Hydrogen in North-Western Europe

A vision towards 2030

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Abstract

This study has been carried out by the International Energy Agency and the Clingendael International Energy Programme to explore the status of hydrogen in the north-western European region and how the sector could evolve towards 2030. National policies and project plans for hydrogen development are brought together to explore opportunities to tap into the full potential of hydrogen as a clean energy vector. This paper aims to foster a deeper discussion about ways for countries in the north-western European region to collaborate and benefit from hydrogen developments in their neighbouring countries with a view to accelerating national deployment and the development of a regional hydrogen market.

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Executive summary

The north-western European region[1] is well placed to lead hydrogen adoption as a clean energy vector. Today, this region concentrates around 5% of global hydrogen demand and 60% of European demand. Moreover, the region is home to the largest industrial ports in Europe, where much of this hydrogen demand is located, and presents a well-developed natural gas infrastructure connecting these ports with other industrial hubs. This gas network could be partially repurposed to facilitate hydrogen delivery from production sites to demand centres. Governments in this region also have ambitious goals for greenhouse gas (GHG) emissions reduction and strong political interest in hydrogen as an opportunity to maintain industrial activity in the region.

North-western Europe has vast, underutilised potential renewable energy in the North Sea, which is central to decarbonisation strategies for countries in this region. Utilisation will require integrating large volumes of variable wind power into their energy systems, which may require upgrading electric grid infrastructure and deploying energy storage capacities. Converting offshore wind electricity into hydrogen adds an additional opportunity to absorb high volumes of wind generation into their energy systems and markets and facilitate sector integration.

The opportunity offered by the North Sea extends beyond offshore wind due to the potential for large underground carbon dioxide storage, which could enable low-carbon hydrogen production using fossil fuels coupled with carbon capture and storage. Furthermore, the potential for offshore hydrogen storage exists, which could provide seasonal energy storage for an integrated system of clean power and low-carbon gases. The north-western European region, therefore, is crucial to the realisation of European hydrogen and decarbonisation ambitions, including for delivering the 40 GW electrolysis capacity target.

While the current policy landscape can create some momentum toward this transformation, tapping into the full decarbonisation potential of hydrogen in this region requires adopting more ambitious policies and strengthening co-ordination among governments in the region that can facilitate development of an integrated regional hydrogen market. Today, hydrogen demand is concentrated in the refining

[1] For this report, the north-western European countries considered are Belgium, Denmark, France, Germany, the Netherlands, Norway and the United Kingdom.

and chemical industries, with more than 96% of production based on unabated fossil fuels or a by-product from industrial processes (also using fossil fuels).

With current policies and confirmed plans from major industrial stakeholders in north-western Europe, the demand for hydrogen decreases slightly by 2030 due to competing forces. On the one hand, there is a significant decline in demand from traditional sectors (mainly refining and ammonia production); on the other hand, a degree of hydrogen adoption in new applications (namely mobility and the iron and steel industry) offsets part of the decline. On the supply side, hydrogen production remains based predominantly on unabated fossil fuels, with electricity-based production making modest inroads to reach less than 5% of overall production by 2030. Under this scenario, the low-carbon hydrogen production ambitions announced by several countries in the region cannot be reached. However, policies to put into national practice the wider European energy transition goals (such as the European Green Deal or the United Kingdom Climate Change Act) can stimulate the adoption of hydrogen technologies in new applications and the deployment of low-carbon hydrogen production, resulting in measurable impacts. Hydrogen demand could grow by a third by 2030 driven by new industrial applications (primarily in iron and steel), mobility, grid injection or power generation. Hydrogen supply would also observe a significant shift toward low-carbon production. Natural gas would remain the main source of hydrogen production in 2030, but close to 50% of this production would use carbon capture, and electrolysis would make significant impacts and reach 20% of total supply. It is important to recognise that the current pipeline of projects is not enough to meet national ambitions, but national policies that include wider European energy transition goals will likely lead to an expansion of the project pipeline from now to 2030, enabling achievement of these targets.

All assessed countries have recently published, or are expected to soon publish, national strategies for the development of low-carbon hydrogen. Previous hydrogen efforts are embedded and expanded on in these, creating more holistic hydrogen approaches. These national strategies and approaches to their respective goals differ between countries, in part reflecting their differences in governance structure. Often, these strategies build upon specific national features, for example intentions to expand hydrogen use out of existing demand centres or to bank on offshore energy potentials. A common priority is focus on hard-to-abate emissions, particularly in industry. Additional potential roles for hydrogen include heavy transport, residential heating, energy trade and transport within the strategies of several countries in the region. These strategies to some extent complement each other; for example, countries aiming to create supply beyond their domestic demand may be able to meet some of the import needs of others. The analysis carried out in this report suggests that it is likely that the evolution of hydrogen demand and supply will vary across the countries in the region, offering a possibility to build on the respective strengths of each country. This also applies to technology development, the significant work done in the region to ensure safe hydrogen use and transport and research that can be of benefit to others through trade and knowledge sharing. Potential obstacles to such cross-border collaboration and the creation of a regional low-carbon hydrogen market include mismatches in standardisation and certification between countries, as well as the lack of a framework for trade, European Union state aid rules, organisation of joint projects and factoring in funding for cross-border projects.

Countries in north-western Europe (Belgium, Denmark, France, Germany, the Netherlands, Norway and the United Kingdom) have made significant progress at a national level and have developed their visions about the role that hydrogen should play in their individual long-term energy strategies. From the analysis in this report, CIEP and the IEA have identified four priorities to be addressed in regional dialogues:

- Build on the large unused potential to cooperate on hydrogen in the north-western European region, which has already cooperative platforms in place (such as The North Seas Energy Cooperation), to identify opportunities to develop cross-border initiatives (like the Important Projects of Common European Interest) and projects that could facilitate the development of an integrated hydrogen market in the region.
- Identify what is needed to develop an integrated regional market. This could include development of a common regulatory framework and standards, as well as support mechanisms to reduce risk and coordinate the development of critical infrastructures.
- Develop supporting schemes to advance technology frontiers and market size scale-up of all steps in the value chain in a coordinated way. Build on strengths of each country to develop an optimal distribution of supply and demand centres for hydrogen in the region and address early potential bottlenecks in infrastructure or manufacturing capacity.
- Design a strategy to address emissions from existing hydrogen producing assets while simultaneously develop new production capacities for low-carbon hydrogen to meet demands originated in new applications.

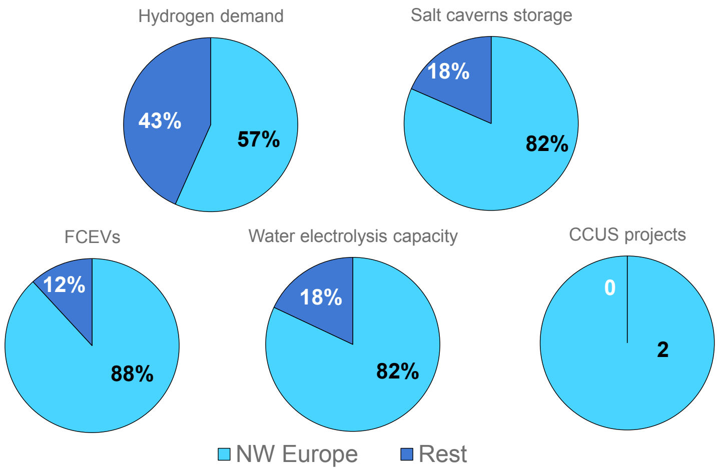
Introduction

Strengthened climate ambitions in Europe affect not only its energy policy planning but also the way countries look at potential opportunities to develop domestic and regional low carbon value chains. North-western Europe[2] played an important role as an oil and gas producer in the past and is poised for similar impact in the future based on the large offshore wind potential of the North Sea. The IEA report, Offshore Wind Outlook 2019, labels the North Sea as one of the most promising regions for offshore wind due to its high load/capacity factors and relative shallow waters. By 2018, 18 GW of offshore wind capacity were already installed in the North Sea, entailing the majority of the 23 GW installed worldwide. Integration of such large volumes of wind energy into north-western European countries' energy systems require investments to upgrade power grids and to incorporate technologies that can facilitate balancing the mismatch between supply and demand that results from a large penetration of renewables in the power system.

Conversion into hydrogen can help increase the volume of wind generation absorbed by energy systems/markets, while high-capacity factors and falling costs of offshore wind can enable scale up of low-carbon hydrogen. This is particularly important in north-western Europe, which today concentrates a significant share of Europe's hydrogen production and demand in its industrial clusters. These clusters, located at the shore and in deep water ports, are ideal locations to start scaling up low-carbon hydrogen production and consumption, as identified in the IEA report, The Future of Hydrogen. Industrial ports in north-western Europe already produce and consume a lot of hydrogen that has been earmarked to be decarbonised, and involve substantial traffic in terms of heavy trucks, river barges and trains which could be converted to hydrogen. Importantly, these ports are all connected to the gas grid which can be re-purposed to carry hydrogen relatively cheaply compared to new built pipelines or grid enlargement. Furthermore, these ports are particularly well placed to become one of the main routes for hydrogen imports into Europe, which are likely required to achieve the continent's net-zero ambitions.

[2] For this report, the north-western European countries considered are Belgium, Denmark, France, Germany, the Netherlands, Norway and the United Kingdom.

The role of north-western Europe in the European hydrogen landscape



Sources: IEA analysis based on IEA statistics; Caglayan et al. (2020); and Fuel Cells and Hydrogen Observatory.[3]
Notes: "NW Europe" includes the countries focus of this study (Belgium, Denmark, France, Germany, the Netherlands, Norway and the United Kingdom). "Rest" includes the rest of the EU countries. FCEV = Fuel cell electric vehicles. "CCUS projects" refers to operating projects to produce hydrogen coupled with carbon capture and utilisation or storage.

This region also has a significant capacity to store hydrogen in geological formations and salt caverns, with a potential for more than 60 000 TWh of hydrogen storage.[4] North-western European countries have taken the lead in Europe in adoption of new hydrogen technologies. These countries have the highest concentration of fuel cell vehicles and installed capacity of water electrolysis and are home to the only two operating projects in Europe to produce hydrogen coupled with carbon capture, utilisation and storage (CCUS). Moreover, this region is particularly well placed for developing geological storage of CO_2 at large scale. Estimates of geological storage capacity in the North Sea range from roughly 50 to 150 billion tonnes (Gt) of CO_2, with the United Kingdom and Norway comprising the bulk of this capacity (35-140 Gt). However, further assessment is required to understand the maximum amount of CO_2 that can ultimately be stored, how the gas is contained in the formation and the risk of leakage.[5,6]

The north-western European region therefore plays a crucial role in realising European hydrogen and decarbonisation ambitions. The large concentration of hydrogen demand in this region combined with the significant potential that the

[3] https://www.fchobservatory.eu/
[4] D.G. Caglayan et al. (2020), Technical potential of salt caverns for hydrogen storage in Europe, International Journal of Hydrogen Energy, 45 (11), 6793-6805.
[5] Höller, S. and Viebahn, P. (2011), Assessment of CO2 storage capacity in geological formations of Germany and Northern Europe. GHGT-10. Energy Procedia 4 (2011) 4897–4904.
[6] IEA (2020), CCUS in Clean Energy Transitions.

North Sea offers for deployment of electrolysis capacity, makes north-western Europe critical in delivering the European 40 GW electrolysis target by 2030.[7] Moreover, the bulk of the hydrogen project pipeline originates in this part of Europe; recent analysis suggests that the countries within this region have the best hydrogen market opportunities in Europe.[8]

For this reason, governments in the region have started dialogues to address the potential development of a regional hydrogen market. Part of these dialogues have been established through the "*Roundtable on the North-West European region"* of the Clean Energy Ministerial Hydrogen Initiative. To inform these conversations, participants in this roundtable have commissioned the International Energy Agency (IEA) and the Clingendael International Energy Programme (CIEP) to develop this study to explore hydrogen developments, policies and potential for collaboration in this region.

A change in policy making

In 2019, Europe witnessed two significant steps in energy policy making. In June, the UK Parliament passed an amendment of The Climate Change Act 2008, becoming the first major economy to adopt a legally binding target of net zero emissions by 2050.[9] Later in December, the European Commission presented the EU Green Deal, also targeting carbon neutrality by 2050[10] which was followed by the proposal in March 2020 of a European Climate Law, incorporating a legally binding target of net-zero greenhouse gas emissions by 2050 and raising the EU emissions reduction target for 2030 from 40% compared to 1990 to 55%.[11] In line with these developments, several countries in north-western Europe published their hydrogen strategies.

Reaching this point has required a progressive transformation of energy and climate policies also at the national level, including in the north-western European countries. The EU Green Deal, with its revised CO_2 reduction targets for 2030, require national policies that involve decarbonisation of the other sectors besides the power sector, such as industry, transportation, agriculture and heating in the built environment. Decarbonisation progress in some of these areas has so far been slow. The national transposition of 2020 targets resulted in different policy approaches and emphasis in terms of CO_2 abatement efforts and types of

[7] A hydrogen strategy for a climate-neutral Europe, COM (2020) 301 final.
[8] https://auroraer.com/media/hydrogen-could-be-120-billion-industry-in-europe-by-2050/
[9] The Climate Change Act 2008 (2050 Target Amendment) Order 2019.
[10] EC proposal for a Climate Act, COM (2020) 80 final, 3 March 2020.
[11] The European Green Deal, COM (2019) 640 final, 11 December 2019.

renewable energy stimuli. Additionally, the 2008 financial crisis hampered governments' ability to support projects and influenced the project portfolio initially considered.

Approaching 2020, the solution space began to converge due to sizeable cost and technological improvements, and solar and wind dominated the power sector investment landscape in many member states. The United Kingdom, Germany and Denmark made major strides in expanding their onshore and offshore wind production, while Belgium increased its solar and on- and offshore wind capacity. France also developed solar and onshore wind capacities and increased its ambitions for offshore wind, while its nuclear capabilities continue to play an important role. In the Netherlands, wind production projects, particularly offshore, grew while costs declined.

With increasing success in scaling up individual low-carbon technologies, particularly in power (solar and wind) and more recently in electrifying passenger car transportation, there has been increased recognition that isolated sectoral views are inefficient for reaching climate targets at the scale and pace required, especially as those targets become more ambitious. This is the case with the new EU 2030 energy and climate policy targets, which will necessarily involve an acceleration of decarbonisation efforts from other energy producing and consuming sectors of the economy. In preparation for these 2030 EU targets and their transposition to national policies, there has been a clear shift among policy makers to an integrated energy system transition.[12,13]

Achieving climate objectives will require comprehensive strategies that move beyond the need to integrate larger volumes of intermittent renewable power in the energy system. Much effort has been focused on decarbonising power, while the rest of the energy system was left largely untouched. In the future, not only the share of electricity is expected to increase but also of low-carbon gases and liquids. These comprehensive strategies must define a space for low carbon gas use in parts of the energy system where direct electrification combined with energy efficiency has limited potential (such as parts of heavy industries and long-distance transport) or can pose challenges to the electric grid (such as increased peak loads due to space heating in winter or electricity transmission issues). In various EU member states, the idea of building on existing integrated energy markets and their supporting infrastructures for natural gas and power to facilitate hydrogen integration and growing offshore wind and solar business has gained

[12] A hydrogen strategy for a climate-neutral Europe, COM(2020) 301 final.
[13] Powering a climate-neutral economy: An EU Strategy for Energy System Integration, COM(2020) 301 final.

traction. This would help integrate these resources into the current energy system and assist with transportation and storage of large amounts of energy to meet various types of demand throughout the year.

This study brings together both national policies and project plans for future development of hydrogen to foster deeper discussion about how countries in the north-western European region can collaborate and benefit from hydrogen developments in their neighbouring countries. It aims to accelerate national deployments and development of a regional hydrogen market. These countries are already part of an integrated regional market which includes a well-developed gas infrastructure, represents a large share of the European hydrogen market and aims to develop the offshore wind potential in the North Sea. For this purpose, the IEA has collected and analysed the current project portfolio in the region and projected hydrogen demand by 2030 under different scenarios, while CIEP reviewed national government strategies.

Governments in the region are willing to underpin hydrogen development with funding and investors are interested in realising the projects. However, several uncertainties remain before the projects and plans under development can reach final investment decision (FID), including a need for technical and safety studies and further changes to legislation in some countries that allow hydrogen to fulfil its envisaged new role. The intention of this report is therefore to provide an evidence-based picture of the potential outlook for hydrogen in the region and the policy needs for tapping into its potential.

The case for hydrogen in north-western Europe

In north-western Europe, the North Sea is a region shared by multiple countries and home to an array of economic and energy activities, such as fisheries, transportation and leisure as well as oil, gas and wind production. Ports such as Rotterdam, Antwerp and Hamburg are notably part of the North Sea region's global trading hub, along with a variety of energy-consuming and -conversion industries, like chemical production and refining. The North Sea has substantial energy potentials; offshore oil and gas production has been carried out for decades, although in recent years the focus has increasingly turned to its large offshore wind potential. Developing an offshore wind industry is now considered an opportunity that could help replace declining economic activity from mature oil and gas production in the area. Furthermore, hydrogen production from this potential offshore wind industry is seen as an opportunity to expand and absorb offshore wind potential into the various energy systems of countries within the region.

Under overarching European targets and policies, each country sees the potential of the North Sea in relation to achieving their own national goals. However, interconnections between various north-western European industrial hubs have increasingly fostered inter-regional collaboration to realise joint backbones for clean energy sources and carriers. Given offshore wind potential, the current infrastructure in north-western Europe, existing and largely integrated energy markets and industrial hubs and challenging CO_2 emission reduction goals for 2030 and 2050, hydrogen can be an important additional energy carrier to support realising both national and regional goals. What remains is how proposed national hydrogen policies, with varying goals and emphases, be coordinated to strengthen a collaborative, regional and coherent approach that achieves a common, more global goal and mitigates competitive interferences from each other?

Reviewing where the discussion is today, all countries in the region can benefit from the trials, pilots and thinking developed within the past few years, and which are increasingly coming together in more robust projects and policies.

As examples: the pioneering work on shipping and electrolysis in Norway;[14] the work on low temperature heating in the United Kingdom,[15] the power to gas studies in Germany and Denmark;[16] the studies about onshore and offshore gas infrastructure suitability for hydrogen transportation in the Netherlands;[17] the thinking around offshore electricity-hydrogen hubs in Denmark, Belgium and the Netherlands;[18] the coastal location of industrial clusters in, for instance, the United Kingdom, the Netherlands and Belgium; and the idea to develop offshore carbon capture and storage (CCS) using obsolete pipeline infrastructure and empty gas fields to decarbonise the current unabated large hydrogen production in the United Kingdom, Norway and the Netherlands. These have all contributed to united ideas and plans for building a low-carbon hydrogen system within the region. Often, public-private partnerships developing plans in various countries within the region include the same internationally operating companies, along with local companies and institutions. Interestingly, with projects of increasing scope and complexity that involve developing the entire hydrogen value chain, large integrated oil and gas and industrial gas companies have also joined. These recently emerged joint ventures provide both technological consistency across countries and benefit parts of the hydrogen value chain for specific countries. Next to policy making, these projects will have the greatest impact shaping the future hydrogen market.

Repurposing infrastructure for hydrogen

Research of European natural gas grid Transmission System Operators (TSOs) has shown the potential for a hydrogen backbone, composed of re-purposed gas grids and new built sections, and emphasising the facilitating role such infrastructure has related to reaching 2030 national targets and beyond.[19] A revision of the TEN-E regulation announced by the European Commission on 15 December 2020 is important for these ambitions.[20]

North-western Europe has the potential to become the starting point of a European-wide, low-carbon hydrogen infrastructure, and some initiatives have begun evaluating the feasibility of starting this process at a national level, such as

[14] https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-ii4-moller-holst.pdf
[15] https://www.h21.green
[16] Power to Gas: Electrolysis and Methanation Staus Review, M. Thema, F. Bauer and M. Sterner, in: Renewable and Sustainable Energy Reviews Journal 112 (2019) p. 775-787.
[17] https://www.rijksoverheid.nl/documenten/rapporten/2020/05/13/adviesrapport-taskforce-infrastructuur-klimaatakkoord-industrie
[18] North Sea Wind Power Hub
https://www.offshorewind.biz/2021/02/12/belgium-and-denmark-probing-north-sea-energy-island-link/
[19] Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, NET4GAS, OGE, ONTRAS, Snam, Swedegas, Teréga (2020), European Hydrogen Backbone
[20] https://ec.europa.eu/commission/presscorner/detail/en/FS_20_2412

HyWay27 in the Netherlands.[21] Industrial hubs in the region are already connected by natural gas transport systems (and a smaller, privately developed and operated hydrogen network), so conversion to hydrogen should be a low regret opportunity while sufficient demand and hydrogen production capacities available throughout the European Union.[22,23] In turn, repurposing this infrastructure can help other sectors (such as mobility or low temperature heating) adopt hydrogen for decarbonisation purposes, although motivation to repurpose infrastructure or built new connections may vary among countries. Reconversion will continue to be highly dependent upon technical and economic challenges, which are not yet fully assessed and will have to account for remaining natural gas supply needs during the transitional period to a decarbonised energy system. In the Netherlands, overcapacity in gas transportation may assist with the first conversions, while this may take longer for the reasons previously stated in other countries.

