of developing a common vision for Europe's future hydrogen network. In the European Union, the revised regulation on trans-European energy infrastructure (TEN-E) set three priority corridors for hydrogen infrastructure: Western Europe (HI West), Central Eastern and South Eastern Europe (HI East) and the Baltic Energy Market Interconnection Plan for Hydrogen (BEMIP Hydrogen). In November 2023 the European Commission published a list of Projects of Common and Mutual Interest (PCI/PMI). Of the 166 selected projects, 31 relate to the development of hydrogen pipelines. The PCI/PMI status allows project developers to apply for funding under the Connecting Europe Facility, which could facilitate reaching FID.

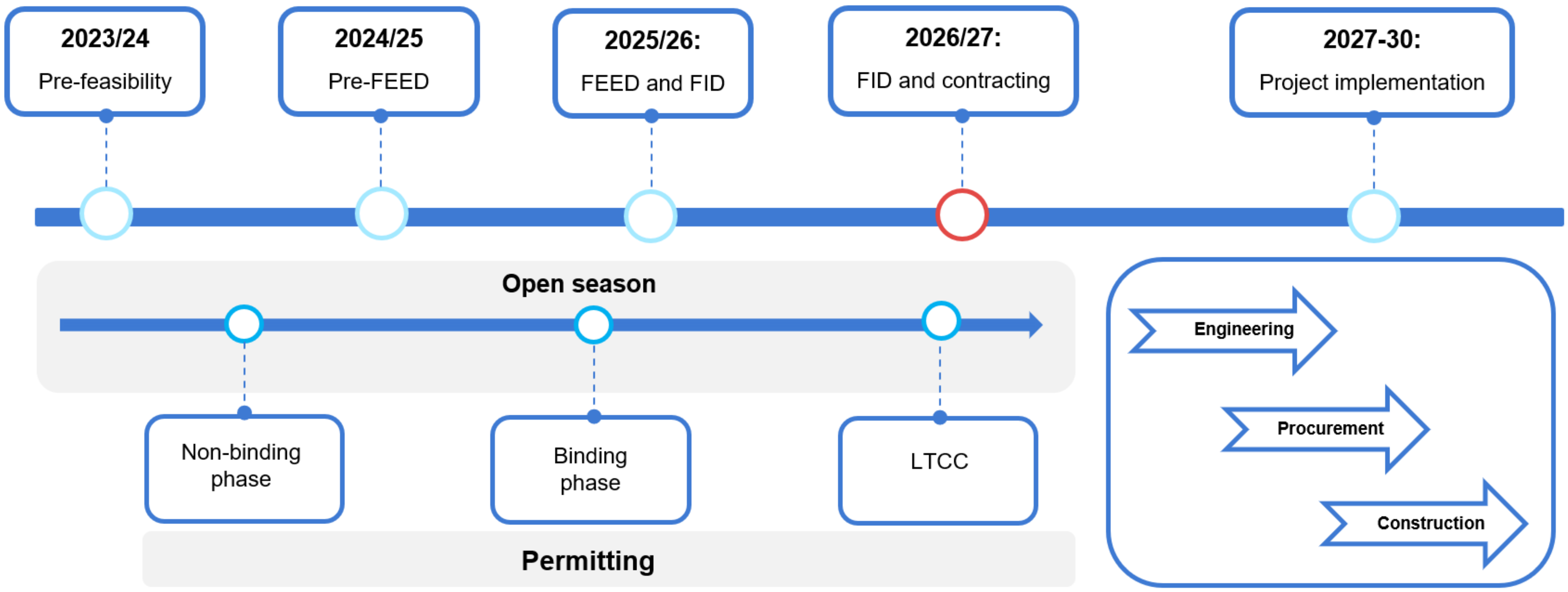
Based on pipeline project announcements, the region's hydrogen network could increase tenfold in length to over 18 000 km by early 2030. Based on public announcements, close to two-thirds of the hydrogen pipelines operational by 2030 would be repurposed natural gas pipelines. Repurposing existing methane pipelines to serve hydrogen can result in substantial cost savings and shorter lead times when compared with new-build hydrogen networks. Repurposing gas pipelines to serve hydrogen 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-emissions hydrogen.