Industrial hubs as springboards

The inclusion of industry in climate change policy planning has brought a new dynamic to energy transition thinking and has emerged as a major driver of future hydrogen demand. In the industrial sector, a substantial, process-related hydrogen demand already exists. Currently this hydrogen in north-western Europe is mainly produced from fossil fuels and residual gases from industry. To reduce CO_2 emissions, existing installations could be either refurbished with CO_2 capture and utilisation or storage facilities (CCUS), or fossil-based hydrogen production could be replaced with electrolysers powered by low-carbon electricity. The volumes of hydrogen needed by industry to meet 2030 targets for CO_2 emission reduction are not yet matched by low-carbon hydrogen production, despite increased efforts to ramp up capacities. Since industry requires a reliable source of hydrogen for their fully continuous production processes, hydrogen produced using natural gas or residual gases coupled with CCUS can be important to early development of a low-carbon hydrogen market. In countries such as the Netherlands, Belgium, Germany and the United Kingdom, where energy carrier conversion is in or near the industrial demand centres, this is particularly relevant to facilitate meeting 2030 CO_2 reduction targets. In countries where industry is less pressured by national 2030 targets but is more focused on longer term 2050 goals, the potential supply of electrolytic hydrogen features more prominently in their

[21] https://www.hyway27.nl/en
[22] No-regret hydrogen. Charting early steps for H2 infrastructure in Europe, Agora Energiewende 2020
[23] https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/

plans. These strategies are not necessarily mutually exclusive and could follow a regional twin track approach to produce low carbon hydrogen.

Energy system integration

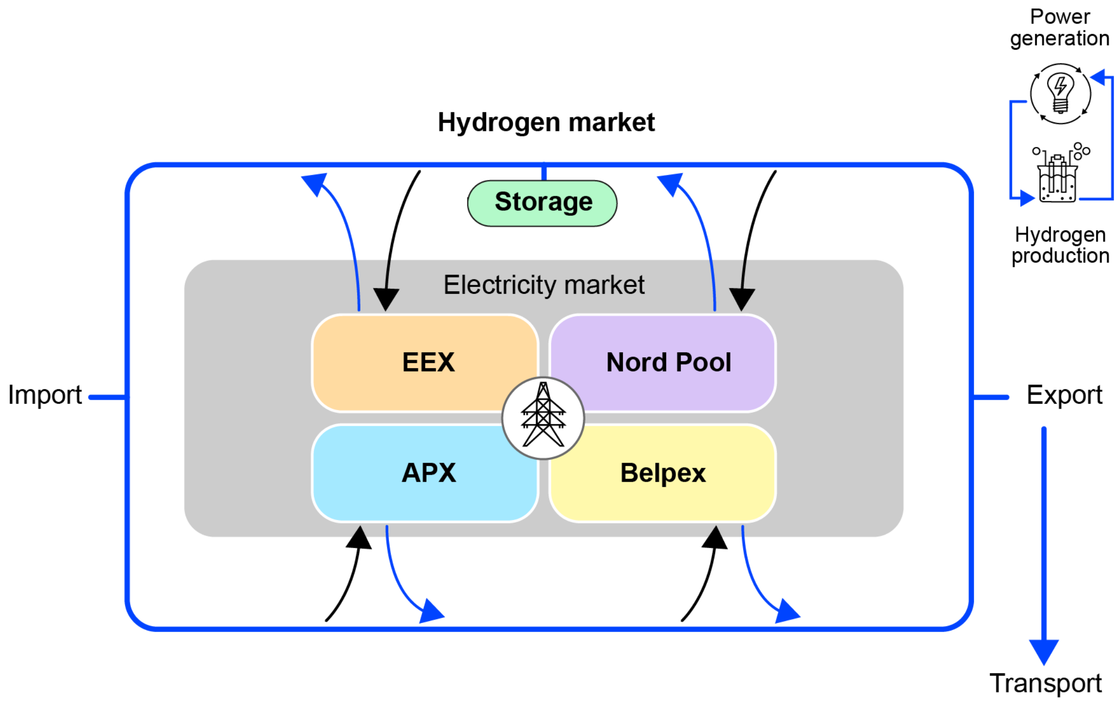
Industry decarbonisation can create the large demand volumes needed to ramp up an integrated system of clean power and low carbon gases. Moreover, both industry and the power grid require substantial volumes of flexible energy. Here, hydrogen can be key to balancing demand and supply, maintaining operations and stability and facilitating energy system integration.[24]

In countries like Denmark, with an available, relatively large potential of offshore wind generation compared to the country's current power demand, conversion to hydrogen that brings this competitively onshore could help attract new investments in energy-intensive industries and potentially develop exports to hydrogen markets in neighbouring countries. It could, at the same time, reduce the need to invest in reinforcing and expanding onshore grid infrastructure required to accommodate larger shares for offshore wind electricity. The Green Hydrogen Hub project is an important step for integrating the country's large offshore wind potential into the energy system.

Some countries are preparing mainly to ramp up their electrolysis capacity to convert solar and wind energy into hydrogen, building the value chain based on their domestic non-fossil energy potential (for instance Denmark, France and Germany), while also preparing for necessary imports. Other countries (such as the Netherlands, Norway and the United Kingdom) are also considering explicitly pre-combustion CCUS technologies to organise sufficient early volumes to warrant early investments in end-use sectors, storage, transportation and distribution infrastructures. In addition, countries like Belgium, Germany or the Netherlands have started exploring the possibility of importing hydrogen to meet their potentially growing demands. Once the hydrogen market matures and new value chains have been organised and expanded, the market should be able to organise both electricity and hydrogen demand in an EU internal market regulatory setting. However, policies and regulations should be put in place to allow the market to develop. Only when a regulatory framework is in place can the market integrate hydrogen and electricity as complementary energy vectors.

[24] https://www.iea.org/reports/conditions-and-requirements-for-the-technical-feasibility-of-a-power-system-with-a-high-share-of-renewables-in-france-towards-2050

Hydrogen and electricity market relations



Note: EEX = European Energy Exchange; APX = APX Group.
Source: Clingendael International Energy Programme (2020), Market co-ordination of Dynamic Energy Flows.

Hydrogen supply and demand

Current status (2010-2020)

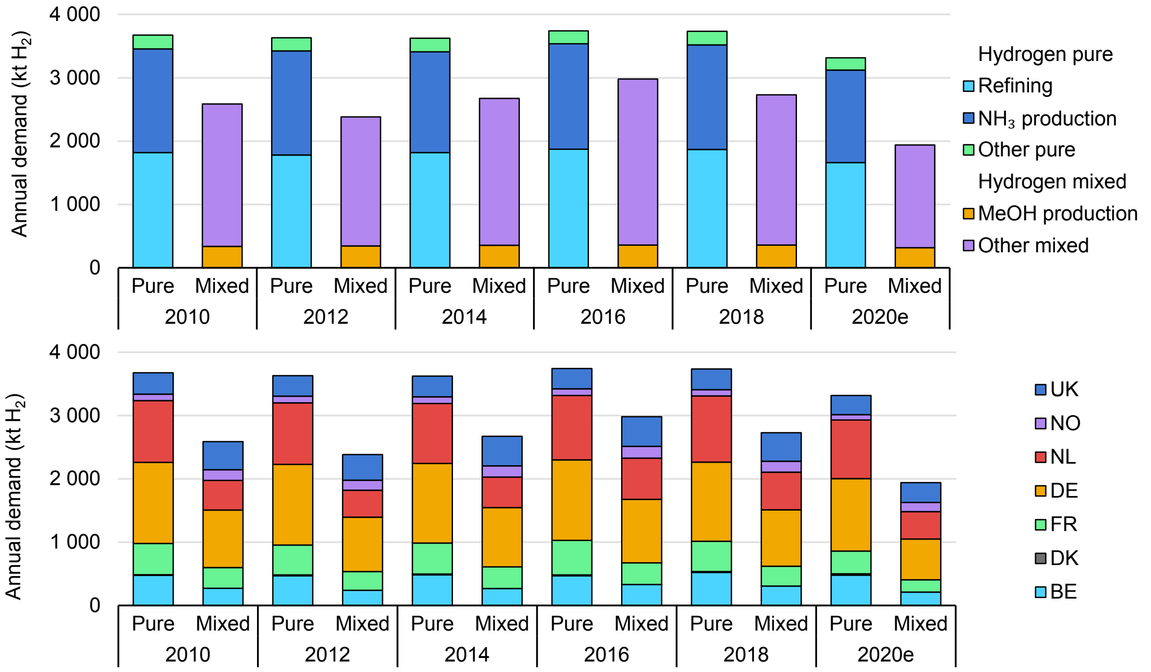
Regional hydrogen demand

North-western Europe is a highly industrialised region, with clusters like the Antwerp-Rotterdam-Rhine-Ruhr Area, which concentrates approximately 40% of the chemical production in the European Union. For this reason, the region is also one of the hot spots for hydrogen production and use in the world. Over the last decade, more than 6.3 Mt of hydrogen have been used in the region every year, which is roughly 5% of the total global hydrogen demand and contains an amount of energy equivalent to the electricity generated in 2019 by Belgium and the Netherlands combined.

Hydrogen can be used as a pure gas, in applications that tolerate only small levels of other gases or contaminants, or as part of a gaseous mixture with other carbon-containing gases to be used as a fuel or as a feedstock in industrial processes (called “Mixed hydrogen” in this report), as in the case of synthetic gas or other residual gases from steel or petrochemical process. The demand for pure hydrogen in the region has remained relatively stable at around 3 700 kt H_2/y over the last decade. Ammonia production (1 800 kt H_2/y) and oil refining (1 600 kt H_2/y) are the main sources of demand with minor contributions from other industries (such as electronics and glassmaking) and new applications (such as transport or grid injection).

In the case of hydrogen mixed with other carbon-containing gases, demand has fluctuated between 2 400 and 3 000 kt H_2/y. A small share of this demand comes from dedicated applications, such as methanol production (350 kt H_2/y) and direct reduced iron (DRI) steel production (25 kt H_2/y). The remainder is a consequence of the utilisation of by-product gaseous mixtures containing hydrogen, mainly from petrochemical processes (between 1 400 and 2 000 kt H_2/y) or the steel industry (between 550 and 700 kt H_2/y). Steam crackers produce large volumes of hydrogen as a co-product of high value chemical (such as olefines and bezene-toluene-xylenes) production, part of which is already utilised as a feedstock for hydrogenation in downstream chemical processes and in oil refining, and part is used as a fuel. The steel industry produces large quantities of hydrogen as a component of steel off-gases (primarily coke oven gas and blast furnace gas), which are commonly used on-site for heat and power generation. The hydrogen component of these gases can also be separated, enriched and re-circulated for use in the blast furnace, or exported for use in other sectors.

Historic hydrogen demand by application and country, 2010-2020



Note: NH_3 = ammonia; MeOH = methanol
BE = Belgium; DK = Denmark; FR = France; DE = Germany; NL = Netherlands; NO = Norway; UK = United Kingdom.
Demands in 2020 are projections based on best information available at the time of preparation of the report. “Other pure” category includes transport, grid injection and the use of by-product hydrogen from chlor-alkali processes. “Other mixed” category includes the use of by-product hydrogen from residual industrial gases.
Source: IEA analysis based on IEA statistics, data from the International Fertilizer Association,[25] Wood Mackenzie[26] and the World Steel Association Steel Statistical Yearbook.[27]

The demand for both pure and mixed hydrogen has been affected by the Covid-19 outbreak. To slow the spread of the virus, governments in the region have adopted measures like full or partial lockdowns, curfews or closure of non-essential business. This has resulted in a slowdown of economic activity, which has seriously impacted operations in the main sectors that today demand hydrogen, such as oil refining or the chemical industry. IEA analysis suggests that demand for pure hydrogen in the region dropped in different applications by approximately 10%, whereas use of mixed hydrogen suffered larger drops,

[25] International Fertilizer Association Database (2020), http://ifadata.fertilizer.org/ucSearch.aspx
[26] Methanol Production and Supply Database (2018), www.woodmac.com/research/products/chemicals-polymers-fibres/
[27] World Steel Association Steel Statistical Yearbook (2020) https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html

reaching, for example, a more than 35% decrease in use of by-product hydrogen from petrochemical processes.

Germany and the Netherlands together account for more than 60% of the pure hydrogen demand in the region, owing to their large refining and ammonia industries, followed by Belgium and France at around 15% each and the United Kingdom 10%. Norway has a significantly smaller demand of around 3%, whereas Denmark's demand is less than 1%, coming only from refining activities. In the case of mixed hydrogen, Germany presents the largest demand in the region (around 35%) due to their concentration of steel and petrochemical industries, followed by the Netherlands and the United Kingdom (around 20% and 15% of the demand) due to their petrochemical industries. Belgium and France concentrate around 10% of the mixed hydrogen demand each, and Norway demands slightly less than 10%, mainly from their petrochemical industry with a small contribution from the steel sector. Denmark currently has no demand for mixed hydrogen.

Regional hydrogen production

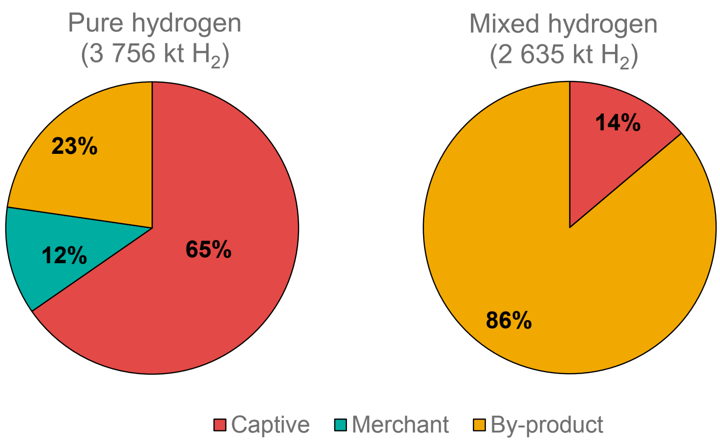
Types of hydrogen production

For this report, the relationship between hydrogen supply and end-users is classified in three categories:

- **Captive dedicated hydrogen production:** this occurs when hydrogen production and consumption are integrated processes. This is the most common way to operate for traditional hydrogen industrial uses, such as ammonia and methanol production or oil refining. Two thirds of the current supply of pure hydrogen in the region is captive dedicated production from the ammonia and refining industries. In the case of mixed hydrogen, methanol synthesis and DRI use captive hydrogen production, but these applications account for only 14% of the total supply of mixed hydrogen.
- **Merchant dedicated hydrogen production:** this occurs when hydrogen production is not integrated with the end use application but is purchased from external producers who can then deliver hydrogen to the end users by trucking or using regional, privately owned hydrogen networks. Merchant hydrogen is used by some refineries that need to top up their hydrogen production capacity, in the case of non-industrial applications (such as hydrogen delivery to refuelling stations for transport) or industries with small hydrogen consumption (i.e., electronics). In the case of large industrial sites, merchant hydrogen can be also produced on-site in plants operated by external companies that distribute hydrogen to end-users. In this region, merchant hydrogen is used only by applications that require pure hydrogen and accounts for no more than 12% of the supply. The majority of this supply is concentrated in Germany, the Netherlands and Belgium.

- **By-product hydrogen:** as mentioned previously, several industrial processes generate hydrogen or a mix of gases containing hydrogen as a by-product. These residual gases can be directly used for different purposes on-site (such as combined heat and power generation), transferred to other users (such as power generation) or the hydrogen component can be purified and used downstream. Around a quarter of the pure hydrogen supply within this region is fulfilled using hydrogen purified from residual gases, mainly from naphtha reforming and steam crackers, which is then used in refining. For mixed hydrogen, the majority of the supply comes from direct residual gas use by petrochemical processes and the steel industry.

Regional supply of pure and mixed hydrogen by type, 2019



Source: IEA analysis based on IEA statistics, data from the International Fertilizer Association,[28] Wood Mackenzie[29] and the World Steel Association Steel Statistical Yearbook.[30]

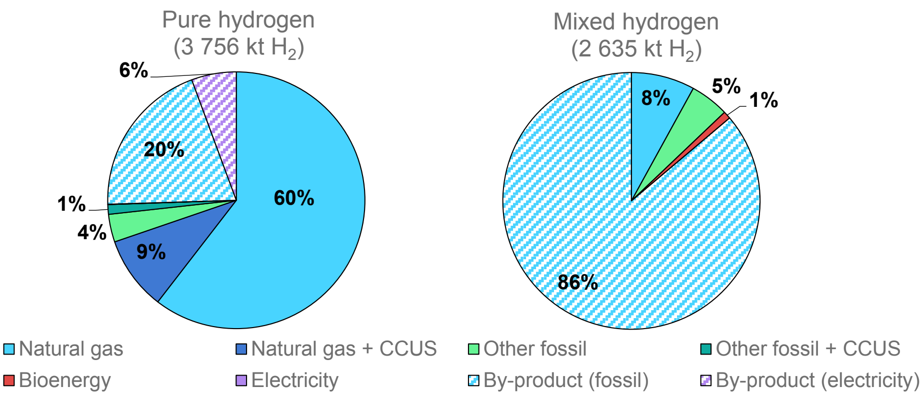
Sources of production

There are significant differences in production sources for the use of pure hydrogen and mixed hydrogen. Focusing on pure hydrogen production, more than two thirds is based on natural gas, or 94% of dedicated production (i.e., excluding by-product gases), which is mainly used to produce hydrogen for ammonia synthesis or oil refining. There is also a small share of pure hydrogen production from other fossil fuels, owing to some oil-based ammonia production capacity in Germany and the United Kingdom. A small fraction of fossil-based production

[28] International Fertilizer Association Database (2020), http://ifadata.fertilizer.org/ucSearch.aspx
[29] Methanol Production and Supply Database (2018), www.woodmac.com/research/products/chemicals-polymers-fibres/
[30] World Steel Association Steel Statistical Yearbook (2020), https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html

(around 15%) captures the CO_2 generated by hydrogen production. The bulk of this capacity is from the fertiliser industry, where CO_2 is captured from ammonia production and used on-site to produce urea. In addition, two hydrogen production projects capture CO_2 for use in industrial or agricultural applications in the region, the Port Jerome project in France and the Shell heavy residue gasification project in the Pernis oil refinery in the Netherlands[31]. As for pure hydrogen obtained as a by-product of residual gases, the majority comes from petrochemical processes that use oil as feedstock and a small fraction comes from the chlor-alkali industry. Finally, there is a fractional regional contribution from water electrolysis (less than 0.1%), limited to demonstration projects. Germany accounts for most of the installed capacity (more than 50 MW), with the rest of the countries ranging from 1 MW to 10 MW of installed capacity each.

Regional supply of pure and mixed hydrogen by fuel, 2019



Note: CCUS = carbon capture and utilisation or storage[32]. "Other fossil" includes both oil and coal.
Source: IEA analysis based on IEA statistics, data from the International Fertilizer Association,[33] Wood Mackenzie[34] and the World Steel Association Steel Statistical Yearbook.[35]

In the case of mixed hydrogen, most of the supply is by-product hydrogen from residual gases complemented by a small dedicated production of synthesis gas from fossil fuel-based methanol production in Germany, the Netherlands and

[31] See IEA (2020), *CCUS in clean energy transitions. Energy Technology Perspectives 2020*, for a complete list of large-scale CCUS projects operating globally.
[32] In this report, CCUS includes both CO_2 capture for commercial use in products and for permanent underground storage. Today, in the North Sea region, CO_2 related to hydrogen production is only captured for use in industry or agriculture, but projects involving geological storage are under development. Unlike geological storage, CO_2 use does not necessarily reduce emissions. For example, the CO_2 used in urea production is ultimately released to the soil when used as fertiliser and, as the urea decomposes, to the atmosphere. Climate benefits are only achieved if a CO_2-derived product displaces an equivalent product with higher life-cycle CO_2 emissions.
[33] International Fertilizer Association Database (2020), http://ifadata.fertilizer.org/ucSearch.aspx
[34] Methanol Production and Supply Database (2018), www.woodmac.com/research/products/chemicals-polymers-fibres/
[35] World Steel Association Steel Statistical Yearbook (2020), https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html

Norway and DRI in Germany. Finally, there is a small amount of methanol production from natural gas in the Netherlands in which the operator buys biomethane certificates; that has been reflected in this analysis as mixed hydrogen production from bioenergy.

Projections to 2030

Over the years, north-western Europe has built a large hydrogen industry that may now be on the verge of an unprecedented transformation driven by ambitious greenhouse gas (GHG) emission reductions goals adopted by governments in the region. The hydrogen industry would face this transformation on two fronts: the replacement of current hydrogen supply with low-carbon hydrogen production technologies, and an expansion of hydrogen use to new applications. This section explores the potential evolution of hydrogen demand and supply in the region by 2030, making projections based on analysis informed by IEA in-house expertise and consultations with government officials and energy experts from different institutions.

Definition of the scenarios

Based on the analysis underpinned for this report, the IEA developed two scenarios for potential evolution of the hydrogen sector in the region: a baseline scenario ("Baseline") and a scenario with an accelerated deployment of hydrogen technologies ("Accelerated"). These scenarios should not be considered as predictions or forecasts. They offer insights about potential impacts to the hydrogen industry by adoption of different levels of ambition and policy support for hydrogen technologies, with an aim to inform high-level discussions about developing the hydrogen sector in the region.

The Baseline scenario describes how demand for hydrogen could evolve considering energy- and climate-related policies already in place in the countries of the region, mature projects already under construction or which have reached FID and an uptake of demonstrated technologies following commercialisation trends observed previously in other low-carbon energy technologies. The Accelerated scenario is based on enacting more ambitious energy- and climate-related policies and implementing supporting mechanisms that could facilitate adoption of hydrogen technologies. This scenario describes trajectories that are compatible with the achievement of wider energy and climate targets in the region, and represents an ambitious vision requiring joint effort from governments, and the industrial and financial sectors to intensify activities across the whole value chain.

On the supply side, the analysis considers an expansion of production capacities based on the pipeline of projects that have been announced by industrial stakeholders in the region. The Baseline scenario assumes successful deployment of those mature projects that are currently under construction or that have reached final investment decision. The Accelerated scenario considers, in addition to these, successful completion of more uncertain projects that are still in their initial stages of development or are under feasibility study.

Definition of Baseline and Accelerated scenarios

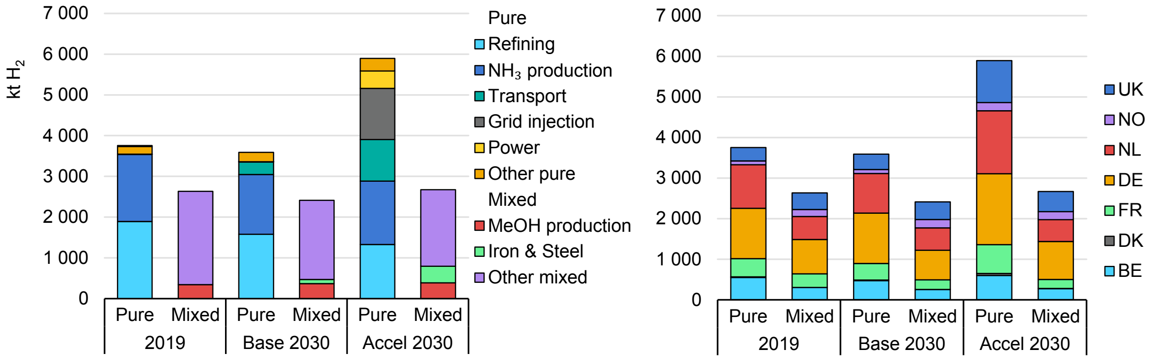
	Baseline	Accelerated
Conditions considered	• Policies in place with specific measures enacted • Projects under construction or that have reached final investment decision • Private sector commitments made publicly to deploy technologies where there have been explicit demonstration or pilot projects already undertaken • Commercialisation of fuel cell electric vehicle technologies that are at the demonstration and early commercial stage, enabled by policy support and by cost reductions realised through economies of scale and technological learning	• Achievement of 2030 emission reduction targets • Achievement of technology deployment targets (to the extent possible by 2030) • Development of announced projects that would require support measures to reach FID • Rapid deployment of enabling infrastructure
Examples	• EU-ETS, EU Clean Vehicles Directive, REDII, EU 2030 Climate and Energy Framework (40% GHG reduction target) • Thyssenkrupp continued deployment of the blast furnace blending technology, transformation of Total's La Mède refinery • Bus (H2BUS) and train (Alston-LNVG agreement) deployments • Projects[36]: RefHyne, H100Fife, HyDeploy, Hybrit	• EU 2030 Climate and Energy Framework (55% GHG reduction target), Climate Change Act 2008 (2050 Target Amendment) Order 2019 • Adoption of measures to deliver the EU and national hydrogen strategies • Adoption of ZEV mandates/purchase incentives, low-carbon fuel standards • Policy support (e.g., through the EU Green Deal, company-level, or country-level deployment targets • Projects: H2M, HyNet, NorthH2

[36] A detailed list of the pipeline of projects considered for the projections of hydrogen supply is included in the Annexes.

Demand projections to 2030

Despite the significant potential for hydrogen to decarbonise several sectors and the strong momentum behind hydrogen technologies, in the Baseline scenario the demand for both pure and mixed hydrogen by 2030 in the region drops slightly from today's level (around 5 and 10% respectively). In addition, the results suggest a change in the distribution of these demands, highlighting that the next decade can be critical to the adoption of hydrogen as an energy carrier beyond industry. Oil refining and ammonia production combined observe a drop of around 500 kt H_2/y in hydrogen demand. These sectors are facing strong international competition from regions with access to lower cost feedstock (e.g. the Middle East, the United States and the People's Republic of China), which has resulted in a slowdown in their activity in recent years. This activity decrease is expected to continue into the next decade. The drop in demand for mixed hydrogen reaches 350 kt H_2/y, a result of a slowdown in the petrochemical industry, which is facing competition challenges similar to that of refining and ammonia production. This drop is partly compensated by the generation of demand from new applications. The deployment of fuel cell vehicles (FCEVs) as a consequence of announced bus and heavy-duty truck deployments coupled with policies such as bans on new internal combustion engines (ICE) can generate a demand for pure hydrogen of around 300 kt H_2/y in the region, although competition arising from electric vehicles may suppress demand growth. New industrial uses in the iron and steel industry generate a demand for mixed hydrogen of around 80 kt H_2/y. This new demand is concentrated in Germany, with its strong iron and steel industry, building on its existing DRI capacity and focused on its fledgling blending concepts for both blast and DRI furnaces. This low-carbon technology deployment in sectors where emissions are hard to abate can be regarded as a successful outcome of energy and climate policies adopted in the region and of the innovation efforts made by major industrial stakeholders.

Current and projected regional hydrogen demand by sector and country in the Baseline and Accelerated scenarios, 2030



Note: “Base” = Baseline scenario; “Accel” = Accelerated scenario.
NH_3 = ammonia; MeOH = methanol
BE = Belgium; DK = Denmark; FR = France; DE = Germany; NL = Netherlands; NO = Norway; UK = United Kingdom.
“Other pure” category includes use of dedicated hydrogen in buildings, biofuels production and the use of by-product hydrogen from chlor-alkali processes. “Iron & Steel” includes both DRI and injection in blast furnaces. “Other mixed” category includes the production of liquid synthetic fuels and the use of by-product hydrogen from residual industrial gases.

In the Accelerated scenario, the hydrogen sector would observe a significant expansion. Demand for pure hydrogen could grow by as much as 60%, reaching close to 6 000 kt H_2/y across the region. The use of hydrogen in oil refining in the region would suffer a sharper decline (more than 500 kt H_2/y) driven by more ambitious policies and targets for deployment of low-carbon transport technologies. The drop in hydrogen demand for ammonia production would be smaller since the successful demonstration of the use of ammonia as a shipping fuel would generate new demand, especially in Belgium, the Netherlands, Norway and the United Kingdom. There is also a strong growth of hydrogen demand in new applications:

- Hydrogen could be blended into the natural gas grid to meet up to 2% of the region’s energy demand for natural gas, resulting in a hydrogen demand of more than 1 200 kt H_2/y. This would require adopting supporting policies such as emission targets or blending quotas. Some countries in the region have taken initiative on this matter, with the Netherlands studying introduction of a blending quota and the UK Government considering that blending could play a strategic role in supporting the expansion and decarbonisation of hydrogen.[37] However, blending hydrogen diminishes its value, and the importance of natural gas in the region is expected to decrease significantly, particularly after 2030. Hydrogen blending should be seen as a transition strategy to deal with the “chicken-and-egg” problem of hydrogen demand and supply. It can facilitate scaling up low-carbon hydrogen production which can be repurposed for other applications

[37] The Ten Point Plan for a Green Industrial Revolution, 2020, HM Government.

(e.g. in heavy industry or long-distance transport) once demands are available and a hydrogen-specific infrastructure has been developed.

- An ambitious deployment of FCEVs along with the adoption of hydrogen in rail and shipping could push the demand for transport purposes over 1 000 kt H_2/y in the region. Adoption of measures such as zero-emission vehicle mandates, ICE bans, direct purchase subsidies or low-carbon fuel standards can accelerate deployment and help to achieve national deployment targets (currently only adopted by France and the Netherlands). These supporting measures should be accompanied by a rapid enabling infrastructure, which otherwise could become a bottleneck.
- Power generation is a sector where hydrogen use has short-term limited potential due to high costs and low efficiencies in the case of the full cycle Power-to-Hydrogen-to-Power. However, it can serve to generate carbon-free peak load electricity. Some projects in the region are being developed with this objective and could be realised if supporting policies and regulations are adopted. We estimate that this could result in more than 400 kt H_2/y of demand by 2030. The largest project under development in the region is the H2M project in the Netherlands that, if realised, could generate up to 300 kt H_2/y of demand by 2030.
- Other small contributions could come from dedicated use of hydrogen in domestic heating or in advanced biofuels production.

Regarding the use of mixed hydrogen, demand in the Accelerated scenario remains at today's level. Like the Baseline scenario, there is a marked drop in the generation of by-product hydrogen from petrochemical processes (close to 300 kt H_2/y) which is compensated by a significant generation of demand in new industrial application. Concretely, the injection of hydrogen into blast furnaces or its use as fuel in high-temperature processes in the iron and steel industry can contribute generation of 400 kt H_2/y. The German Hydrogen Strategy[38] puts the focus on hydrogen use in industrial activities where emissions are hard to abate, and its large iron and steel industry would be the main contributor to this demand (more than 300 kt H_2/y). This sector would also generate new demands in the United Kingdom (around 50 kt H_2/y), with some small projects in Norway and the Netherlands contributing around 10 kt H_2/y between them. The industrial stakeholders in the region have been spearheading adoption of this technology and are well placed to extend it. However, adoption of a long-term CO_2 pricing framework with clear and consistent policy signals for industry players and measures that ensure a level playing field for this trade-exposed industry would facilitate a faster deployment. Finally, a small demand to produce synthetic liquid fuels could develop in the Accelerated scenario. This is limited to developing a

[38] The National Hydrogen Strategy, Federal Ministry for Economic Affairs and Energy (2020).

small production capacity fed by supporting policies, as 2030 is a short time frame for the commercial adoption of this type of fuels.

Hydrogen in refining and industry sectors

Oil refining

Hydrocracking for upgrading heavy oil fractions and hydrotreatment for removing sulphur are the key processes where hydrogen is used in refineries. Despite more stringent sulphur content requirements in refined oil products, the lower demand for oil-based transport fuels in the Baseline scenario mean that hydrogen demand in refineries drops around 15% by 2030 in the region compared to 2019. In the Accelerated scenario, there would be a sharper decline of oil-based fuels, leading to a reduction of 35% in hydrogen demand for oil refining. These trends are the result of a combination of factors, such as moving to higher fuel efficiency in vehicles, adoption of low-carbon transport technologies (such as battery electric vehicles, fuel cell electric vehicles or biofuels) or the international competition faced by the oil refining sector within the region. The production of advanced biofuels (such as hydrotreated vegetable oils) will also generate some demand for hydrogen, but it will be considerably lower to the demand lost due to the drop in the use of oil-based fuels.

Captive dedicated production and merchant hydrogen for refineries is almost exclusively produced in this region from natural gas in reformers today, but it is complemented with a significant contribution from by-product gases at refineries (catalytic naphtha reformers) and chemical facilities. Substituting dedicated and merchant hydrogen sourced from unabated fossil fuels with low-carbon hydrogen can be an early opportunity to scale-up low-carbon hydrogen production. This can be enabled by retrofitting existing plants with CCUS (depending on access to CO_2 transport and storage infrastructure) or by using electrolysers with renewable electricity. Indeed, a 5 MW facility is already in operation in a refinery in Hamburg and the HySynergy (20 MW) and Refhyne (10 MW) projects are underway in Denmark and Germany. Several projects that aim to reach hundreds of MW of electrolysis for this application are at different stages of development and could be deployed if a supporting policy framework is put in place.

Ammonia and methanol production

Ammonia and methanol production (the former more significant in the region) are almost exclusively covered today by the use of fossil fuels, apart from some biomass-based methanol production in the Netherlands. Pure hydrogen demand for ammonia in the region drops in both scenarios (more markedly in the

Accelerated scenario). European ammonia production has declined by about 15% since the turn of the millennium, with other regions proving more attractive for new capacity additions in the market for this globally traded commodity. Methanol production in the region accounts for less than 2% of global output, with the absolute output level remaining broadly flat to 2030. Ammonia accounts for around 40% and 20% of pure hydrogen demand in the region in the Baseline and Accelerated scenarios, respectively, and methanol accounts for around 20% of mixed hydrogen demand in both scenarios.

Unlike hydrogen production in refineries, both the carbon and hydrogen contained in fossil fuel feedstock are used in ammonia and methanol value chains; in methanol directly and, for ammonia, downstream in the production of urea, commonly in integrated facilities. In the region, around three quarters of ammonia production occurs without the concurrent production of urea alongside it, representing 'low-hanging fruit' when it comes to switching over to electrolysis. Some projects in Belgium, the Netherlands and Norway are exploring the possibility to start blending electrolytic hydrogen in their facilities, replacing part of their fossil-based hydrogen generation. However, this would only take place at large scale under a favourable policy landscape. For the remainder and for methanol production, CCUS-equipped facilities are likely to be more cost-competitive. Even in the case of deploying CCUS facilities, there will be some degree of CO_2 emission downstream (when methanol is used in an oxidising application, or when urea is applied to pastures). As in refining, the technologies required to deploy both CCUS-equipped and electrolytic facilities in ammonia and methanol production are at relatively advanced stages of development, and so progress can be made rapidly in terms of substituting existing emissions-intensive production, either using retro-fit or new-build arrangements.

Iron and steel production

Hydrogen has the potential to replace fossil fuels in primary production facilities in the iron and steel sector—both in existing installations (generally only a partial substitution of the fossil fuel input) and in the longer term (post-2030), in 100% or near-100% hydrogen-based facilities. Hydrogen is less relevant in the context of reducing emissions from secondary steel production from scrap, which is typically 25-35% of production in the region. While the use of pure hydrogen does not factor into steel production in the north-western region of Europe today, its use would increase in both scenarios, with steel production accounting for 4% (Baseline) and 15% (Accelerated) of mixed hydrogen demand.

There are two main methods used to produce steel from iron ore: blast furnace-basic oxygen furnace (BF-BOF) and direct reduced iron-electric arc furnace (DRI-EAF) steelmaking. BF-BOF steelmaking is prevalent in multiple countries in this region, whereas DRI-based production only takes place in Germany at relatively small scale (around 600 kt annually).

BF-BOF production can have substantial portions of the coal used in existing facilities substituted with pure hydrogen. Europe is at the forefront of experimenting with this process. In Germany, Thyssenkrupp is injecting hydrogen into one of its blast furnaces in North-Rhine Westphalia. This option is a good way to achieve partial substitution of fossil fuels with low carbon hydrogen, while still using existing equipment. Substantial progress can be made in the coming years, and potential hydrogen volumes are large.

There are three ways to utilise hydrogen to reduce emissions from DRI-EAF facilities: blend hydrogen into existing facilities that are fuelled by natural gas; equip existing or new facilities that produce hydrogen with carbon capture; and switch to pure hydrogen for the iron ore reduction step (100% H_2 DRI-EAF). The first two methods present better short term prospects. Carbon capture and storage is already applied to a commercial plant in the Middle East, with CO_2 used to enhance oil recovery.[39] The first results from pilot projects seem to indicate that substituting part of the natural gas input in a DRI facility is achievable with no major alterations to existing commercial process equipment.[40] However, 100% H_2 DRI-EAF is a less developed technology, currently being demonstrated in Sweden, and it is not expected to be available at commercial scale before 2030.[41]

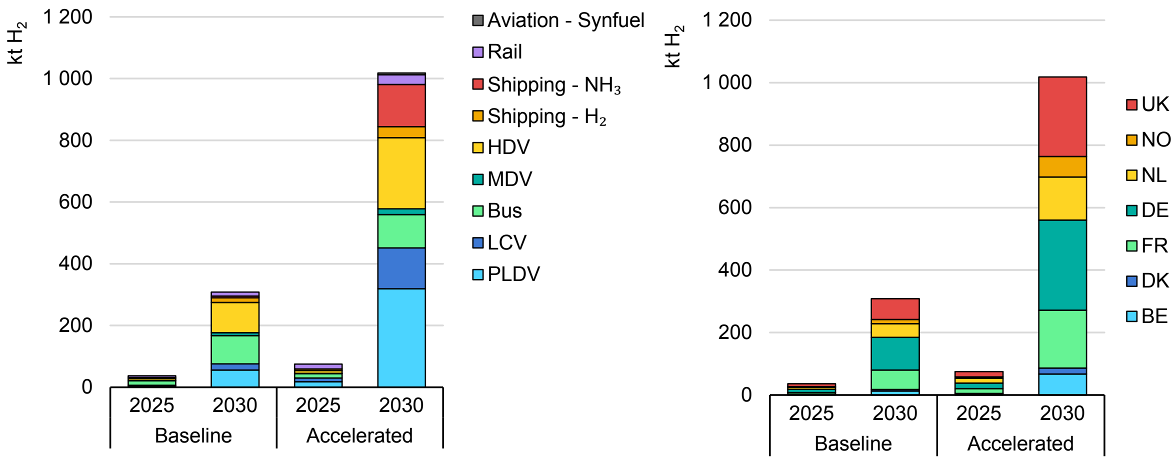
Hydrogen in transport

Energy use in the transport sector in north-western Europe is dominated today, as in other parts of the world, by oil use, accounting for more than 90% of transport energy demand. In the Baseline case, hydrogen demand for transport in the region would reach around 300 kt H_2 by 2030, driven by hydrogen use in fleets, such as buses and trucks, corresponding to close to 10% of the hydrogen demand in the region. Urban transit buses represent a major opportunity, since many municipalities and governments have already committed to decarbonisation of this public transport mode leading to higher market shares compared to other vehicle segments. In particular, national targets for fuel cell bus deployment are deemed more feasible relative to passenger light-duty vehicles (PLDV), resulting in a stock

[39] www.cslforum.org/cslf/sites/default/files/documents/AbuDhabi2017/AbuDhabi17-TW-Sakaria-Session2.pdf.
[40] https://www.midrex.com/tech-article/midrex-h2-ultimate-low-co2-ironmaking-and-its-place-in-the-new-hydrogen-economy/
[41] https://www.ssab.com/company/sustainability/sustainable-operations/hybrit.

share of around 10% in the Netherlands. A potential niche for intercity buses ("coaches") may also exist in the context of ambitious decarbonisation goals: where charging time and power draw requirements may constrain the market potential and technical feasibility of pure battery electric coaches, shorter refuelling times for FC buses may be advantageous.

Projections of hydrogen demand in transport in the region in the Baseline and Accelerated scenarios, 2025-2030



Notes: HDV = heavy-duty vehicles, MDV = medium-duty vehicles, LCV = light-commercial vehicles, PLDV = passenger light-duty vehicles. In the case of "Shipping – NH_3" and "Aviation – synfuels" the shown hydrogen amounts correspond to the hydrogen inputs required to produce these fuels.