The targets set by transmission system operators establish a vision for the development of Northwest Europe's future hydrogen network. Despite these plans, the number of pipeline projects that have reached FID and/or are under construction remains limited and certain entities consider these plans "quite optimistic". Before reaching FID, project developers typically carry out an open season. Open seasons are usually divided into binding and non-binding phases. The binding phase would be concluded through the conclusion of long-term capacity contracts between the project developer and market participants. Long-term capacity contracts effectively function as a risk-sharing mechanism and enable project developers to recover their initial investment costs through the payment of tariffs associated with the hydrogen transmission service provided.

Assuming that hydrogen pipelines have similar lead times to natural gas transmission systems, it could take six to seven years from the conceptual phase to the start of commercial operations to develop a new-build hydrogen pipeline. Hence, concentrated and immediate action by all stakeholders would be required to meet the targets set for 2030.

The development of a new-build hydrogen pipeline can take six to seven years

Simplified timeline of hydrogen transmission project development



Note: LTCC = long-term capacity contract.

Austria

Austria's Ministry for Climate Action and Energy published an extensive study, Gas infrastructure in a climate-neutral Austria 2040, in July 2023. In the same month it also published an integrated grid infrastructure plan (NIP) for consultation. The plan is a new systemic planning tool for the future Austrian energy system as part of the energy transition. For the first time, it integrates the expected energy generation, demand and infrastructure.

Austria's gas market and distribution area manager (AGGM) published a Hydrogen Roadmap, which expects the country's hydrogen network to reach over 700 km by 2030. Over 70% of the hydrogen pipelines operational by 2030 are expected to be repurposed natural gas pipelines.

The key hydrogen transport projects in Austria include:

- H2 Collector East: a 100% hydrogen-ready gas pipeline that is to be built in eastern Austria – partly by adapting existing infrastructure. From 2026 renewable hydrogen is expected to be transported from northern Burgenland to Lower Austria and Vienna.
- H2 Backbone WAG + Penta-West project: this creates cross-border hydrogen transport possibilities between Slovakia and Austria and between Austria and Germany up to a maximum of 150 GWh/day. Hydrogen could be transported in both directions. Within the framework of the project, more than 200 km of new pipeline will be built and 140 km of the existing pipeline will be repurposed. The project has received PCI status.
- H2 Readiness of the TAG pipeline system: one of the three methane pipelines of the existing Trans Austria Gasleitung (TAG) pipeline system will be converted into a hydrogen pipeline. This is also intended to create a hydrogen transport corridor between Austria and the neighbouring countries of Italy and Slovakia. The project has received PCI status.

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 during the 1960s and 1970s.

As noted in the federal 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-emissions hydrogen. The government expects the future hydrogen network to connect the ports of Zeebrugge, Ghent and Antwerp with the country's industrial areas and the adjacent countries.

In July 2023 Belgium's Council of Ministers approved EUR 250 million of public funding for the build-out of a hydrogen network. This includes funding for the following projects:

- Construction of a hydrogen connection with Germany.
- Development of the hydrogen transport network in and between the industrial clusters of Ghent, Antwerp, Mons, Charleroi and Liège.

At the time of writing, Fluxys, the country's gas TSO, has already published five specific infrastructure proposals, of which two are 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 according to participants' feedback. Fluxys expects the first phase to be developed by mid-2026 and the open-access hydrogen network by 2030.

In addition, Belgium's gas TSO, the Port of Antwerp, the Port of Zeebrugge and other relevant partners are part of the Green Octopus 2.0, which aims to contribute to the formation of an integrated hydrogen market between Benelux, Germany and France, fostering cross-border co-operation.

Denmark

In Denmark, Energinet, the Danish gas TSO, is considering export options for low-emissions hydrogen. In November 2023 Energinet and Gasunie agreed on the next steps for the development of the Danish–German hydrogen network as part of a co-operation agreement. The two companies are aiming to establish a cross-border transmission connection between Denmark and Germany by 2028 to enable the transport of low-emissions hydrogen. The cross-border network under consideration is expected to reach from the planned hydrogen underground storage facility at Lille Torup in northern Denmark to Heidenau south of Hamburg, with a total length of approximately 550 km. Part of that network will be the Danish Backbone West project, stretching 360 km from the planned underground hydrogen storage facility at Lille Torup to the border with Germany at Ellund. The Danish Backbone West is expected to consist of both converted natural gas pipelines and new-build hydrogen pipelines. The project was included in the European Commission's PCI list of November 2023.