In the Accelerated scenario, hydrogen use expands to light-commercial vehicles (LCV) and PLDV as well as shipping (mainly in the form of ammonia), resulting in an overall hydrogen demand of more than 1 Mt H_2 by 2030 (around 15% of the region's overall hydrogen demand). Taking into consideration national targets for hydrogen vehicles and hydrogen refuelling stations as well as the impact of zero-emission vehicle targets or mandates, the largest hydrogen demand could come from PLDVs and heavy-duty vehicles (HDVs), as opposed to buses in the Baseline case. PLDVs would reach over 1 million vehicles by 2030 and a share of around 1% of the stock. The stock number of HDVs by 2030, at 33 000, is much lower, but their typically higher annual mileage boosts hydrogen demand. In the long term, a higher share of fuel cell trucks could be expected, but for the time frame of this study, their technology readiness limits their deployment. PLDVs offer the largest opportunity in the Accelerated scenario, because they are the largest energy consuming segment of transport in absolute terms; however, barriers to deployment (e.g. permitting requirements for refuelling stations, etc.) and lack of successful co-ordination for rolling out hydrogen refuelling stations (HRS) can significantly limit this potential, as can the priority many countries are putting on electric cars roll out. The realisation of the Accelerated scenario would require expanding from the less than 200 HRS currently operating in the region to a range of 3 000 to 4 400.[42] The adoption of hydrogen vehicles in captive fleets (e.g. taxis, buses, delivery trucks) could help support the construction of hydrogen refuelling stations, which can also enable further light-duty vehicle adoption.

Outside road transportation, the demand for hydrogen and hydrogen-based fuels is relatively modest in rail, shipping and aviation. In the Accelerated scenario, hydrogen and ammonia combined account for 1.6% of the total shipping fuel demand, with higher shares for domestic than for international shipping, reaching around 6% for domestic shipping in the Netherlands and Norway due to national decarbonisation goals. For Germany, the proposed quota of 2% of domestic aviation fuel substituted with synthetic kerosene would result in a necessary hydrogen demand of around 5 kt H_2 in 2030.

Stock and sales shares of fuel cell electric vehicles (FCEVs) in 2030 in the Baseline and Accelerated scenarios

Vehicle category	Baseline		Accelerated	
	Sales	Stock	Sales	Stock
Passenger light-duty vehicles	0.8%	0.2%	5.5%	0.9%
Light-commercial vehicles	0.9%	0.2%	7.3%	1.7%
Bus	8.5%	2.6%	11.8%	3.9%
Medium-duty trucks	2.2%	0.4%	6.5%	1.1%
Heavy-duty trucks	1.9%	0.4%	6.7%	1.3%

Hydrogen in buildings

Energy use in the buildings sector in north-western Europe is dominated by electricity and natural gas, each accounting for about 35% of buildings energy consumption. Space heating and domestic hot water production are the main uses of natural gas and the cause for CO_2 emissions from the buildings sector within the region. Further energy efficiency improvements and electrification will be central to CO_2 emission reductions, with heat pumps reaching higher efficiency compared to other low-carbon alternatives. For instance, more than 5 times more

[42] Assuming an average size of the HRS in the range of 1 000-1 500 kg H2/day and a 50% utilisation factor

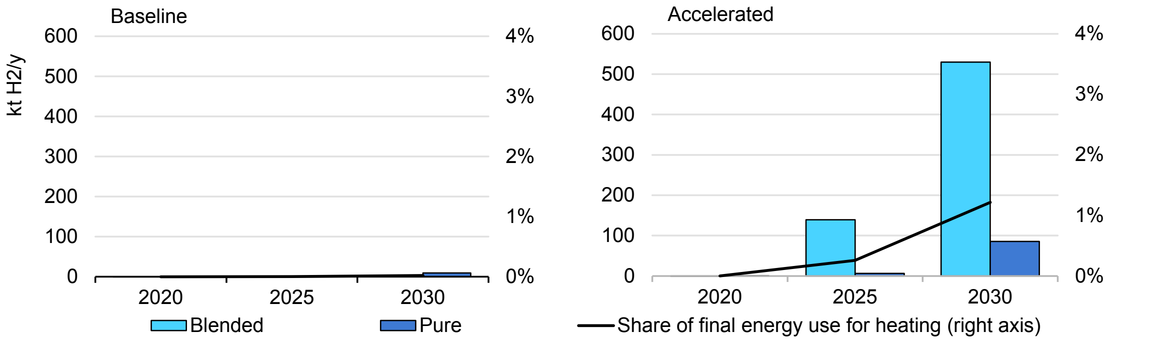
green electricity is typically required to heat a household with electrolytic hydrogen than with a heat pump.[43] However, the electrification of heat must be accompanied by a strategy that addresses peak demand and seasonal variability (particularly marked in this region), including better performing envelopes, demand-response and storage. Hydrogen, alongside other low-carbon heating options, such as biomass and other renewables, could also be a way to alleviate these adverse impacts on the electricity system. There are two ways to use hydrogen in buildings:

- **Blending hydrogen in existing natural gas networks**, with few infrastructure upgrade requirements. Demonstration projects in Ameland (Netherlands) and Dunkirk (France) showed that the blending of hydrogen up to 20% in volume required no or few adjustments to distribution grids or indoor installations, including domestic boilers and stoves.[44,45] However, a blending rate of 20% in volume can only be a transition strategy as it reduces only 6-7% of the carbon footprint of natural gas. It also affects the cost for the final users, and depending on the type and age, heaters might have to be certified or exchanged. Meeting the 2% blend in energy (7% in volume) of the Accelerated scenario could increase the cost of blended gas by 4-7.5% compared to the cost of natural gas, depending on the production cost of low-carbon hydrogen. However, the impact of this cost increase in the final price paid by the consumer would be lower (2-4%, considering that the cost of gas normally accounts for about half of the final price, excluding taxes).
- Using **pure hydrogen in dedicated infrastructures**, and direct use in buildings in specific boilers, fuel cell micro cogeneration units and cooking appliances. Forthcoming demonstration projects will need to focus on requirements and conditions for a safe reutilisation of existing gas infrastructures as well as the deployment of hydrogen-ready devices, including boilers.

In the Baseline scenario, hydrogen blending in the gas grid remains limited to some demonstration projects. Similarly, dedicated use would take place in only a few thousand households based on a handful of announced pilot and demonstration projects, such as the H100 Fife (300 households from 2022) in the United Kingdom or the projects in Hoogeveen and Stad aan 't Haringvliet (600 households from 2025) in the Netherlands.[46,47,48]

[43] https://www.iee.fraunhofer.de/en/presse-infothek/press-media/overview/2020/Hydrogen-and-Heat-in-Buildings.html.
[44] https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_7c0ff368de.pdf.
[45] GRHYD project, https://grhyd.fr/ .
[46] H100 Fife project, https://www.sgn.co.uk/H100Fife .
[47] First homes on a hydrogen network in 2022, https://fuelcellsworks.com/news/netherlands-first-homes-on-a-hydrogen-network-in-2022/ .
[48] https://www.newenergycoalition.org/en/research-waterstofwijk-hoogeveen-hydrogen-can-also-be-used-in-existing-buildings/.

Projections of hydrogen demand for heating in buildings in the Baseline and Accelerated scenarios, 2020-2030



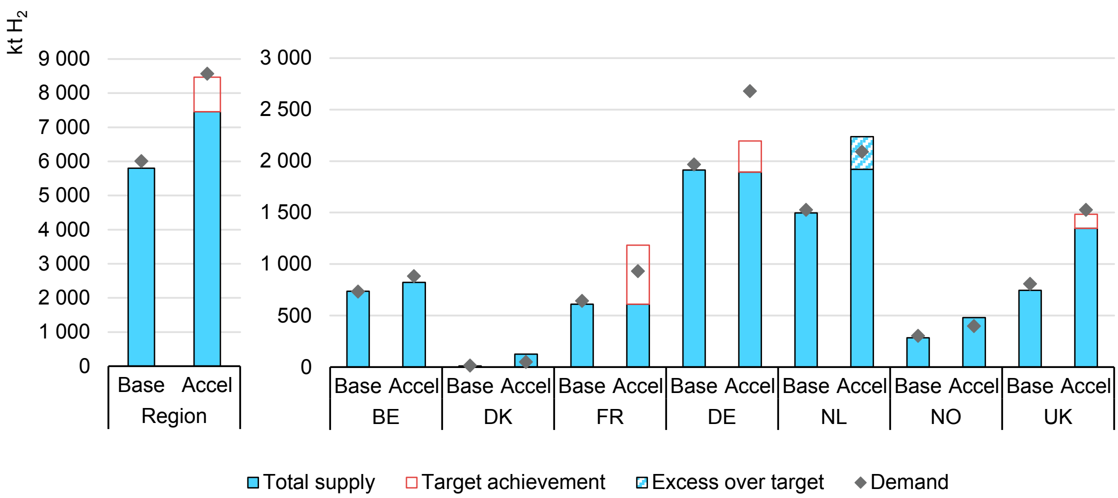
In the Accelerated scenario, blending rates rise rapidly, to around 7% in volume of natural gas demand in the region. This does not mean that blending would occur across the entire gas network in the region by 2030, since the practice is uncertain at this time, but certain areas of the network could accept larger blending shares to compensate those areas where blending may present more challenges. The use of hydrogen would rise faster in the second half of the decade, as demonstration projects need to establish clear safety protocols over the coming years. This leads to a demand for more than 1 200 kt H_2/y, reducing CO_2 emissions related to the use of natural gas in buildings by around 2%.

Overall, the use of dedicated hydrogen in buildings makes modest inroads. Less than 1.5% of the region's hydrogen demand comes from dedicated use of hydrogen in buildings by 2030 in the Accelerated scenario. In addition to the efficiency and cost barriers, other factors, such as developing the safety case, or the timings and workforce required to switch extensive areas from natural gas to hydrogen can hold back deployment. Priority areas for dedicated hydrogen deployment include districts with high heat density, a majority of buildings that are difficult to renovate thoroughly (e.g., difficult to improve their thermal performance or to install heat pumps with the possibility of shared business models, such as with vehicle fleets or flexible co-generation of heat and power) and including buildings with a mandatory resilience to electricity supply disruptions (e.g., hospitals). In the medium to long-term, hydrogen technologies can offer other opportunities to deliver low-carbon heat. For example, through the integration in heat networks of the heat generated by large fuel cell power generation units.

Supply projections to 2030

Hydrogen supply in the region would also evolve differently under the Baseline and Accelerated scenarios, although both scenarios share a feature: the pipeline of announced projects seem to not be enough to meet expected hydrogen demand by 2030.

Current and projected regional and country hydrogen supply and demand in the Baseline and Accelerated scenarios, 2030



Note: This figure combines pure and mixed hydrogen demands. The white columns labelled "Target" represent the potential expansion of electricity-based production in FR and DE and low-carbon production in UK that could be developed if national targets were achieved. The striped column labelled "Excess over target" represents the supply of hydrogen that would originate from the installed electrolysis capacity in the Netherlands that would exceed the deployment national targets.

There are some caveats about this finding:

- The supply projections are based on current production capacities and the potential expansion that can be achieved with the pipeline of announced projects.[49] Most of the projects currently in the pipeline are small-medium size projects (capacities under 20 kt H_2/y) with target commissioning dates between 2021 and 2025. At the opposite end is a small fraction of large projects (with capacities in the hundreds of kilotons of hydrogen per year) with target commissioning dates close to 2030. It can be expected that the project portfolio will grow in coming years helping to close this gap.
- Several countries in the region have defined deployment targets or ambitions for low-carbon hydrogen production that cannot be met with the current projects announced in any scenario. The adoption of supporting policies that can help to achieve those targets can significantly close this gap. The Netherlands is a

[49] Projects included in the IEA Hydrogen Projects database by February 2021.

particular case. The project pipeline is particularly large and, if completely realised, the electrolysis capacity deployment would be much larger than the national targets. A significant fraction of this potential for electrolysis capacity deployment comes from the NorthH2 (up to 3 GW of installed electrolysis capacity by 2030) which is one of the first cross-border initiatives in the region.

National targets and ambitions for hydrogen production in north-western Europe countries

Country	Targets/Ambitions by 2030	Baseline	Accelerated
France	6.5 GW electrolysis	46 MW	960 MW
Germany	5 GW electrolysis	117 MW	1970 MW
The Netherlands	3-4 GW electrolysis	215 MW	6980 MW
United Kingdom	5 GW low-carbon hydrogen	18 MW	4100 MW

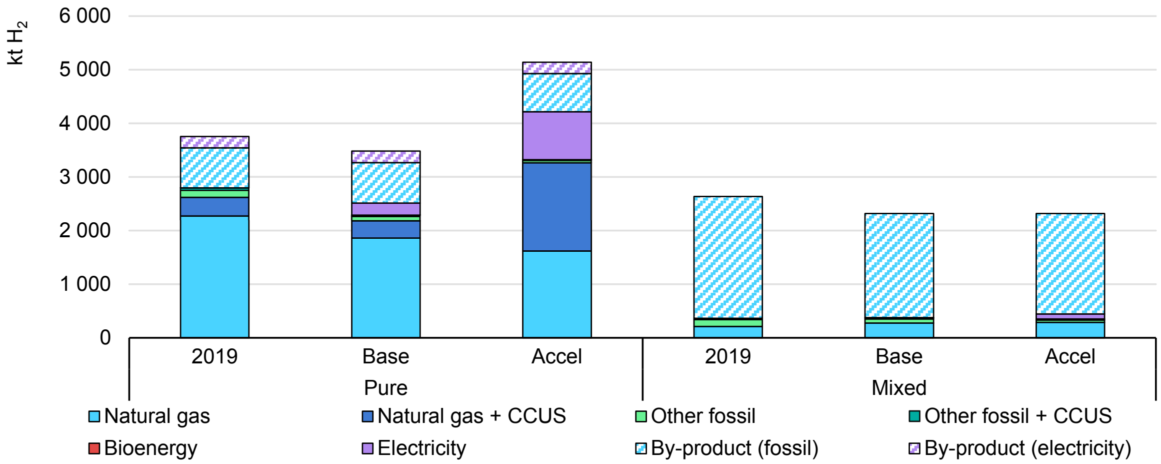
Note: For electrolysis, values in the table are expressed in power input.

- Deployment of low-carbon hydrogen production capacity could be used to generate new capacity or to replace current production capacity. This analysis has considered the retirement of current production only for those projects that have clearly stated this goal. However, this information is not always publicly available, or the decision has not been made since it may depend on financing or permitting issues. For this reason, some projects and the potential decommissioning of current capacities could be larger than our projections.
- A series of industrial hubs that are considering large carbon capture deployments and storage technologies present a strong potential to deploy new production capacities of low-carbon hydrogen through natural gas reforming with CCUS could be developed in the region. Occasionally, projects with specific information about their size have been announced, like the H2morrow project (to produce hydrogen in Germany and transport and store the CO_2 under the seabed in the Norwegian North Sea), the HyDEMO project (Norway) and the H2H Saltend project (United Kingdom). Further hydrogen production capacity could be developed in those hubs and others where no specific projects have been announced, such as the Northern Lights hub (Norway) or the Acorn Aberdeenshire hub (United Kingdom), which would significantly close the supply-demand gap.
- Dedicated captive hydrogen production for ammonia and oil refining is linked to demand from these sectors. Therefore, if demand drops, production drops as well. This would leave part of the current captive production capacity unused, which could likely be used to deliver merchant hydrogen and meet a share of growing demands for new applications. The extent to which this practice could take place will depend on factors such as production costs, infrastructure availability and regulation.

Sources of production

Focusing on how hydrogen is produced, hydrogen supply in the Baseline scenario would be similar to current supply. The supply of pure hydrogen from fossil fuels drops around 500 kt H_2/y due to lower oil refining and ammonia production. The deployment of some small projects for the production of hydrogen through electrolysis compensate for part of this drop and help electrolysis to make some dent in the hydrogen supply, reaching around 1% of the total supply and consuming around 1.7 TWh of electricity.[50] However, the shares of natural gas- and oil- based production, both with and without CCUS, remain almost unchanged. This is due to the lack of supporting policies that provide incentives for low-carbon technologies deployment, either for replacing current high-carbon production or for expanding production capacities to meet new demands. In the case of the use of mixed hydrogen, there are practically no changes, with by-product hydrogen present in residual gases from petrochemicals, the steel industry dominating supply and with a small contribution from oil and gas to produce methanol.

Current and projected regional hydrogen supply by fuel in the Baseline and Accelerated scenarios, 2030



In the Accelerated scenario, a more drastic transformation would take place. Natural gas would remain the primary source of pure hydrogen production, still meeting around two thirds of the total supply or 75% of dedicated production (i.e. excluding by-product gases). However, unabated production would drop by more than 600 kt H_2/y whereas hydrogen production coupled with CCUS would grow

[50] Assuming an electrolysis efficiency (lower heating value) of 69% by 2030.

almost five-fold, reaching more than 1 600 kt H_2/y, matching the supply level of unabated natural gas. This would require capture and storage (or utilise in an application that could permanently store the carbon) between 7 and 10.5 Mt of CO_2 every year.[51] This expansion involves both projects developing new production capacity and projects aiming to replace or retrofit current unabated production. Oil-based production would also fall significantly due to the decreasing output of naphtha reformers and petrochemical processes. On the contrary, pure hydrogen production from electricity would reach close to 900 kt H_2/y in 2030, consuming close to 44 TWh of electricity annually in its production. In the case of mixed hydrogen, by-product hydrogen use from residual gases remains the main route of supply, although electrolysis can also make some dent (reaching around 4% of supply and requiring more than 4 TWh of electricity).

In this scenario, low-carbon hydrogen production would meet more than a third of the total supply, or more than half of dedicated production. This contrasts with the current situation where low-carbon hydrogen meets only approximately 5% of the supply (little more than 10% of dedicated production). The adoption of policies whose objective is to ensure the achievement of national low-carbon hydrogen deployment targets would significantly increase this contribution to around 45% (two thirds of dedicated production).

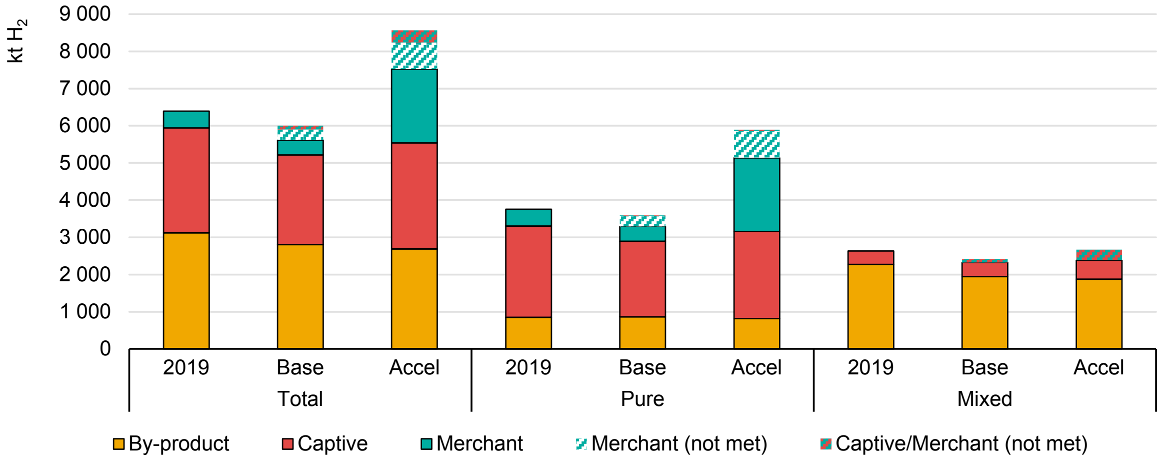
Hydrogen delivery to end users

The link between supply and the end-use of hydrogen would also evolve differently in the two scenarios. In the Baseline scenario, shares of captive, merchant and by-product hydrogen would remain practically the same as today. Part of the gap between supply and demand could be met by repurposing current captive capacity to produce hydrogen that could be sold as merchant hydrogen. This could help to meet the demand from new applications, mainly mobility and blending in blast furnaces, although this will result in little benefit from the point of view of GHG emissions reduction (and could even lead to an increase in emissions). Mobility will require merchant hydrogen, but the demand in blast furnaces could be met either by captive production or by sourcing merchant hydrogen, depending on which option is more economical. However, using current capacities in these new applications will have a limited (or even no) benefit from the point of view of reducing CO_2 emissions. Moreover, under the Baseline scenario it does not seem

[51] Assuming a capture rate in the range of 60-90%. Most CO_2 utilisation applications involving permanent storage are either in early stages of development and/or difficult to scale up to make a meaningful contribution to reducing 7-10.5 Mt CO_2/y. The bulk of the emissions reductions will therefore have to come from geological storage of CO_2. The captured quantities do not include the CO_2 that would be captured in ammonia plants for the production of urea (around 3 Mt by 2030 in the Accelerated scenario).

obvious that a competitive hydrogen market would develop in the region, and those applications that could meet their demand with either captive production or merchant hydrogen could then lean towards developing their own captive capacity.

Current and projected regional hydrogen supply by source category in the Baseline and Accelerated scenarios, 2030



Note: The shaded columns reflect the type of hydrogen delivery that can be used in applications for which demand is not met by supply capacity.

The Accelerated scenario offers better prospects to develop a regional hydrogen market. The level of captive production would remain similar to today and the Baseline scenario, but the contribution of merchant hydrogen to the regional supply would expand from around 400 kt H_2/y to close to 2 000 kt H_2/y, meeting approximately 40% of the supply. This would require a significant development of new hydrogen infrastructure or repurposing of the current natural gas infrastructure to enable hydrogen distribution from the producers to the end users. Some initiatives in the Netherlands [52] and Germany [53] have taken the first steps in this direction. However, early co-ordination between the countries for planning will facilitate a faster and more efficient deployment of such infrastructure. Another factor that could favour the development of this regional market is that those hydrogen demands that are not met by supply come from applications that require merchant hydrogen or that can opt for both merchant and captive production.

Moreover, development of a regional hydrogen market allows trade across the different countries in the region. Excess hydrogen supply in countries like the

[52] https://www.hyway27.nl/en.
[53] https://www.eon.com/en/about-us/media/press-release/2020/unique-project-in-germany-natural-gas-pipeline-is-converted-to-pure-hydrogen.html.

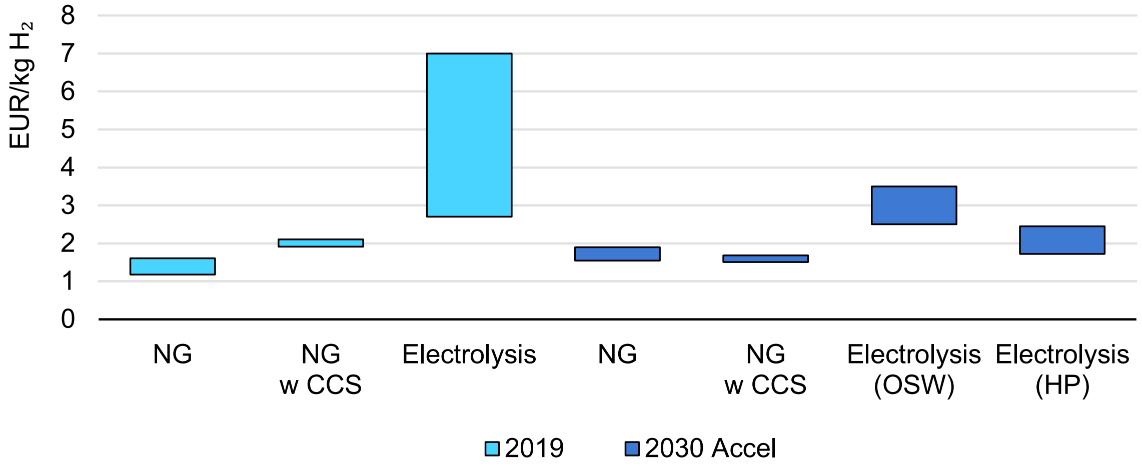
Netherlands, Norway or Denmark (provided that all expected projects are realised) could be traded to Belgium, France, Germany and the United Kingdom to meet their markets' demand. This situation would be different for France and the United Kingdom if these countries meet their national targets for low-carbon hydrogen production capacity. If that is the case, supply in both countries would meet, or even exceed, their demand. On the other hand, the significant expansion in hydrogen demand that could be achieved in Germany would mean that, even meeting its national target for low-carbon hydrogen production, it would require a certain level of hydrogen imports to meet its demand.

Production costs (2019-2030)

Hydrogen can be produced in various ways, such as from fossil fuels, from biomass or from water using electricity. In north-western Europe, hydrogen production today is dominated by natural gas due to favourable economics, with production costs in the range of EUR 1.2-1.6/kg H_2, depending on local gas prices. This production from natural gas without carbon capture, however, leads to direct CO_2 emissions of around 10 kg CO_2/kg H_2.[54] The opportunities for low-carbon hydrogen production exist in the region, with the potential for offshore CO_2 storage (in depleted oil and gas fields and saline aquifers) and excellent offshore wind potentials in the North Sea as well as hydropower resources in Norway. However, these low-carbon alternatives are today still more expensive than the production via unabated natural gas, with production from natural gas with CCS costing EUR 1.9-2.1/kg H_2 and from electrolysis EUR 2.7-7/kg H_2.

[54] IEA (2019), *The Future of Hydrogen*, https://www.iea.org/reports/the-future-of-hydrogen.

Current and projected hydrogen production costs in the Accelerated scenario, 2019-2030



Notes: NG = unabated natural gas-based hydrogen production; NG w CCS = natural gas-based hydrogen production with carbon capture and storage; Electrolysis (OSW) = electrolysis powered by offshore wind electricity; Electrolysis (HP) = electrolysis powered by hydropower. The results for Electrolysis (OSW) assume offshore hydrogen production and include hydrogen transport costs to shore.

Assumptions: 6% discount rate, 30 years system lifetime, natural gas price EUR 4.0-6.3/MBtu (2019) and EUR 3.0-4.7/MBtu (2030), hydropower electricity cost EUR 22-37/MWh (2019 and 2030), Offshore wind electricity costs EUR 60-110/MWh (2019) and EUR 38-70/MWh (2030). CO_2 transport and storage costs EUR 47-68/t CO2 (2019) and EUR 38-51/t CO_2 (2030), based on internal estimates and costs indicated for the Porthos and Northern Lights projects.[55] CO_2 price EUR 20-30/t CO_2 (2019) and EUR 80-90/t CO_2 (2030).

NG: CAPEX EUR 827/kW H2, OPEX 4.7% of CAPEX, LHV efficiency 76%, load factor 95%.

NG w CCS: CAPEX EUR 1478/kW H_2 (2019) and EUR 1234/kW H_2 (2030), OPEX 3% of CAPEX, LHV efficiency 69%, load factor 95%, capture rate 95%.

Electrolysis: CAPEX EUR 962/ kW_e (2019) and EUR 581/kW_e (2030), OPEX 2.2% (2019) and 1.6% (2030) of CAPEX, LHV efficiency 64% (2019) and 69% (2030), Load factor (hydropower) 40%, Load factor (offshore wind) 40-60%. Electrolysis CAPEX calculated as the average of global alkaline and PEM CAPEX.

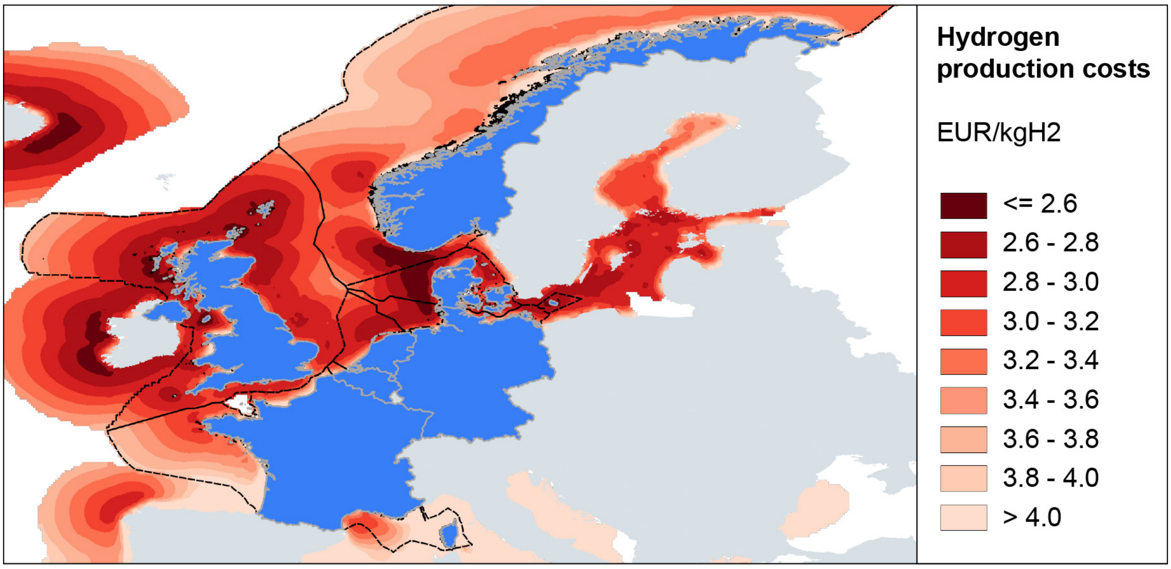
With technology cost reductions for CO_2 capture equipment, electrolysers and offshore wind turbines due to learning effects, this cost gap will narrow in the future. By 2030, hydrogen production from natural gas with CCS in the region could fall to EUR 1.5-1.7/kg H_2, while CO_2 prices reaching the range of EUR 80-90/t CO_2 would increase the production costs from natural gas without CCS to EUR 1.6-1.9/kg H_2.

In the Accelerated scenario, IEA analysis suggests that cost reductions for offshore wind would result in electricity generation costs of below EUR 40/MWh (excluding transmission costs and assuming a CAPEX of EUR 1 700-1 800/kW and 60% load factor). In combination with declining costs for electrolysers, hydrogen production costs from offshore wind could fall to EUR 2.5-3.5/kg H_2, assuming an offshore hydrogen production and including hydrogen transport costs

[55] Xodus Advisory (2020), Porthos CCS – Transport And Storage (T&S) Tariff Review. The Dutch Ministry of Economic Affairs and Climate Policy,https://repository.overheid.nl/frbr/plooi-contentbeheer/rijksoverheid/2020/plooicb-2020-3905/1/pdf/plooicb-2020-3905.pdf (Visited: 17-02-2021)

to shore. Pilot and demonstration projects for offshore hydrogen production are underway, such as the Dolphyn project in the United Kingdom, the Oyster project in Denmark, or have been announced, such as the AquaVentus project in Germany, aiming to reach a 10 GW electrolyser capacity by 2035. There could be opportunities to further reduce costs by repurposing existing oil and gas assets, such as using existing platforms for electrolyser installations or oil and gas pipelines for the transport of hydrogen. However, there are uncertainties about the suitability of certain oil and gas assets for these purposes and challenges to simultaneously phase out oil and gas activities while ramping up electrolysis deployment. Potentially attractive sites for hydrogen production are, for example, located west of Denmark or north of the United Kingdom, benefitting from locations relatively close to the shore and at shallow water depths.

Hydrogen production costs from offshore wind in the Accelerated scenario, 2030



Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. The analysis is based on hourly wind speed data from Copernicus Climate Change Service (2020).[56]

Assumptions: CAPEX for offshore wind EUR 1 700-1 800/kW; offshore hydrogen transport costs: EUR 0.27/kg H_2/100 km; other assumptions see notes of previous figure.

[56] Copernicus Climate Change Service (2020), ERA5 hourly data on single levels from 1970 to present (https://doi.org/10.24381/cds.adbb2d47), European Centre for Medium-Range Weather Forecasts.

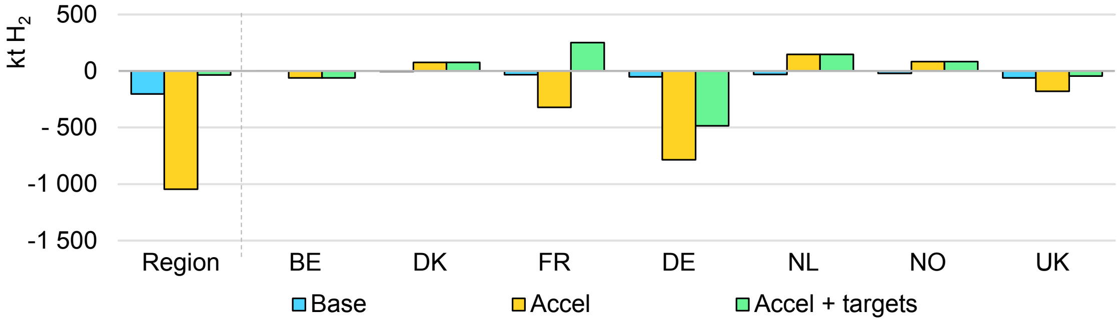
An opportunity for trade

North-western Europe has strong drivers to develop a robust regional hydrogen market which could be one of the first nodes of a future international hydrogen market:

- The region has a substantial hydrogen demand (around 5% of global demand).
- A strong concentration of industrial activities with potential to expand the hydrogen demand significantly.
- Ambitious goals for GHG emissions reduction that could expand the use of hydrogen and political interest in the hydrogen industry as an opportunity to maintain industrial activity in the region.
- Hydrogen pipeline infrastructure is already in place and a significant natural gas infrastructure that could be repurposed as natural gas demand drops in the region.
- The region is home to the largest industrial ports in Europe, such as Rotterdam, Antwerp, Hamburg or Bremerhaven.
- The ports of Rotterdam and Zeebrugge together are an important liquefied natural gas hub and would be an ideal candidate to become a hydrogen hub if the market develops in the region, facilitating hydrogen trade within the region and with other regions of the world.

The development of hydrogen trade across the countries in the region would depend upon evolution of hydrogen demand and supply in each country, in addition to other factors such as further development of cross-border hydrogen infrastructure and regulation. In both the Baseline and the Accelerated scenarios, there are differences between demand and supply across countries and in the whole region, with some countries developing a supply capacity that could exceed their demand (creating a positive gap between projected demand and supply) and others unable to meet the demand that they could develop (creating a negative gap between projected demand and supply).

Regional and country gaps between hydrogen demand and supply in Baseline and Accelerated scenario, 2030



Notes: A negative value means that the projected demand in the country/region is larger than the projected supply. "Accel + targets" represents the gap if national targets for low-carbon hydrogen production capacity were achieved.

Several factors suggest that the size of these gaps (both at the regional and country level) could be lower than those projected in this analysis:

- As explained in the supply section, the project pipeline is likely to grow in the next decade especially if a supporting policy framework is in place and as a response to the generation of new demands. A lack of demand can hold back deployment of new production capacities due to uncertain business cases that hinder reaching FID, but this can change if demands are stimulated.
- Four countries (France, Germany, the Netherlands and the United Kingdom) in the region have adopted targets or ambitions for low-carbon hydrogen deployment, but only one of them (the Netherlands) meets them in the Accelerated scenario. Achieving these deployment targets or ambitions can close these gaps for certain countries or even result in a change from lack of supply to a surplus of supply.
- Part of the current captive production capacity that would be left unutilised in traditional sectors with declining demands could be repurposed to deliver merchant hydrogen and meet demands in new applications. However, part of that capacity is likely to be decommissioned due to the deployment of new projects for low-carbon hydrogen production aiming to decarbonise current capacities. Moreover, repurposing current production capacities to supply new hydrogen application, could result in little benefit for the reduction of GHG emissions or even in an increase of those emissions.
- The strong development of hydrogen demand in the Accelerated scenario requires adoption of ambitious policies and targets to stimulate hydrogen demand as well as support of innovation in certain end-use applications (such as in the iron and steel industry or heavy road transport). Without these supporting policies, many potential demands for hydrogen will remain locked. Contrary to the case of hydrogen supply, where several countries have announced ambitious targets, there are currently essentially no targets adopted for end-use sectors apart from FCEVs targets in France and the Netherlands.

In both the Baseline and Accelerated scenarios, the expansion of the production capacity that could be achieved with the current pipeline of projects would not be able to meet the projected demand, although the size of the gap is significantly different. In the Baseline scenario, the difference between supply and demand would be around 200 kt H_2/y, whereas in the Accelerated scenario it could reach more than 1 000 kt H_2/y. The achievement of national targets for low-carbon hydrogen production could almost close this gap, if these targets are used to expand the production capacity. However, it could also increase if a significant fraction of new deployments for production capacity of low-carbon hydrogen replaces current capacities.

Despite uncertainty about the evolution of hydrogen demand and supply and its potential imbalances in the region, this report finds two main conclusions about the potential development of hydrogen trade in this region:

- **Internal trade:** there are marked differences between countries for generation of new hydrogen demands and deployment of low-carbon hydrogen production capacities. Some countries in the region have a strong potential to expand the use of hydrogen to new applications by 2030 to meet their decarbonisation targets but could have difficulty meeting those demands with an expansion of national low-carbon hydrogen production capacity. Conversely, other countries have less potential to generate new national hydrogen demands but show tremendous potential to expand production capacity, which will only be unlocked if there is a matching evolution of demand in neighbour countries. All countries in the region would benefit from establishing a regional dialogue to co-operate with an objective to develop cross-national initiatives that take advantage of the complementarities that different countries in the region present.
- **External trade:** there is a non-negligible possibility that by 2030 the region could require imports from third countries to meet its demand. This would require developing large-scale hydrogen supply chains with other world regions. Even if this need for imports does not materialise by 2030, it seems advisable to lay foundations for these supply chains. Development of these value chains within only 10 years is a challenging endeavour and would require strong co-operation within the countries of the region, as well as with countries in other regions where low-carbon hydrogen could be produced cost-effectively and which could become potential exporting regions. Some governments in the region have anticipated this scenario and have kick-started collaborations with potential exporters with the objective to lay groundwork for development of those large-scale hydrogen supply chains. The German government has already established collaborations to

develop low-carbon hydrogen projects in Morocco,[57] Saudi Arabia,[58] and Chile,[59] while the Dutch government[60] has signed a Memorandum of Understanding with Portugal to explore development of a large-scale supply chain.

[57] https://www.bmz.de/en/press/aktuelleMeldungen/2020/juni/200610_pm_031_Federal-Government-adopts-National-Hydrogen-Strategy-and-establishes-National-Hydrogen-Council/index.html.
[58] https://www.reuters.com/article/thyssenkrupp-hydrogen-saudi-arabia/germany-to-contribute-1-5-million-euros-to-thyssenkrupps-saudi-hydrogen-plant-idUSKBN28Q25R.
[59] https://www.reuters.com/article/germany-hydrogen-siemens/germany-makes-near-10-mln-contribution-to-siemens-hydrogen-plant-in-chile-idUSL8N2II2WW.
[60] https://www.government.nl/latest/news/2020/09/23/portugal-and-the-netherlands-strengthen-bilateral-cooperation-on-green-hydrogen.

National hydrogen policies

Convergence of ideas

Momentum for low-carbon hydrogen has been building over recent years and has now reached an unprecedented intensity. All stakeholders understand the scale of energy transition required to meet global sustainability goals, and low-carbon hydrogen is now considered to be a key part of that transition by an increasing number of countries around the world and by a diverse number of participants. Most actors are aware of the positive aspects of embracing low-carbon hydrogen due to its versatility. Moreover, hydrogen conversion can build upon existing knowledge bases within the current energy industry; for example, with offshore facilities, through connecting energy demand and supply over long distances and through molecular conversion into energy carriers and products. This applies to current oil and gas producing countries, as well as to countries elsewhere. Furthermore, low-carbon hydrogen has the potential to become an international tradeable commodity in the future. Adoption by these diverse stakeholders makes developing hydrogen and attracting investment capital much easier than a smaller, localized, regional solution or one that has only one industrial application. This convergence of ideas and consensus on the opportunity that low-carbon hydrogen offers is therefore important: it boosts the overall appeal and probability of low-carbon hydrogen development.

Country reviews

In the past year, an approach to hydrogen became clear for most north-western European countries, with many also publishing hydrogen strategies. At the same time, countries were co-operating on a joint strategy for north-western Europe. The joint political declaration of The Pentalateral Energy Forum, signed 11 May 2020, affirmed such international collaboration on hydrogen.[61] These efforts are geared towards strengthening the hydrogen sector by similar developments in countries across the region, and aim to design a common long-term vision for low-carbon hydrogen as a means to integrate the large potential in

[61] Pentalateral Energy Forum (2020), Joint political declaration on the role of hydrogen to decarbonise the energy system in Europe. Signed by Austria, Belgium, France, Germany, Luxemburg, the Netherlands and Switzerland, and supported by Bulgaria, Portugal, Romania, and Denmark. The declaration affirms the commitment to strengthen co-operation on hydrogen produced in a CO_2 reducing manner with the aim of contributing to the full decarbonisation of the energy system.

offshore wind within their energy system, develop hydrogen for hard-to-abate CO_2 emissions, achieve their climate ambitions and create new, sustainable business opportunities. It is clear from this joint declaration that individual national approaches, which consider the issues from each country, are important when determining each country's level of co-operation. The EU hydrogen strategy[62] and the manifesto for an IPCEI on hydrogen[63] are important steps forward in organising co-operation among European countries. Before assessing the further potential for co-operation among the countries in the region, individual hydrogen approaches and strategies are explored.