France

France has over 300 km of operational hydrogen pipelines. Based on project announcements, more than 1 000 km of hydrogen pipelines could be developed by 2030. This will comprise new infrastructure and converting part of the existing gas network. France's key hydrogen pipeline projects were included in the European Commission's PCI list in November 2023, although none of them have reached FID yet:

- The mosaHYc (Moselle-Saar-Hydrogen Conversion) project is being developed in a 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. FID is expected to be taken in 2024. The project is expected to be commissioned in 2027.

- 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.
- GRTGaz's DHUNE project is planned in the Dunkirk industrial zone, with an extension to Belgium. The total length of the project would be 50 km. An investment decision is expected by 2025.
- GRTgaz's Hy-Fen Project would run between Fos-Marseille and the Grand-Est region, guaranteeing the connection between geographically distant production and consumption sites. The project could be commissioned in 2030 with a total length of 1 200 km.
- The WHHYN project is being jointly developed by GRTGaz and Belgium's Fluxys. The first phase of the project will link the Valenciennes area of France, where both production and consumption projects are located, with the industrial zone of Mons in Belgium. The first phase of the project would be 40 km and could be commissioned before 2030. The project could be expanded by 465 km by the mid-2030s.

In addition, GRTGaz is advancing the HYnframed project, which would span from the Fos-sur-Mer region up to Manosque. The total length of the project would 150 km and an FID is expected by 2025.

Germany

Germany has over 370 km of operational hydrogen pipelines. The National Hydrogen Strategy Update foresees the development of a hydrogen network of 1 800 km by 2027/28. Germany's association of supra-regional gas transmission companies (FNB Gas) presented a draft concept of the hydrogen core network in November 2023. In its view, the length of the network is expected to total 9 700 km by 2032 at an investment cost of EUR 19.8 billion. Reused natural gas pipelines are expected to account for around 60% of this future hydrogen network.

Several pipeline repurposing projects are currently being undertaken in Germany, including the following selection:

- Flow – making hydrogen happen is a project to develop a north-south transport route with a length of 1 100 km in

Germany. The commissioning of the first sections is expected by 2025, with expansion to Baden-Württemberg planned by 2028. The project is included in the European Commission's PCI list of November 2023.

- Under the HyPerLink Project, a 610 km repurposed pipeline will connect low-emissions 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 project is included in the European Commission's PCI list of November 2023.
- The H2ercules Project is expected to have a length of 1 685 km, mostly using repurposed pipelines, and is expected to start between 2026 and 2030. The project received PCI status in November 2023. 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 October gas transmission operators OGE and Nowega started the conversion of a 46 km gas pipeline segment to serve hydrogen. The pipeline runs from Lower Saxony to North Rhine Westphalia and is expected to carry hydrogen by 2025.

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 transport network. It 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 for and supply of low-emissions hydrogen will increase rapidly here. Connections with storage sites in the northern part of the Netherlands and interconnectors to Germany are also planned under Phase 1.

- 2026-2027/28: 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 June 2023 Gasunie took FID for the first part of the country’s planned hydrogen network. The investment associated with this first section exceeds EUR 100 million and is being developed by Gasunie's subsidiary, HyNetwork Services. Construction works started in October 2023, where Dutch King Willem-Alexander performed the official ceremony to start work on the construction of the national hydrogen network. A first section of 30 km is being built in Rotterdam to connect the Tweede Maasvlakte industrial park to Pernis. The hydrogen pipeline is expected to be operational by 2025.

The national hydrogen network would ultimately have a length of 1 200 km and connect the Netherlands’ major industrial areas with each other and Germany and Belgium. The overall costs associated with its development are estimated at EUR 1.5 billion. Around 85% of the network would consist of repurposed natural gas pipelines. In December 2023 Hynetwork Service published the transport and connection contracts that parties must sign to gain access to the future national hydrogen network.

Norway

In March 2022 Germany and Norway issued a joint statement on co-operation on hydrogen imports, including via offshore pipelines. In November 2023 the German Energy Agency (dena) and Gassco published a feasibility study on a hydrogen value chain from Norway to Germany.

Gassco and the German Energy Agency have led the work on an industrial feasibility study of a hydrogen value chain from Norway to Germany. Several industrial companies have participated in the study. Two main options have been evaluated. The first concept would entail the building of 725 km of new pipeline and the conversion of Europipe (approximately 650 km) to serve hydrogen. The second option would be a slightly shorter pipeline system, consisting of 1 250 km of new-build hydrogen pipelines. In the final quarter of 2023 the authorities of Norway and Germany agreed to set up a joint task force. Its aim is to follow up on the results of the industrial feasibility study and to consider issues that must be resolved by the German and Norwegian governments, including a regulatory framework.

Switzerland

Switzerland has only minor hydrogen pipelines in industrial areas. Switzerland's National Hydrogen Strategy is currently under development and is expected to be published in 2024.

United Kingdom

The United Kingdom has approximately 40 km of operational hydrogen pipelines.

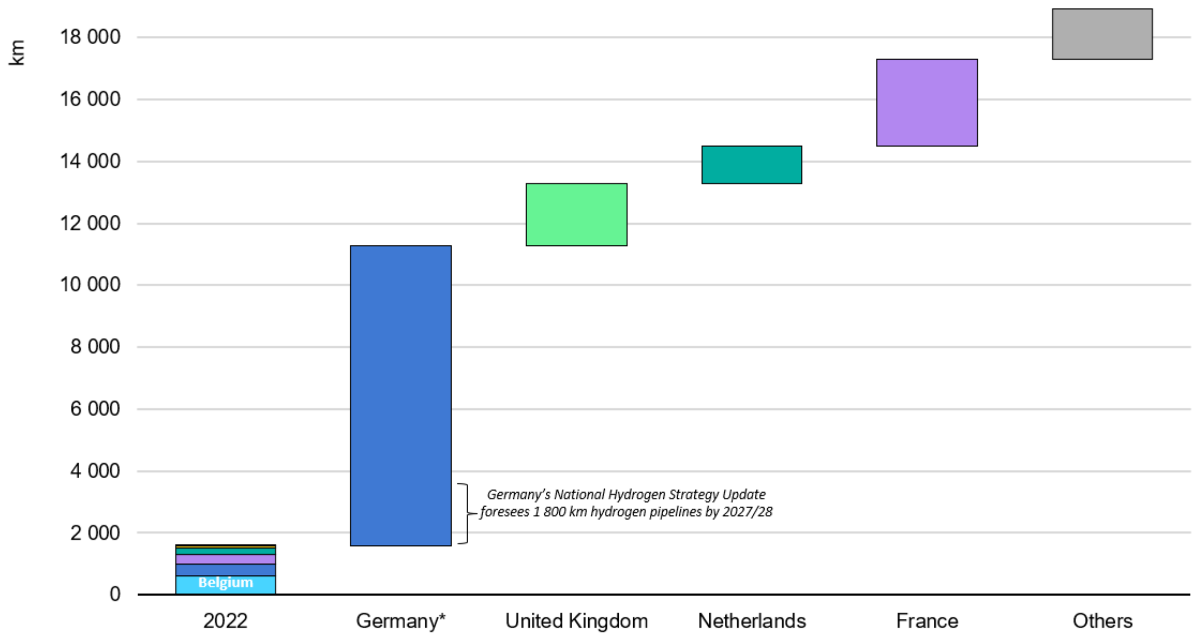
National Grid's Project Union is exploring the development of a UK hydrogen network to connect strategic hydrogen production centres with storage and consumption to support the creation of a UK hydrogen market. This project will identify potential pipeline routes, assess the readiness of existing natural 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 by the early 2030s.