Belgium

- **Bottom-up hydrogen strategy making.** With a developing national hydrogen strategy, current regional hydrogen strategies and initiatives are at the foreground in creation of this low-carbon hydrogen value chain.
- **Strong infrastructure, industry and technology sector.** Home to a robust industrial sector with considerable existing hydrogen demand, an accompanying natural gas grid and privately-owned hydrogen pipelines, Belgium is well placed to introduce low-carbon hydrogen.
- **International co-operation and imports boost low-carbon hydrogen supply.** A comparably small and busy North Sea exclusive economic zone where offshore wind power is only a limited part of their low-carbon hydrogen supply. International co-operation in joint offshore wind development, low-carbon hydrogen production projects or regional imports (both hydrogen and electricity) are attractive methods that can boost supply.

Belgium is a federation consisting of the regions of Wallonia, Flanders, and Brussels. Responsibilities and aspects of energy policy making are distributed among the different regional governments.[64] The regions are responsible for electricity and gas distribution grids, for renewable energy (except offshore wind), for electricity and gas retail markets regulation, for the promotion of energy efficiency and for energy R&D programmes. The federal government is

[62] European Commission (2020), A hydrogen strategy for a climate-neutral Europe.
[63] Manifesto for the development of a European ‘Hydrogen Technologies and Systems’ value chain, signed by 23 European nations.
[64] IEA (2016), Energy Policies of IEA countries: Belgium 2016 review, page 22.

responsible for monitoring of supply security, conventional energy production, offshore wind power, nuclear energy policies and electricity and gas transmission, among others. In this institutional landscape, energy policy is created in collaboration with and co-operation between the different levels. [65]

When the IEA published the Country Review 2016 for Belgium, hydrogen was mostly mentioned related to R&D programmes focusing on hydrogen applications in the transport sector. Since that time, much has changed. In late 2018, the Wallonia industry sector published a government-approved hydrogen roadmap.[66] In 2020, the Flanders Minister for Innovation presented a Hydrogen Vision for Flanders.[67] Support for hydrogen has been expressed at the federal level as well, with announced development of federal hydrogen policies in co-ordination with regional governments[68] and studies were undertaken by the Federal Planning Bureau to shape their energy policy.[69] While a public policy framework is typically established in an organic way through federal and regional efforts, a range of other factors in Belgium will also shape their hydrogen developments in the coming decades. This includes, for example, participation in the EU Important Project of Common Interest (IPCEI) on hydrogen and hydrogen-related projects in the framework of the Belgium EU Recovery and Resilience Facility (RRF).

Role(s) assigned to hydrogen

In the 2018 hydrogen roadmap for Wallonia, targets have been set for 2030 and 2050 in both the (public) transport and heavy industry sectors (glass, steel and cement); the latter of which is, historically, a pillar of Wallonia's economy. The 2020 Flemish Hydrogen Vision specifically targets heavy-duty applications in the transport sector and additionally expects that hydrogen will contribute to decarbonisation of the industrial sector, as this presents an opportunity to integrate CO_2 and hydrogen flows as feedstock to the chemical industry producing low-carbon (intermediate) products. It furthermore recognises the significance of hydrogen imports.[70] Opportunities to blend hydrogen in natural gas networks are also being investigated.

[65] For example, ENOVER is a monthly discussion platform, chaired by the Federal Public Service Economy, members are the federal and regional governments, and includes multiple working groups. Also, EU required energy policy such as The National Energy and Climate Plan 2021-2030 is created in collaboration between the regional and federal government.
[66] Cluster TWEED (2018), Roadmap hydrogène pour la Wallonie.
[67] VARIO (2020), Flemish Hydrogen Vision 'European frontrunner through sustainable innovation'.
[68] Belgium Chamber of Representatives (2020), Policy Statement - Energy.
[69] Federal Planning Bureau (2020), Fuel for the future – More molecules or deep electrification of Belgium's energy system by 2050.
[70] Research to the feasibility of this is for example supported by VLAIO, through the work of the Hydrogen Import Coalition (2021), Shipping sun and wind to Belgium is key in a climate neutral economy.

Supporting (legacy) factors

Several important legacy factors affect Belgium's energy future and the role of hydrogen therein. In the coastal region, the ports of Zeebrugge, Ostend, Ghent and Antwerp are home to energy-intensive industries and energy import facilities. In the petrochemical industrial clusters in Flanders, the Port of Antwerp foremost, today's hydrogen consumption is especially considerable relative to the country's size. These clusters are connected to international oil and energy markets, and to industrial clusters in Belgium's inland, the Netherlands and Germany. Moreover, there is a hydrogen pipeline network, privately owned by the French company Air Liquide, connecting these industrial clusters.

Belgium is home to both a low-calorific and high-calorific natural gas transmission system, has well-developed gas distribution grids and an LNG import facility in Zeebrugge. The system simultaneously serves domestic consumers and is important to both low-calorific natural gas transit from the Netherlands to France and eastward transit of high-calorific natural gas received from North Sea pipelines and the Zeebrugge facility. Gas TSO Fluxys participated in research to establish a European-wide hydrogen backbone, including its infrastructure in the plan and investigating where new infrastructure is needed.[71]

Domestic fossil energy resources are absent in Belgium, and there is limited potential for solar and wind energy due to the relatively small land area, high population density and relatively small exclusive economic zone in the North Sea. Nuclear power, which has provided approximately half of the country's power generation for many years, is subject to a legally defined phase-out between 2022 and 2025.[72] This creates limited options for renewable hydrogen production, while hydrogen adoption and its attendant energy transport, storage and conversion options could improve Belgium's energy system's resilience. As a technologically advanced nation, Belgium hosts many companies that contribute to hydrogen technology development.[73] It also boasts a strong automotive sector, with companies focussed on hydrogen mobility solutions.[74]

[71] Gas for climate (2020), European hydrogen backbone.
[72] The phase-out is reaffirmed in amongst others the 2018 Energy Pact between the governments, and the 2020 energy policy statement of the Chamber of Representatives. Nonetheless, in November 2021, an evaluation of the security of electricity supply is scheduled to monitor the situation. This monitoring report might reveal the need for remediate measures.
[73] These include, for example, producers of membranes for alkaline electrolysers (Agfa), of electrolysers (Cummins, formerly Hydrogenics, and John Cockerill), of bipolar plates for electrolysers (Borit) and of hydrogen compression technology (Atlas Copco and John Cockerill).
[74] These include, for example, engineering and manufacturing companies such as Van Hool and E-Trucks (heavy-duty vehicles), and automotive suppliers such as Plastic Omnium and CMB/ABC.

Putting plans into practice

Following Belgium's institutional landscape and pending a federal hydrogen strategy, the hydrogen sector in Belgium has developed in an organic and partly bottom-up process. Hydrogen strategies and projects have been created by regional governments and private parties and are eligible for support or funding by the federal government. Funding can also be at the EU level, allocated through the federal government to regional governments.

The Hydrogen Vision for Flanders explicitly formulates five strategic objectives: (1) strengthening the hydrogen knowledge base, (2) strengthening the industrial ecosystem, (3) stimulating the use of hydrogen and hydrogen technologies, (4) developing an international focus with neighbouring countries, (5) developing supporting policies that focus on areas such as skills and training. The Flanders vision identifies the use of hydrogen produced from fossil fuels coupled with CCUS as essential for developing a hydrogen market that supports the development and growth of renewable electrolytic hydrogen. Flanders seeks to take part in the IPCEI on hydrogen, and has made available EUR 125 million for hydrogen research and innovation.[75]

In the Walloon region, since the publication of its hydrogen roadmap, a EUR 50 million regional investment plan is currently being executed.[76] These initiatives will further be extended and intensified with funding received in the framework of the EU Recovery and Resilience Facility (RRF).[77] In addition, Wallonia is also host to privately-led projects such as a Carbon Capture and Utilisation (CCU) project that targets methane production from lime kiln CO_2 emissions and hydrogen produced by a 75 MW electrolyser.[78]

In the Brussels region, using funding awarded by the energy transition fund[79], the natural gas DSO is researching feeding hydrogen into the natural gas grid, which it believes will contribute to integrating surplus electricity in the energy system.[80]

International (North Sea) prerequisites

Several factors make regional north-western European co-operation relevant for Belgium. Firstly, its energy infrastructures for gases, liquids and electricity are

[75] Announcement by the Flemish Minister of Economy, Innovation & Work, 27 November 2020.
[76] The first project call for electrolytic hydrogen production and hydrogen refuelling stations (HRS) for use by the public transport sector are being tendered.
[77] The Wallonia government allocated EUR 160 million of the RRF for strengthening the Wallonia hydrogen sector with a specific focus on hydrogen research, production and applications.
[78] In a joint-venture of Carmeuse, John Cockerill, Engie and Storengy, the EUR 150 million project has applied for funding.
[79] Project H2GridLab is initiated by natural gas DSO Sibelga, and in co-operation with John Cockerill and Fluxys.
[80] Sibelga (2020), Sibelga – Motor van de energietransitie voor Brussel

firmly integrated within the regional infrastructures. Secondly, its energy economy is embedded within the region's energy economy, and many active commercial actors in Belgium have assets in other countries in the region, notably France, Germany and the Netherlands. Thirdly, Belgium is dependent upon energy imports and its share of the North Sea continental shelf is limited. Sharing the energy potential of other North Sea nations appears attractive, and evidence for this can be found, for example, in the Flemish Vision for Hydrogen, which explicitly states 'internationalisation with a focus on the neighbouring countries', demonstrating an international orientation embedded in the political and business culture of the country.

Denmark

- **Extensive low-carbon hydrogen production potential.** Excellent offshore wind power potential and experience utilising this demonstrate a high potential for low-carbon hydrogen production.
- **Opportunity for new industry and for energy export.** The low-carbon hydrogen production potential coupled with the proximity of large potential importers create an ideal situation for new hydrogen-consuming industries domestically as well as for low-carbon hydrogen exports.
- **Positioning for low-carbon hydrogen.** Building upon earlier support for hydrogen projects and a broadly supported energy and industry agreement, further support and funding for hydrogen is expected in the upcoming CCUS/Power-to-X strategy.

Denmark has been a frontrunner in wind energy and private actors and the government now seek to expand their position in offshore wind further, potentially into low carbon hydrogen. Denmark enjoys a relatively large offshore wind potential compared to its potential domestic demand, and as a result is exploring how to harvest this energy and transport and store it in the most efficient manner.

Hydrogen developments are set against a background of Danish GHG emissions reduction ambitions laid out in the Climate Act of 6 December 2019.[81] This Act includes a legally binding target to reduce GHG emissions by 70% relative to 1990 levels by 2030 and to reach net zero emissions by 2050. In June 2020, a broad

[81] Danish Ministry of Climate, Energy and Utilities (2019), Climate Act.

majority of the Danish parliament passed a climate agreement for energy and industry.[82] Among other mandates, this agreement mandated the development of a joint strategy for CCS, CCU and Power-to-X (PtX), which is expected to be published in 2021, and plans for two energy islands (Bornholm and an artificially created island in the North Sea) with a minimum connected wind power capacity of 5 GW. These islands will serve as hubs to connect offshore wind power and, in a later stage, possibly could expand to convert power into low carbon fuel offshore.[83] Alternative solutions are being considered, such as on-shore electrolyser plants which allow for waste heat utilisation and integration with carbon capture plants for CCU-applications. In parallel development, Denmark's TSO Energinet has been collaborating with the Dutch TSO's Gasunie and TenneT in the North Sea Wind Power Hub programme. This joint development is important because both latter companies also manage part of the German offshore infrastructure, creating a broader market base. Supported by the strategies of several crucial Denmark based companies, Denmark may develop into an important hub connecting the Scandinavian and North Sea electricity and hydrogen markets. The strength of the Danish proposition lies within its strong position in the wind energy value chain and its collaboration with the oil and gas industries and industrial gas sector.

Role(s) assigned to hydrogen

Opportunities for hydrogen are primarily considered in industry, power, and potentially heavy transportation. There are already (government supported) ongoing developments in this direction in Denmark, with Power-to-X plants being planned to produce hydrogen and synthetic fuels. This includes, for example, a 20 MW electrolyser near the refinery in Fredericia with future options to expand to 1 GW,[84] a 12 MW plant near Skive for hydrogen and methanol production[85] and large-scale energy storage through use of hydrogen in northern Jutland.[86] Once available in larger volumes, hydrogen use in industry can be significant in reducing emissions and attracting new industrial activities around the conversion sites.

[82] Climate agreement for energy and industry by the Danish government and various political parties.
[83] Announcement of the Danish Energy Agency on the decision for construction of an artificial island as wind energy hub.
[84] In a joint project, Everfuel is developing the HySynergy project with EUR 6.5 million support of the Danish Energy Agency.
[85] The GreenLab consortium aims to be operating the P2X project by 2022 and has received EUR 10 million funding from the Danish Energy Agency.
[86] The Green Hydrogen Hub consortium intends to combine 350 MW electrolytic hydrogen production, hydrogen salt cavern storage and compressed air energy storage.

Supporting (legacy) factors

The legacy factors for Denmark consist of a combination of (offshore) oil and gas industry and pipeline networks and a strong wind sector. Moreover, the district heating system also allows multiple new energy solutions to be introduced, including residual heat from electrolysers, without requiring a massive repurposing of gas distribution grids, household dwellings and offices. This could be an important factor in support of policies in the coming decade.

Putting plans into practice

The energy and industry agreement includes developing an encompassing strategy for CCUS and PtX that embeds the ongoing developments in a holistic document, expected in 2021. Stated in the agreement is the establishment of a subsidy scheme through government tenders for developing PtX systems (not necessarily limited to hydrogen). This scheme is to be funded through revenue generated by a renewable energy statistical transfer agreement, amounting to at least DKK 750 million (around EUR 100 million).[87] Additional funding of CCUS over 2024-2030 is included, increasing to DKK 815 million (around EUR 110 million) in 2030. The agreement further stipulates funding for the transportation sector, targeting the charging infrastructure as well as heavy transport and ferries, the latter of which could potentially benefit hydrogen.

The approach to hydrogen by public and private actors in Denmark follows the ambitious climate act and their large wind potential. Producing ever more wind energy without the ability to convert it into hydrogen could create integration issues for the electricity grid and associated costs as well. Moving beyond the electricity sector to include industry has opened new venues for developing their large offshore wind potential and achieving greater industry decarbonisation, perhaps even attracting new industries and developing dispatchable hydrogen-based power. Most major players in Denmark's hydrogen sector are organised in a branch (Brintbranchen), which combines both private companies and government agencies, such as the TSO Energinet (through subsidiary Gas Storage Denmark). Energinet has developed a strategic plan, suggesting a framework for all parties and ensuring roles, framework conditions, market model development, regulation, landing zones identification, infrastructure, infrastructure utilisation, demand and commercial activities.[88]

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[87] Using the Danish overachievement on renewable energy targets, a statistical transfer in the framework of EU targets and legislation is agreed upon with the Netherlands.
[88] Energinet (2020), Winds of Change in a Hydrogen Perspective.

International (North Sea) prerequisites

Supported by the strategies of several crucial, Denmark based companies, Denmark may develop into an important hub to connect the Scandinavian and North Sea electricity and hydrogen markets. Their strength lies within their strong position in the wind energy value chain and collaboration with the oil and gas industries and industrial gases sector. Denmark's potential to develop hydrogen supplies for other markets is significant, particularly beyond 2030 when successes in the domestic economy could be translated into an export model. Denmark is expected to use a part of their potential to decarbonise their own economy, given the ambitious and legally binding goal of 70% GHG emission reduction by 2030. Much like in they have built a strong wind value chain and related industry, Denmark could create a similar model with hydrogen through government tendering for hydrogen systems. Their post-2030 strategy depends very much upon hydrogen market development in neighbouring countries and the infrastructure to deliver hydrogen to those markets. The decision to make the first step with the energy islands shows the Danish government's continued drive to tap into its offshore wind energy potential and could pave the way for new approaches to integrating offshore energy in all sectors of their economy.

France

- **Strong government.** Through a well-developed national hydrogen strategy, subsidy schemes and stakes in hydrogen-related companies, the national government has a strong role in creating a hydrogen value chain.
- **Development of a full hydrogen value chain.** The creation of this complete hydrogen value chain builds on existing industrial and production capacities and aims to include supplying industries and hydrogen-related technology.
- **Opportunity for decarbonisation beyond power and heating.** With an already largely decarbonised power sector and a relatively high level of electrification in domestic heating, low-carbon hydrogen can help decarbonise both mobility and the industrial sector.

The French government published its national hydrogen strategy in early September 2020.[89] While the central government has been crucial in setting the framework for hydrogen development, it is important to mention some other actors who will jointly shape hydrogen development in France. The major electricity producer in the country is Électricité de France (EDF), in which the national government has an 85% stake. EDF owns France's nuclear power generation and recently established Hynamics, which focuses on hydrogen activities. In 2018, EDF acquired a 21.7% stake in the French electrolyser and hydrogen refuelling station manufacturer McPhy. The national electricity transmission systems operator RTE is a subsidiary of EDF. Enedis, another EDF subsidiary, holds 95% of all distribution grid concessions. EDF is also part of the consortium that makes up Teréga, the gas TSO active in the Southwest of the country. The other major gas TSO in France is GRTGaz, which is a subsidiary of Engie. Engie is active in energy markets worldwide, and its focus has shifted increasingly to renewables and it has also embraced hydrogen.[90] Total, France's largest oil and gas company, is increasingly shifting its strategy towards renewable energy and hydrogen projects. These French companies have united in an organisation that promotes hydrogen and fuel cell technologies and co-ordinates actions,[91] establishing in January 2021 a National Hydrogen Council, consisting of high-level executives from the relevant industries.[92]

Role(s) assigned to hydrogen

Through their presentation of the national hydrogen strategy in September 2020, Ministers Pompili (Ecological Transition) and Le Maire (Economic Affairs and Finance) clearly stated the roles the French government sees for hydrogen. It is the French government's conviction that low-carbon hydrogen will be one of the great revolutions of the 21st century, for industrial sector decarbonisation, for developing emission-free modes of transport, for energy storage and addressing variable power generation from renewable energy capacities. Broadly speaking, the French hydrogen strategy does not solely tackle environmental questions, it contributes to economic development and job creation, to energy sovereignty and a reduction of dependence on fossil fuel imports, as well as to technological independence and France's overall competitive global position.

[89] Ministry of Economy, Finance and Recovery (2020), National strategy for development of decarbonised hydrogen in France.
[90] Engie (2020), 2020 Integrated Report.
[91] The French Association for Hydrogen and Fuel Cells - AFHYPAC.
[92] Joint statement of the minister of Ecological Transition, minister of Economy, Finance and Recover, minister of Higher Education, Research and Innovation, and minister of Industry.

Supporting (legacy) factors

Electricity generation in France was largely decarbonised when its nuclear generation fleet was commissioned in the 1980s.[93] Although its relative share in the mix of nuclear power is planned to continue to decrease, there is currently no intention to completely phase out nuclear power use.[94] For producing low-carbon hydrogen using electrolysis, this is an excellent starting point.

Future solar and wind capacity deployment in France can scale up in tandem with the introduction of electrolysers and establishing new hydrogen supply chains, decarbonising the industrial sector, mobility and gas grids, as mentioned in the previous section.[95] By strategically locating offshore wind parks and electrolysers, congestion in the existing electricity grid, which was also designed for major nuclear power plant sites, can be limited while building renewable energy capacities.[96] Furthermore, gas TSOs have been exploring how they can contribute to building an integrated electricity and gas system and how they can blend hydrogen with natural gas.[97] With respect to internal electricity and gas networks in France, hydrogen can help balance the electricity system over time, tapping into hydrogen storage potential towards 2050. In the shorter term, *RTE* has identified opportunities, primarily for low-carbon hydrogen, to substitute existing hydrogen supplies in industry, to blend with natural gas in existing gas grids, and to use in the transport sector, while system balancing can be achieved in other ways. They have additionally been involved in the European consortium promoting deployment of a European hydrogen backbone.[98]

[93] IEA (2016), Energy Policies of IEA Countries: France 2016 review.
[94] World Nuclear Association (2021), Country profiles – France.
[95] As explored in, for example, an 2020 assessment of low-carbon hydrogen by RTE to use dedicated solar PV capacity for electrolysis, without necessarily feeding power into the grid.
[96] For example, in the RTE assessment of low-carbon hydrogen, there are opportunities for location of electrolysers and offshore wind power connections close by nuclear power generation sites.
[97] GRTgaz, GRDF, Teréga, Storengy, Elengy, Géométhane, Régaz Bordeaux, R-GDS, SPEGNN (2019). Conditions techniqueset économiques d'injection d'hydrogène dans les réseaux de gaz naturel.
[98] Gas for climate (2020), European hydrogen backbone.