In October 2023 the National Infrastructure Commission (NIC) published its Second National Infrastructure Assessment, recommending that the government should commit to the development of a core hydrogen pipeline network that is operational no later than 2035. The core hydrogen network would connect the major industrial areas of Grangemouth and North East Scotland, Teesside, Humberside, Merseyside and South Wales. The NIC also recommended the build-up of a carbon network. The total cost of building the core hydrogen and carbon networks is estimated to be in the range of GBP 12-22 billion. In December 2023 the United Kingdom published the Hydrogen Transport and Storage Networks Pathway, setting out the government's approach to enabling the build-out of transport and storage infrastructure to support the development of the hydrogen economy and provide wider energy system benefits. This will help identify and prioritise early strategically important projects and inform the allocation of the hydrogen transport and storage business models. The pathway also set out the government's agreement in principle with the NIC's recommendation on the value of a core network connecting multiple hydrogen producers to users and to hydrogen storage at scale, but maintained that determining the most suitable routing and timeline for such a network requires further evidence.

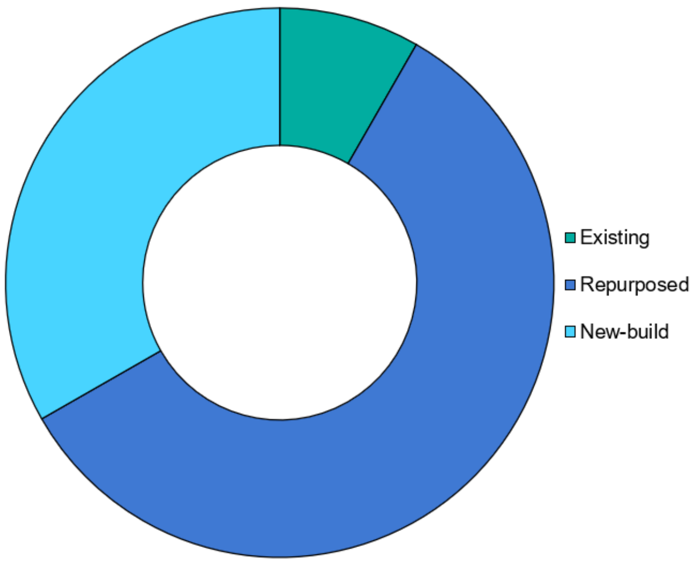
The pathway sets out the strategic ambition for the first allocation rounds of government support for hydrogen infrastructure, to support up to two storage projects at scale and associated regional pipelines to be under construction or operational by 2030. In addition to Project Union, there are several pipeline projects being developed across the United Kingdom, for example Cadent's HyNet pipeline project and the pipeline projects by Northern Gas Networks, National Gas and Cadent that form part of East Coast Hydrogen.

Northwest Europe's hydrogen network could reach over 18 000 km by the early 2030s, largely supported by repurposing existing natural gas pipelines

Existing and planned hydrogen pipelines in Northwest Europe, 2022 and 2030



Hydrogen pipelines in Northwest Europe in 2030, by origin



* Germany's National Hydrogen Strategy Update foresees the development of a hydrogen network of 1 800 km by 2027/28, while 9 600 km of hydrogen pipeline projects with a start-up date of 2030 are identified in the IEA Hydrogen Infrastructure Projects Database.
Source: IEA (2024), Hydrogen Infrastructure Projects Database.

Underground storage will play a key role in unleashing the full potential of low-emissions hydrogen as an energy carrier

Underground storage will be crucial for hydrogen to reach its full potential as an energy carrier and respond to the evolving flexibility requirements of a more complex energy system:

- **Short-term flexibility:** Considering that low-emissions hydrogen production facilities, SMR plants and electrolysers will have either flat or volatile supply patterns – especially when produced from variable renewables – storage will be key in responding to the short-term variability in both hydrogen supply and demand, driving the extrinsic value of storage. This will require highly flexible assets, with fast-cycling capabilities, which is typically provided by salt and hard rock caverns.
- **Seasonal storage:** This could meet seasonal swings in hydrogen demand and provide a **security buffer** against supply disruptions and sudden demand peaks.
- **Security buffer:** Hydrogen storage will also allow for a more optimal development of hydrogen networks and improve the load factor of electrolysers.
- **Market development:** Storage will be instrumental in enabling short-term, physical hydrogen trading.

Based on the IEA's Hydrogen Infrastructure Projects Database, Northwest European could develop over 3 TWh of hydrogen storage capacity by 2030. However, just 10% of the expected capacity by 2030 has reached FID and/or is under construction.

Austria

Austria was one of the countries to pioneer research into the storage of hydrogen in porous reservoirs. 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. In April 2023 the facility's testing of pure hydrogen storage in a depleted gas field entered into operation in Gampern, with a capacity of 4.2 GWh of electricity storage (i.e. equating to approximately 2.5 GWh of hydrogen storage).

Denmark

In July 2023 Gas Storage Denmark announced that it is working on plans to convert two of the caverns at the Lille Torup gas storage facility into hydrogen storage. One of the hydrogen caverns is to be dedicated to the Green Hydrogen Hub, while the second is to be offered to customers on ordinary market terms. The commissioning of the hydrogen caverns is expected by late 2028/early 2029. The Green Hydrogen Hub project, promoted by Corre Energy, Eurowind Energy and Gas Storage Denmark, is undertaking FEED of hydrogen storage in a salt cavern with a working capacity of 200 GWh.

France

France has several hydrogen storage projects, the majority of them at the early stages of development. They include the following:

- The HyGéo Project was launched in July 2020 and aims to explore the possibility of hydrogen storage in a repurposed salt cavern with a capacity of 1.5 GWh.
- The HyGreen Provence Project was launched in March 2021. The project is expected to be in operation in 2028 with a planned working storage capacity of 200 GWh located in the salt caverns of the Manosque storage site. Géométhane launched a non-binding open season from 1 February to 15 March 2023 to assess interest in hydrogen storage in two salt caverns (with a total capacity of 200 GWh) located in Manosque. No results of this non-binding open season have been disclosed to date.
- The HyPSTER Storage Project started engineering studies 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. In September 2023 the demonstration phase of the HyPSTER project was inaugurated. Following this initial experimental stage, the project is expected to be scaled up, until the salt cavern's full capacity is used up in 2026.
- As part of the HySOW Project, Teréga is planning to develop a hydrogen storage facility in a salt cavern with a capacity of 500 GWh by 2030 and expand it to 1 TWh by 2050. In June 2023 Teréga launched a call for expressions of interest.

Germany

Germany's Hydrogen Strategy Update recognises the importance of developing hydrogen storage both via the construction of new hydrogen storage facilities and the successive conversion of existing natural gas storage facilities to serve hydrogen. The broader value of hydrogen storage is also recognised in the context of the power system being increasingly geared towards volatile renewable energy sources and the potential for hydrogen storage facilities to provide them with intermediate storage options. The strategy foresees Germany playing a central role in the European hydrogen network, considering the country's large existing gas storage potential.

Germany has several hydrogen storage projects under development. They include the following:

- The HyCAVmobil Project is being developed by EWE, a major German utility, and the German aerospace centre DLR. The project 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.

Several projects are considering the repurposing of salt caverns, which currently store natural gas, to serve hydrogen. Uniper plans to convert the former Krummhörn salt cavern to hydrogen service with a storage volume up to 250 000 m^3. The project is expected to start operations in 2024.

Netherlands

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. HyStock held an open season from 15 June to 14 July 2023, offering market participants the ability to reserve capacity in its A5 hydrogen salt cavern (216 GWh). The first salt cavern is expected to be commissioned in 2028, with leaching already started. Three additional hydrogen caverns could be developed soon after 2030, depending on market interest. Further research is being conducted to assess the locations, quantity and distribution of future salt caverns for underground hydrogen storage. The goal is to strategically integrate these underground structures into the future energy system, determining both the number and specific locations of these caverns. This will be done in alignment with communities and regional interests.