In addition to legacy energy infrastructure, other economic sectors are boosting France's hydrogen opportunities. France is a technologically advanced nation with robust automotive, aerospace and defence industries, and bus and train manufacturers.[99] Moreover, France has developed (petro-)chemical and steel industries that can benefit from the hydrogen strategy. The hydrogen strategy highlights that 225 000 people are employed in the automotive sector. In such a diverse and well-developed industrial landscape, partnerships are more easily found.[100]

Putting plans into practice

The French hydrogen strategy sets three objectives: (1) installing sufficient electrolysers to make meaningful contribution to energy system decarbonisation, (2) developing clean mobility, particularly heavy transport, and (3) establishing a creative industrial sector that is put to work. By 2030, 6.5 GW of electrolysers should be installed. Regarding industry, the strategy particularly targets the refining sector, ammonia and methanol production and the agri-food sector (which uses smaller quantities of hydrogen). For the coming years, to accelerate investments in carbon-free hydrogen, the French government makes available EUR 7 billion, of which EUR 2 billion is from Covid-19 recovery plans. For the 2020-2023 period, EUR 3.4 billion is available to be divided among industrial decarbonisation (54%), hydrogen transport development (27%) and research and development (19%).

International (North Sea) prerequisites

Bordering the southern portion of the North Sea, France is in the heart of Europe. Existing energy infrastructures in Northern France, including the *Air Liquide* hydrogen network, are integrated with the infrastructures of other North Sea nations, notably Belgium, the Netherlands and Germany. In addition, offshore wind developments begin in this region. France has other relevant neighbours that do not have a direct stake in North Sea developments, but which are, nonetheless, relevant to France's broader hydrogen ambitions, to which it makes explicit reference in the European Commission and its Clean Hydrogen Alliance initiative.

[99] Relevant companies include Safra (buses), Alstom and SNCF (trains), Faurecia (tanks), Ariane (space technology), Symbio (fuel cells), Air Liquide (producer of industrial gases and service provider for the chemical industries), and McPhy (manufacturer of electrolysers).

[100] Exemplified by, amongst others, (space) technology provider ArianeGroup collaborating with energy company Engie in the development of liquefied hydrogen technology and applications.

Germany

- **High potential demand.** As an industrialised nation with important energy demand centres that rely on energy imports, there is large potential role and demand for low-carbon hydrogen.
- **Policy recognition of co-operation and imports.** Alongside ambitious targets for domestic production and substantial financial support, the importance of energy imports via low-carbon hydrogen is recognised and included in their national hydrogen strategy.
- **Positioning for hydrogen technology.** With advanced technological capabilities and long-running governmental support for hydrogen research and development, Germany is positioned to be a hydrogen technology leader.

In June 2020, the German federal government presented their national hydrogen strategy.[101] This strategy is the culmination of the preceding years of work in research, programs and strategies by various governmental ministries and (semi)governmental organisations, focused on various individual sectors and aspects. With substantial financial support announced alongside the national strategy, hydrogen is established firmly and through a holistic German policy making approach.

The Federal Ministry for Economic Affairs and Energy (BMWi) establishes energy policy at the federal level within the Federal Republic of Germany.[102] This ministry is also responsible for industrial policy and, in collaboration with the Federal Ministry of Environment, Nature Conservation and Nuclear Safety, for spatial planning in the German North Sea exclusive economic zone (EEZ). Federal energy innovation research and development is managed by BMWi, with hydrogen mobility related activities promoted by the Ministry of Transport and Digital Infrastructure (BMVI).[103] Gas and electricity transmission networks are controlled by the Federal Network Agency. In turn, the 16 federated states of Germany have legislative power over (and often ownership of) gas and electricity grids at the distribution level. If national policies lead to industrial projects, the federated states also have power over these.

[101] Federal Ministry for Economic Affairs and Energy (2020), The National Hydrogen Strategy.
[102] IEA (2020), Germany 2020 Energy Policy Review (Institutions, page 24).
[103] Federal Ministry for Economic Affairs and Energy (2018), 7th Energy Research Programme of the Federal Government.

In this multi-level governance structure, decisions made at the state-level are thus relevant to reach targets set at the national level.

Role(s) assigned to hydrogen

The national hydrogen strategy proposes hydrogen within the context of the commitment to achieve net-zero emissions by 2050. Within this, hydrogen is specifically viewed as a potential abatement option for “hard to reduce emissions”, emphasising, among a broader range of demand applications, industrial demand (including feedstock) and heavy transport. This represents an evolution in the thinking around hydrogen as, during earlier cycles, hydrogen was regarded foremost from an automotive perspective for use in personal vehicles. While an extensive network of hydrogen refuelling stations has been constructed and is still being expanded, hydrogen in the transportation sector is now predominantly regarded from a context of heavy road transport with an increasing role for rail transportation on rail routes where electrification is not feasible. Furthermore, the concept of integrated energy transition between electricity and other energy systems is promoted. This is against a background of existing bottlenecks within electricity transmission, which a gradually growing hydrogen transmission network of repurposed and purpose-built pipelines can alleviate.[104]

Also recognised in the hydrogen strategy is the creation of a hydrogen value chain, including ‘upstream’ hydrogen production, fostering innovation and ramping up production capacity for required equipment. With a value chain approach, the hydrogen strategy incorporates and builds upon earlier governmental programs[105] and research,[106] including the prior achievement of a network of nearly 100 hydrogen refuelling stations.

Visions for a hydrogen value chain and hydrogen demand are generally solid, but hydrogen supply is a more diverse story. The German hydrogen strategy acknowledges a potential future supply and demand gap. Within the national debate, a strong political preference exists for electrolytic hydrogen production using renewable electricity. Offshore wind power production is regarded as indispensable, and the recent increased offshore production target is in line with this.[107] As the German EEZ on the North Sea is relatively small, international co-

[104] FNBGas (2020), Entwurf Netzentwicklungsplan Gas 2020-2030.
[105] Following an innovation program ending in 2006, a 10-year hydrogen and fuel cell technology program is in place since 2016.
[106] For example, the opportunities and position of the German industrial sector regarding an electrolyser value chain are explored.
[107] Federal Ministry for Economic Affairs and Energy (2020), Bundestag beschliesst wichtige Windenergie-Gesetzesvorhaben.

operation is vital for the creation of additional hydrogen supply. Here, a diversity of routes is pursued. The strategy explores co-operation within the North Sea region[108] and geographically broader initiatives, such as the Hydrogen IPCEI as well as hydrogen imports from other continents via pipelines and shipping. Additionally, there is interest in methane pyrolysis, as the solid carbon residue enables different options for CCUS when compared to conventional (gaseous) underground storage with CCS.

Supporting (legacy) factors

Germany is home to a strong industrial sector, covering demand sectors including chemicals production, oil refining and steel making, as well as renewable energy and hydrogen technology and equipment providers, such as electrolyser manufacturers.[109] This leads to both a relatively high energy demand and to many parties who potentially benefit from a hydrogen value chain. There is strong domestic support for hydrogen in an otherwise contentious energy discourse. The political decision to phase out nuclear and coal power production and low public acceptance of CCS limits the available technological options. There is an increased need for an alternative energy carrier, with potential import options, such as hydrogen, particularly within the context of a strong public preference for hydrogen produced from renewable energy sources via electrolysis.

There is a well-developed natural gas grid in Germany, which could be partly repurposed for hydrogen transport. There are plans by TSOs to do so gradually, starting in clusters and branching out from these.[110] There is a leading role foreseen for the states of North Rhine-Westphalia, Lower Saxony and Bremen, and for the Schkopau / Leuna industrial cluster, due to their promising combination of industrial demand centres, existing dedicated hydrogen infrastructures and natural gas pipelines potentially suited for reconversion.

Putting plans into practice

The German hydrogen strategy aims for an electrolyser capacity of 5 GW in 2030 and 10 GW in 2040, which by 2030 will produce approximately 14 TWh of hydrogen. To achieve this, also as part of an economic stimulus package, funding of EUR 9 billion was announced to realise the hydrogen strategy. Of this,

[108] Federal Ministry for Economic Affairs and Energy and the Minister of Climate, Energy and Utilities of the Kingdom of Denmark (2020), Letter of intent on co-operation on jointly analysing joint and hybrid offshore renewable energy projects between the countries.
[109] Notable players include Siemens and ThyssenKrupp.
[110] FNB Gas (2020), Entwurf Netzentwicklungsplan Gas 2020-2030.

EUR 7 billion is intended for domestic spending, while EUR 2 billion is earmarked for international partnerships. To reduce operational costs and thereby electrolytic hydrogen costs, it is proposed to create an exemption from the Renewable Energy Act surcharge[111] on electricity consumed by electrolyser installations built in 2020-2030, over a period of 20 years.

International (North Sea) prerequisites

As potential demand exceeds domestic production potential, the option to import hydrogen will be important for Germany. This includes the production potential of its North Sea neighbours: transport distances are relatively short, there is ongoing work to create a hydrogen system and the prospect of electrolytic hydrogen production using offshore wind fits well within the domestic narrative. However, a considerable amount of work and investment is required before this can materialise. For one, creation of transport capacity is crucial. Furthermore, while there is a domestic preference for electrolytic hydrogen, this preference may be less of a complicating factor for hydrogen imports than it is for domestic production initiatives, potentially allowing for relatively large volumes of hydrogen from a range of sources.

The Netherlands

- **Decarbonisation of industrial hubs.** Decarbonising existing hydrogen production and industry and adding new low-carbon hydrogen supply allow industrial clusters to serve as hubs for new demand.
- **Two hydrogen supply tracks for multiple targets.** Low-carbon hydrogen production is pursued through both electrolysis using offshore wind power and through fossil production as low-cost CCUS. These help realise 2030 climate targets and provide new business opportunities as (regional) economic stimulus, respectively.
- **Hydrogen transport and transit.** The opportunity to repurpose soon-to-be redundant natural gas transmission pipelines for hydrogen transport and for positioning as regional hydrogen transit hubs is recognised.

A small country with a relatively large coastline, the Netherlands already enjoys significant space in the North Sea EEZ, including shipping lanes, fishing, marine

[111] Under the Erneuerbare-Energien-Gesetz (EEG) legislation, renewable energy generation subsidies are funded through a surcharge on electricity consumption.

reserves and oil and natural gas production, but now has an opportunity to add offshore wind power generation. The country is home to five large industrial clusters, four of which are coastal. The energy system is traditionally gas-oriented, in part owing to a now declining domestic production. Favoured geographically with ports, inland waterways and large demand centres in proximity, the Netherlands has developed important hub functions for import and agricultural goods and energy trade.

Enshrined in a climate act, the Netherlands targets 49% greenhouse gas emissions reduction by 2030, and 95% reduction by 2050 (relative to 1990 levels).[112] To achieve this, a consensus-based Climate Agreement between the government and various parties was reached in 2019.[113] Energy production and imports are liberalised, while power and gas transmission grids are operated by wholly state-owned companies *Tennet* and *Gasunie*, respectively.

Role(s) assigned to hydrogen

Like many other countries, the Netherlands sees hydrogen as important primarily when other forms of decarbonisation are not technically possible or not as cost efficient.[114] Demand for low-carbon hydrogen is expected for industrial use, for pilots and demonstrations of residential heating in parts of the country and for mobility. This also requires policy attention.[115] For industry, hydrogen is perceived as indispensable in the transition towards sustainable industrial production, serving as both an energy source as well as feedstock.[116] Considering mobility, the focus is on heavy-duty transport applications where electrification is difficult. Here, the benefits of hydrogen use in mobility are two-fold: to decarbonise the transport sector and to introduce hydrogen to the wider public.[117] In the coming years, hydrogen is also expected to be significant in zero-emissions dispatchable power generation,[118] as the climate agreement states that demand for such power generation could grow to 17 TWh by 2030.

Aside from demand, hydrogen is expected to be a cost effective medium for seasonal energy storage in underground salt caverns.[119] There are good

[112] Targets as adopted in the 2019 Climate Act, and expected to be updated to revised EU targets.
[113] Government of the Netherlands (2019), Climate Agreement.
[114] Ministry of Economic Affairs and Climate Policy (2020), Government Strategy on Hydrogen.
[115] RLI, Waterstof, de ontbrekende schakel, januari 2021, https://www.rli.nl/sites/default/files/advies_waterstof_de_ontbrekende_schakel_-_def.pdf
[116] Ministry of Economic Affaris and Climate Policy (2020), Letter to parliament - Vision sustainable industry 2050.
[117] TKI Nieuw Gas (2019), Hydrogen for the Energy Transition.
[118] For example, the MAGNUM project of Vattenfall, Equinor and Gasunie New Energy considers conversion of a natural gas fired Combined Cycle Gas Turbine power plant to hydrogen fuel.
[119] As for example explored in the HyStock project of EnergyStock and Gasunie.

subsurface conditions for this in the Netherlands, building on their experience with large scale natural gas storage. The Netherlands also sees a future for hydrogen to unlock wind energy potential further offshore through electrolysis and to prevent or reduce congestion in electricity grids by strategically locating electrolysers in the grid. By 2027, the Netherlands wants to realise a hydrogen network that connects the country’s industrial clusters and possibly also those in neighbouring countries.[120]

Supporting (legacy) factors

Owing to domestic resources and historical developments, the Netherlands is home to both an extensive low-calorific and a high calorific natural gas system. As domestic production of low-calorific natural gas declines and industrial consumers are pressured to reduce their consumption of it, combined with efficiency gains in gas consumption since the gas grid construction, an increase in pipeline transport capacity will become available. As parts of this pipeline can be repurposed cost-effectively, the newly available capacity is driving plans to create a hydrogen transmission network alongside natural gas systems.[121] Such a hydrogen backbone should initially connect the Netherlands domestic industrial hubs by 2027 and potentially include cross-border connections to Germany that can be gradually expanded over time. The presence of industrial hubs is an additional incentive for the Netherlands hydrogen strategy, as the hubs have existing conventional hydrogen production facilities and demand. Additionally, four of the five industrial hubs are located near substantial offshore wind potential and could boost efficient renewable energy integration into the energy system.

With this large offshore wind potential, the Netherlands recognises the opportunity to sustainably meet a meaningful part of its domestic energy and hydrogen demand. The hydrogen strategy also foresees the development of an international hydrogen market, in which the Netherlands could be an importer and hub as well as a producer, since Dutch offshore wind potential is expected to be insufficient to serve the entirety of its domestic hydrogen demand and beyond. The geographic location of the Netherlands also is also an important factor in its hydrogen market development, creating an ambition that the Netherlands could become a hydrogen hub for north-western Europe. This could be achieved by combining gas infrastructure knowledge with the experience

[120] Ministry of Economic Affairs and Climate Policy, Tennet and Gasunie work on the HyWay 27 project.
[121] Taskforce Infrastructuur Klimaatakkoord Industrie (2020), Meerjarenprogramma Infrastructuur Energie en Klimaat.

gained as a north-western European natural gas hub, along with the storage potential for hydrogen in salt caverns within the region.

Putting plans into practice

As set out in the Netherlands national Climate Agreement of 2019, the ambition is to have 500 MW electrolysers installed by 2025 and 3-4 GW by 2030. The government increasingly supports both capital and operational costs with funding. This includes EUR 35 million annually with the aim to establish economies of scale, an annual demonstration and innovation subsidy (under the DEI+ scheme) of around EUR 70 million annually and operating costs subsidy covering both electrolytic[122] and fossil with CCUS technology (both under the SDE++ subsidy scheme). In addition, hydrogen projects have submitted for support of the so-called Growth Fund[123] and Invest NL Fund.[124] Approximately 80 active hydrogen pilot and demonstration projects currently exist in the Netherlands, including the more prominent hydrogen-related projects, H-Vision[125] and HEAVENN.[126] Innovation is fostered in the New Gas Top Sector and Electrochemical Conversion and Materials research programme, while a National Hydrogen Programme[127] is under development to commence in 2021. Joint investigation of what is needed to realise a national hydrogen infrastructure is conducted in the HyWay 27 project, to underpin the hydrogen project portfolio.

International (North Sea) prerequisites

In the Netherlands, the government and industrial actors see themselves as part of the international frontrunner group, with an increasing number of cross-border initiatives. Given the enormous task to develop hydrogen at scale, the need for international co-operation is acknowledged. This includes several overarching themes, which can be best addressed collectively, such as legislation and regulations, safety and risk management, standardisation, certification and infrastructure.[128] This also applies to the alignment of cross-border hydrogen

[122] Initially covering up to 2000 full-load hours per year considering net emission savings over the lifetime of supported projects (due to expected decreasing electricity emission factors), after ruling of the European Commission this is limited to initially around 800 hours per year and increasing yearly, under argumentation that supported projects should decrease emissions during each year in operation.
[123] Presented in 2020, the National Growth Fund aims to boost the Dutch economy's long-term competitiveness by investing in public infrastructure and services, and prioritises projects that help transition to a more sustainable future.
[124] Invest NL is a publicly funded (EUR 1.7 billion) private investment organisation focussing on start-ups and scale-ups in the energy transition and innovation.
[125] By a consortium of private and public parties, aimed at the production of low-carbon hydrogen using refinery off-gases in the Port of Rotterdam, with the CO_2 transport and storage outsourced to the Porthos project.
[126] Development of a hydrogen value chain in Northern Netherlands through 31 sub-projects.
[127] National Hydrogen Programme (2021), Introduction of the National Hydrogen Programme.
[128] TKI Nieuw Gas (2019), Hydrogen for the Energy Transition.

infrastructure in gas pipelines and hydrogen refuelling stations, stemming from continued uncertainty about how hydrogen will be traded, transported and used, e.g., as a pure gas or blended into the natural gas grid, in liquefied form, or as (part of) ammonia or other synthetic fuels.[129]

With a long-term target of renewable electrolytic hydrogen production, the Netherlands is developing an additional supply of renewable electricity in parallel with the development of electrolysers. Currently, electrolyser projects, particularly those connected to the grid, face difficulties with EU state aid legislation when requesting funding because operating the plants beyond a limited number of hours increases CO_2 emissions due to their relatively high emission factor within the current composition of the power mix. It is considered important to further step up existing roll-out plans for sustainable electricity production so that hydrogen production ambitions based on electrolysis can be realised within the overarching target for GHG emissions reduction of 55% by 2030. This will require a programmatic approach to be devised by parties in both national and international industry and government to achieve the desired growth path.

Norway

- **Experiences with hydrogen and CCS.** Building on domestic hydrogen demand and experience with CCS, Norway aims to utilise low-carbon hydrogen for cost-effective decarbonisation of domestic industries.
- **Export diversification opportunity.** Benefitting from favourable wind power potential, natural gas resources, and extensive carbon storage potential, low-carbon hydrogen provides a new and future-proof energy export opportunity for Norway.
- **Facilitating role in international projects.** Through participation via state-owned companies in international projects and by creation of a CCS service for international customers, the Norwegian government plays an important facilitating role and helps realise national targets in the region.

Norway has a long history in co-operative development of the hydrogen value chain.[130] The interest in hydrogen applications was early oriented to transportation (both road and maritime), and this is still predominantly the case today for

[129] DRIFT for transition (2020), Hydrogen for the Port of Rotterdam in an International Context.
[130] For example, the Norwegian Hydrogen Forum, an association of companies, research institutes and others, has been working on hydrogen applications and developing electrolysis technology since 1996.

domestic hydrogen demand developments. Domestic oil and natural gas use are mainly in transportation and industry, while residential heating is already largely electrified. The energy system has a relatively high share of electrification, owing to plentiful hydropower. Norway's oil and gas production primarily exports to the United Kingdom, the European Union and world markets.

Role(s) assigned to hydrogen

Previous periods of hydrogen enthusiasm have perhaps made the government cautious about how quickly these applications can be adopted in the market. The Norwegian hydrogen strategy refers to the intensified attention to hydrogen in various countries in and outside the European Union,[131] and the various projects in which Norwegian companies are involved to develop hydrogen-based strategies.[132]

The current hydrogen strategy focuses on the safety of hydrogen applications and accessibility from a user point of view, to create broader acceptance of the technology. Regarding exports, the strategy prioritises low-carbon hydrogen production from natural gas, allowing Norway to continue monetising their natural gas reserves in a low-carbon future. This also allows time to establish a (potentially floating) offshore wind capacity, banking on Norway's vast offshore wind potential. To accommodate market conversion of natural gas into hydrogen, the Norwegian strategy also promotes CCUS, in which the Longship CCS project can play an important facilitating role.[133] This project aims to store CO_2 from domestic and European industrial sources safely on the Norwegian shelf in offshore, subsurface geological formations. This solution could enable conversion of Norwegian natural gas to low-carbon hydrogen near the consumer market, as has been considered, for example, in steelmaking projects in Germany[134] or for dispatchable power production in the Netherlands.[135]

[131] Norwegian Ministry of Petroleum and Energy, Norwegian Ministry of Climate and Environment (2020), The Norwegian Government's hydrogen strategy.
[132] Projects are for example in the UK (H21), Sweden (HYBRIT) and the Netherlands (MAGNUM), or a project by Alstom to deliver H_2-powered trains to Germany to replace diesel-electric trains.
[133] Norwegian Ministry of Petroleum and Energy (2020), Longship – Carbon Capture and Storage.
[134] The H2morrow project of Equinor, Thyssenkrupp and OGE considers low-carbon hydrogen production in Germany or the Netherlands for use in steelmaking in Germany, with CCS potentially in Norway.
[135] The feasibility of conversion of the Magnum power plant in the Netherlands to low-carbon hydrogen fuel produced near site with CCS in Norway is considered by Vattenfall, Equinor and Gasunie.