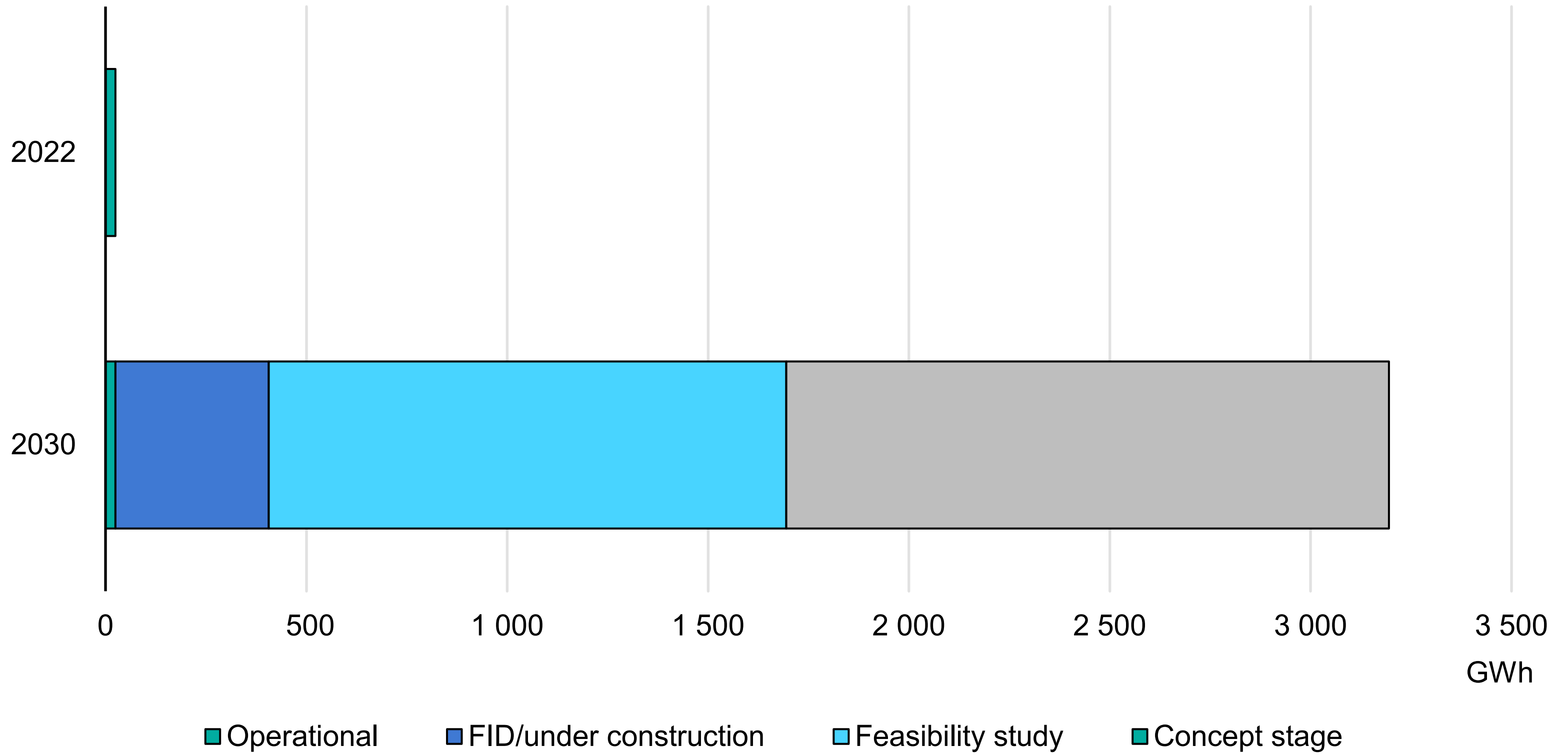
United Kingdom

The United Kingdom has one operational large-scale hydrogen storage facility, consisting of three salt caverns. The facility was commissioned in 1972 by Sabic Chemicals and has a storage capacity of approximately 25 GWh.

The Second National Infrastructure Assessment of the NIC notes that at least 8 TWh of hydrogen storage capacity will be needed by 2035. The Hydrogen Transport and Storage Networks Pathway sets the ambition to support up to two storage projects at scale and linked regional pipelines, to be under construction or operational by 2030. The pathway indicates that, based on demand analysis, storage infrastructure requirements are likely to increase significantly from 2035 onwards, particularly to enable hydrogen to power. The UK government intends to conduct further research into future transport and storage infrastructure needs to determine its scale and scope, including setting ambitions for future allocation rounds of the hydrogen transport and storage business models. 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.

The majority of hydrogen storage projects remain at the early stage of development

Potential underground hydrogen storage capacity in Europe by 2030, based on project announcements



Source: IEA (2024), Hydrogen Infrastructure Projects Database.

Annex

Terminology

Terminology relating to low-emissions hydrogen

In this report, low-emissions hydrogen includes hydrogen which is produced through water electrolysis with electricity generated from a low-emission source (renewables, i.e. solar, wind turbines or nuclear). Hydrogen produced from biomass or from fossil fuels with carbon capture, utilisation and storage (CCUS) technology is also counted as low-emission hydrogen. 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 is permanently stored to prevent its release into the atmosphere. The same principle applies to low-emission feedstocks and hydrogen-based fuels made using low-emission hydrogen and a sustainable carbon source (of biogenic origin or directly captured from the atmosphere). The IEA does not use colours to refer to the different hydrogen production routes. However, when referring to specific policy announcements, programmes, regulations and projects where an authority uses colours (e.g. "green" hydrogen), or terms such as "clean" or "low-carbon" to define a hydrogen production route, we have retained these categories for the purpose of reporting developments in this review.

Terminology for carbon capture, utilisation and storage

In this report, CCUS includes CO_2 captured for use (CCU) as well as for storage (CCS), including CO_2 that is both used and stored, e.g. for enhanced oil recovery or building materials, if some or all of the CO_2 is permanently stored. When use of the CO2 ultimately leads to it being re-emitted to the atmosphere, e.g. in urea production, CCU is specified.

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

ACER	Agency for the Cooperation of Energy Regulators
BMWK	Federal Ministry of Economic Affairs and Climate Action (Germany)
AFC	alkaline fuel cells
ALK	alkaline electrolyser
ATR	autothermal reforming
CAPEX	capital expenditure
CEM	Clean Energy Ministerial (IEA)
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
CREG	Commission for Electricity and Gas Regulation (Belgium)
DKK	Danish kroner
EC	European Commission
EHB	European Hydrogen Backbone
ENNOH	European Network of Network Operators for Hydrogen
EIB	European Investment Bank
EU	European Union
EU ETS	EU Emissions Trading System
EUR	Euro
FEED	front-end engineering design
EV	electric vehicles
FC	fuel cell
FCEV	fuel cell electric vehicles
FID	final investment decision
FT	Fischer-Tropsch
GBP	British pound
GHG	greenhouse gas
GO	guarantee of origin
H_2	hydrogen
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
ITO	independent transmission system operator
LCOH	levelised cost of 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
OPEX	operating expenditure
PCI	Project of Common Interest (EU)
PEM	proton exchange membrane
PMI	Project of Mutual Interest (EU)
PtX	power-to-X
PV	photovoltaic
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
TTF	Title Transfer Facility (Netherlands)
UK	United Kingdom
US	United States
USD	United States dollars

Units of measure

bcm	billion cubic metres
g	gramme
Gt	gigatonnes
GW	gigawatt
GWh	gigawatt-hour
kg	kilogramme
kg H_2	kilogramme of hydrogen
km	kilometres
kt	kilotonnes
kt H_2	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
Mt H_2-eq	million tonnes of hydrogen equivalent
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 Monitor was designed and directed by Gergely Molnár, Gas Analyst. The principal IEA authors were (in alphabetical order): Gergely Molnár, Francesco Pavan and Frederick Ritter. The Monitor extensively benefited from the guidance and support of colleagues from the Hydrogen and Alternative Fuels Unit: Jose Miguel Bermudez Menendez, Francesco Pavan and Amalia Pizarro. Mirko Uliano provided data support.

Dennis Hesseling (Head of the Gas Coal and Power Markets Division) and Uwe Remme (Head of the Alternative Fuels Unit) provided valuable comments and expert advice. Paolo Frankl (Head of the Renewable Energy Division) and Ilkka Hannula (Senior Analyst) provided valuable suggestions.

The Northwest European Hydrogen Monitor 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:

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Many thanks to the IEA Communications and Digital Office for their help in producing the report, particularly to Poeli Bojorquez, Astrid Dumond, Merve Erdil, Jethro Mullen, Isabelle Nonain-Semelin, Clara Vallois, Lucile Wall, Therese Walsh and Wonjik Yang. Justin French-Brooks edited the manuscript.

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

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Typeset in France by IEA - April 2024
Cover design: IEA
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