Supporting (legacy) factors

Norway's national hydrogen strategy is in context of, and supported by, other relevant action plans. This includes the Norwegian climate action plan,[136] which aims to improve the competitiveness of low-carbon solutions (such as hydrogen) outside of ETS sectors, and the government's action plans for transport[137] and for green shipping.[138] The Norwegian government's strategy also emphasises its long industry experience and its assets (natural gas, sub-surface geological storage space, hydropower and offshore wind potential) that create an advantage in hydrogen production and applications.

In the domestic energy sector, hydrogen applications will have to compete with adjustable and storable hydropower. The Norwegian energy system differs from that of other European countries because of its available hydropower capacity (32 GW) and system flexibility. This makes hydrogen for renewable energy storage less valuable in Norway compared to other countries. It does, however, have the potential to develop off-grid wind farms. Existing natural gas (export) pipelines could be converted to transport hydrogen, however with the hydrogen strategy prioritising near-term market conversion, commercial considerations by market players should decide future feasibility of pipeline hydrogen exports vis-à-vis market conversion.

Putting plans into practice

Regarding the domestic market, the Norwegian government intends to use the relevant parts of its large procurement market portfolio of NOK 500 billion (around EUR 48 billion) to stimulate both hydrogen demand and its long-term plan for research and higher education to improve applied clean technologies. This includes, for example, procuring hydrogen-fuelled ferries and busses.

The Norwegian government is looking at hydrogen from a value chain perspective and has a funding scheme for businesses to accelerate development and deployment.[139] Despite a number of proposals from companies and research institutions, the hydrogen strategy expresses that the number of proposals received for end-user applications is deemed too low and calls for more activity in this field. Another striking part of the focus on applications is the interest to develop

[136] Norwegian Ministry of Climate and Environment (2021), Climate plan for 2021-2030.
[137] Norwegian Ministry of Transport and Communications (2018), National Transport Plan 2018-2029.
[138] Norwegian Government (2019), The Government's action plan for green shipping.
[139] The Pilot-E funding scheme by the Research Council of Norway, Innovation Norway and Enova has awarded hydrogen-related projects in for example value chain development, ferries, and maritime shipping.

hydrogen applications in the armed forces. Hydrogen research and development is stimulated through the Research Council of Norway, using the NOK 480 million (around EUR 47 million) ENERGIX-programme.[140] International collaboration will be facilitated and fostered, for example, through potential participation in European Union hydrogen programs.

International (North Sea) prerequisites

The Nordic countries of Sweden, Finland, Denmark, Iceland and Norway collaborate in the Scandinavian Hydrogen Highway Partnership on transportation and other applications. Collaboration around the North Sea could be attractive to enlarge the potential market for hydrogen and use the already existing power and pipeline connections to kick-start a regional market.

Norwegian companies are already collaborating in hydrogen and also collaborate with research institutions and energy expert groups or consultants, such as Sintef, Bellona and universities. In Norway, companies like Equinor, Shell, Air Liquide, NEL Hydrogen and others are active in hydrogen.

United Kingdom

- **Hydrogen is embedded in industrial and energy strategies.** With a hydrogen strategy under development, it is already well embedded and supported through industrial and energy system strategies and innovation funding.
- **Twin track hydrogen production approach.** For low carbon hydrogen supply, both CCUS-enabled and electrolytic production routes are supported.
- **Industry as hydrogen hubs.** Industrial decarbonisation is regarded an important application for low-carbon hydrogen, with the prospect to expand to other hydrogen applications from these hydrogen hubs.

In the United Kingdom, targets for greenhouse gas reduction are legally embedded by the Climate Change Act 2008. In 2019, it passed a law to change its 2050 target to net zero and it recently announced the upward revision of the

[140] In the ENERGIX-programme, hydrogen is one of the prioritised themes for 2021.

2030 target to at least 68% reduction relative to 1990 levels.[141] The Department for Business, Energy & Industrial Strategy (BEIS) leads on hydrogen, energy and climate policies in the United Kingdom government. The Climate Change Act included setting up the Climate Change Committee (CCC), which provides the government with independent advice regarding how to achieve established climate targets, including through energy policy.

The UK hydrogen strategy is expected in early 2021, however the national government has already made its support for hydrogen clear through the Prime Minister's ten-point plan for a green industrial revolution[142] and the energy white paper on a net zero future.[143] In addition, the devolved governments of Wales,[144] Scotland[145] and Northern Ireland[146] have expressed policy support for hydrogen development and are developing hydrogen plans. These recent and forthcoming policy announcements build on earlier research and existing support for hydrogen, its value chain development and its role in a net-zero energy system.[147]

Role(s) assigned to hydrogen

Expressed in the ten-point plan and Energy White Paper are roles for hydrogen in industry, power, residential heating and mobility. In industry, hydrogen can fuel otherwise hard-to-abate processes, serve as feedstock, and help reduction of greenhouse gas emission through application of CCUS.[148] Creation of hubs with concentrated hydrogen demand, CCUS and renewable energy (so called "SuperPlaces") are considered for technological development. Alongside electric options, hydrogen could also assist with decarbonisation of residential heating. Trials are underway and planned for both blending of hydrogen with natural gas on the gas distribution system level, and conversion of distribution systems to pure hydrogen. From a supply side perspective, the United Kingdom is taking a twin track approach, aiming to support both CCUS-enabled and electrolytic production. This approach to policy development will enable production to be brought forward at the necessary scale during the 2020s, to drive investment in

[141] After amendment in 2019, the Climate Change Act 2008 targets 100% net GHG reduction by 2050, relative to 1990 levels (net zero). In December 2020, the 2030 target is increased from the previous 53% reduction target.
[142] HM Government (2020), The Ten Point Plan for a Green Industrial Revolution.
[143] HM Government (2020), The Energy White Paper – Powering our Net Zero Future.
[144] Welsh Government (2020), Written statement: energy statement.
[145] Scottish Government (2020), Scottish Government Hydrogen Policy Statement.
[146] Statement of 10 July 2020 by Economy Minister D. Dodds, Department for the Economy.
[147] For example, this includes CCC research papers such as 'Hydrogen in a low-carbon economy' (2018) or 'Net-zero Technical Report' (2019), and the GBP 100 million 'Low Carbon Hydrogen Production Fund' of the Department of Business, Energy and Industrial Strategy.
[148] The outlines of this are expressed in the ten point plan for a green industrial revolution, with more details expected by the publication of the Industrial Decarbonisation Strategy in spring 2021.

the wider value chain, grow supply chains and build confidence in the sector, while scaling up electrolytic hydrogen. The 2030 levels of electrolytic and fossil coupled with CCUS hydrogen production will depend upon market developments in the 2020s.

Supporting (legacy) factors

Residential heating demand in the United Kingdom is 85% met by natural gas, for which an extensive natural gas distribution grid is present. Following renewal under a safety-driven replacement program,[149] this distribution grid would, to a large extent, be suitable for hydrogen transport. The United Kingdom has a large oil and gas sector, resulting in technological expertise in hydrogen production, handling and applications. There is also knowledge of the North Sea subsurface and extensive CO_2 storage potential found in offshore reservoirs, required for successful deployment of CCUS technologies. In addition, the UK North Sea EEZ provides vast offshore wind power potential, potentially eclipsing domestic power demand. This potential provides a longer-term narrative for electrolytic hydrogen production. The United Kingdom is home to businesses advanced in hydrogen technology which could become competitive in an international hydrogen value chain, with potential strong domestic labour and economic benefits.[150]

Putting plans into practice

The ambition set by the UK government is for 5 GW of low-carbon hydrogen production capacity by 2030. To achieve this, GBP 240 million has been made available in a “Net Zero Hydrogen Fund” through 2025, with further private sector bolstering through a revenue mechanism expected in 2021. A “Hydrogen Neighbourhood” trial is set for 2023, with follow-ups by a “Hydrogen Village” in 2025, and creation of a first Hydrogen Town” set for 2030. This builds on support schemes initiated earlier, including, for example, funds for hydrogen safety testing in residential heating.[151] In addition, hydrogen blending up to 20% for all homes connected to distribution grids will be tested. In the United Kingdom hydrogen has been confirmed as a priority for the GBP 1 billion Net Zero Innovation Portfolio. Hydrogen fuelled heavy-duty vehicles will be supported in freight trials and through procurement of hydrogen buses. In key industrial hubs around the country, CCUS development alongside hydrogen will be promoted. Support for CCUS in these so

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[149] The Iron Mains Replacement Program started in 2002 and aims to replace all cast iron gas mains within 30 metres of property in 30 years.
[150] For example, as identified in Vivideconomics (2019), Energy Innovation Needs Assessment – Sub-theme report Hydrogen & Fuel cells.
[151] For example, BEIS has awarded government funding to development of prototype hydrogen boilers through a Network Innovation Competition to the ‘Hy4Heat’ demonstration project, which is due to conclude in summer 2021.

called “SuperPlaces” is through a GBP 1 billion “CCUS Infrastructure Fund”. This CCUS support, if applied to hydrogen production, also indirectly benefits low carbon hydrogen production.

International (North Sea) prerequisites

The UK-EU trade and co-operation agreement of December 2020 (the “Future Relationship Deal”), recognises strengthening both UK and EU energy and climate ambitions through co-operation and commits to new electricity arrangements and efficient gas and electricity trading.[152] Furthermore, the agreement explicitly mentions the potential and importance of co-operation on renewable energy in the North Sea, opening up the possibility of hybrid interconnectors and offshore windfarms, and development of a North Seas grid. For now, this indicates few trade barriers and hindrances to international co-operation on development of a hydrogen market and the associated international energy flows. However, the agreement is temporary and calls for a new electricity trading agreement by April 2022, and an expiry of the current energy title by June 2026, although it can be reapplied annually by the United Kingdom and the European Union from 30 June 2026 onwards. Though international energy trade and investments are used to changing political realities, this long-term uncertainty should be reduced to bolster investor confidence and benefit from existing and planned interconnections across the North Sea to develop competitive hydrogen supplies.

Collectively building on national strategies

After support for hydrogen in previous periods of interest, by Norway and the United Kingdom among others, all assessed countries have recently revealed, or are close to publication of, hydrogen strategies. The fact that these countries commonly, yet each uniquely, have hydrogen policy support should help deliver on cost reductions and economic viability.

Norway is positioning for a market conversion strategy in which its hydrogen approach is combined with an encompassing CCS strategy (spearheaded by the Northern Lights project) to store CO_2 from exported natural gas, domestic industry and other CO_2 sources in north-western Europe, in its offshore subsurface geological formations or structures as a way forward. Building a full-scale CCS value chain will help move forward several low-carbon hydrogen projects in the region. In addition to Norway, the United Kingdom and the Netherlands are looking

[152] The UK-EU trade and co-operation agreement as agreed upon 24 December 2020 and effective from 1 January 2021.

to develop their own CCS capabilities as part of an integrated CO_2 reduction approach for hard to abate sectors.

In Denmark, the hydrogen value chain will be based on the country's large wind potential, and the need and opportunity to convert electricity into hydrogen to absorb even larger flows of electrons into its energy system. The maturity of its oil industry and associated infrastructure coupled with new built pipeline segments offer possibilities to transport hydrogen in Denmark, but also, once production has grown beyond domestic needs, to export hydrogen to neighbouring countries. A similar strategy might work for the UK, although most of its domestic supply will be absorbed in the home market.

Though the North Sea is only a part of the United Kingdom's EEZ, the combination of favourable circumstances for low-carbon hydrogen production, existing infrastructure and neighbouring markets makes it attractive to start hydrogen developments there. Opportunities for partnerships lie not only in potential reuse of existing oil and gas infrastructure, but also in industry knowledge related to, for example, residential hydrogen heating systems.

Potential hydrogen demand is large in Germany, and may become the vehicle that brings offshore wind to inland and more southern domestic markets, supplying Germany's strong manufacturing industry with renewable energy. These industries will want to be part of the expected innovations in energy and process technologies. In addition to domestic supplies, Germany is expected to need large import volumes, both from neighbouring countries and, further in the future, from beyond north-western Europe. The German hydrogen strategy covers both domestic hydrogen value chains and imports. Its success will thus in part rely on the realisation of sufficient hydrogen infrastructure in the region and on collaboration with other countries, for example in the framework of the 'IPCEI on Hydrogen' launched under the Germany Presidency of the European Council.

For France, an opportunity lies in increased use of domestically produced energy in sectors that are now still reliant on imported carbon-based fuels, since the electricity sector is already largely decarbonised, while substantial renewable energy potential remains throughout the country and offshore. In the process, this opportunity enables French manufacturing industries to innovate and compete in future markets for products including cars, trucks and aeroplanes.

Offshore wind potential, the maturity of the offshore oil and gas sector and offshore pipelines, and an energy intense industry are amongst the driving forces behind the adoption of low-carbon hydrogen in the Netherlands. Early repurposing of parts of the Netherlands existing extensive natural gas grid and some new dedicated hydrogen infrastructure can connect not only domestic industrial hubs, but also inland hubs in neighbouring countries. Energy trades are longstanding between Belgium and the Netherlands, and Belgian parties have joined Dutch efforts to develop offshore CCS, while also developing Belgium's own hydrogen projects near its industrial hubs. Moreover, both countries are also aiming to develop a renewable hydrogen import value chain.

Hurdles to overcome

Funding for the different national hydrogen strategies in north-western Europe varies in size and scope. Some strategies emphasize stimulating production, some value chain development, some generation of demand and some integral developments. The recent surge in hydrogen project proposals and Front-End Engineering and Design (FEED) studies demonstrate investor interest to act on these strategies, even if the business models are partly unclear. Emergence of merchant low-carbon hydrogen that can be traded in the region could be a signal that low-carbon hydrogen developments have moved beyond the current dedicated industrial use market. The realisation of such new markets, however, will require the development and adoption of standards for various low-carbon hydrogen technologies, ones that do not serve specific domestic preferences. Moreover, some attention should be given to national and European regulations on state aid related to decarbonisation efforts, where the availability of sufficient renewable energy supplies may not grow in line with hydrogen demand or available infrastructures in the early stages of the ramp up. The commoditisation of low-carbon hydrogen is important for the market to develop.

The hydrogen strategies are based on the various countries' unique locational benefits. Collaboration can help address transition issues and barriers among the countries. For instance, where to best locate hydrogen hubs and how to interconnect them to other demand centres. Moreover, current strategies focus largely on national deployment and could benefit from joint efforts to connect the plans early to leverage public support across all countries.

Next steps in regional discussions

Countries in north-western Europe are at the forefront of hydrogen technology and policy development. These countries have made significant progress at a national level and have developed their vision about the role that hydrogen should play in their long-term energy strategies and their ambitions to transform their respective energy systems. These visions have many elements in common and complementarities, suggesting that a common regional long-term vision for low-carbon hydrogen could benefit the strengths and help address the weaknesses of individual country visions.

Some activities have been triggered with the purpose of developing this common approach to hydrogen, including the Joint Political Declaration of the Pentalateral Energy Forum or the "*Roundtable on the North-West European Region*" of the Clean Energy Ministerial Hydrogen Initiative.[153,154] From the analysis in this report, CIEP and the IEA have distilled four priorities to address in the regional dialogue to accelerate developments:

Build on the large unused potential to co-operate on hydrogen in the north-western European region.

There is a huge untapped potential for international co-operation in the region. From the national strategies and ambitions, we learn which countries want to develop both domestic capacities and imports (Belgium, Germany, Netherlands and the United Kingdom), while other countries seek to expand their domestic capacity and exports to neighbouring markets (Norway, Denmark). Successful achievement of national hydrogen ambitions will depend to a large extent on successful developments from other countries in the region. For example, the projected large demand for imported hydrogen in Germany before 2030 aligns with the export potential and ambitions of Norway and Denmark (and France if its national target for electrolysis deployment is met).

With some exceptions, such as of the North Sea Wind Power Hub project and some collaborations in IPCEI on hydrogen, there few cross-border initiatives. Governments should more intensively explore opportunities for intergovernmental co-operation and with industry to make optimal use of available instruments and

[153] Joint political declaration of the Pentalateral Energy Forum on the role of hydrogen to decarbonise the energy system in Europe.
[154] Clean Energy Ministerial Hydrogen Initiative.

policy tools (such as TEN-E, IPCEI or Connecting Europe Facility) to help develop cross-border projects. In cross border projects, co-financing projects using public funding could assist in launching these projects and create leverage for national investments in value chain development.

Identify what is needed to develop an integrated regional market.

This region leads the thought and planning for creation of an integrated market, but it is a challenging endeavour involving the agreement of several jurisdictions. Creating cross-border projects that develop supply, demand and infrastructure is a first step, but will not be enough to spawn a fully integrated regional market. Collaboration should extend beyond these projects to find a common basis for the development of a regulatory framework. Although national hydrogen strategies have only been recently announced and many of the instrumentation discussions are still ongoing, co-operation among governments are an opportunity to share strategies and lessons learned to address regulatory issues, standards and certificates and to help investments in the value chain.

Progress on this regulatory framework is fundamental to the development of interconnections between countries, which together with building storage capacities, are key elements for a full hydrogen value chain to emerge and to link production with demand. Governments can lead the way by ensuring that the hydrogen infrastructure will be available on time, creating certainty for companies developing these new value chains as a first step towards an integrated market.

Develop supporting schemes with a holistic view of the hydrogen value chain.

Tapping into the full potential of hydrogen as a clean energy vector will require both the large-scale deployment of low-carbon hydrogen production and build up demands through adoption of hydrogen in new applications in the region. This requires significant public support, and it is important to find the most efficient way for these investments to deliver "value-for-money" and capture the potential synergies and complementarities unlocked by regional co-operation. Development of a hydrogen supply in some countries partially depends on a creation of demand in others. Some countries have several projects ready to be deployed but not enough public support is yet in place, while others have significant funding available but a limited number of projects ready to be implemented.

The foreseen public support in the region, when defined and regionally calibrated, could benefit from a holistic view of the supply chains to ensure that it develops coherently. It should stimulate demand, support low-carbon supply, develop the required infrastructure and ensure that enough manufacturing capacity of key technologies (electrolysers, fuel cells or HRS) are in place. Regional co-operation can help to identify strengths and weaknesses across the countries in the region and help develop balanced value chains.

Identify best opportunities to simultaneously decarbonise current hydrogen production and deploy additional low-carbon supply.

Meeting the climate and energy targets of the region will require a dual approach to secure low-carbon hydrogen production. It is important to simultaneously replace current production capacities (which, to a large extent, will remain in place by 2030) with low-carbon supply and deploy new low-carbon production capacity to respond to new demands, which are likely to grow. Regional co-operation can help to identify the best opportunities to decarbonise current hydrogen production, which is concentrated in industrial hubs (some of which are in or close to border areas) while simultaneously identifying the best geographical areas in which to deploy new low-cost and low-carbon hydrogen production. This will be fundamental to minimise the cost impact on the final users and facilitate widespread adoption of new hydrogen technologies.

Conclusion

Over the years, north-western Europe has developed a strong industrial complex where hydrogen plays a significant role as an industrial feedstock. Currently, the hydrogen sector in this region could be on the edge of an unprecedented transformation driven by growing governmental ambitions for GHG emissions reduction. This transformation in the north-western European region is fundamental to the achievement of EU Hydrogen Strategy targets.

This region concentrates 60% of European current hydrogen demand. Moreover, it is home to the largest industrial clusters in Europe, from which much of this demand originates and has a well-developed gas infrastructure connecting these clusters to the largest ports in the region. The expected decline of the role of natural gas in this region offers a significant opportunity to repurpose its infrastructure to transport hydrogen and facilitate developing an integrated market. Additionally, the North Sea has an unparalleled potential for offshore wind and the geological sequestration of CO_2, while the region has an enormous potential for underground hydrogen storage. This combination of factors results in a tremendous opportunity to develop a large-scale, low-carbon hydrogen value chain.

However, the extent and pace of this transformation will depend on factors such as lowering the production costs of low-carbon hydrogen, the deployment of large-scale production of low-carbon hydrogen technologies, the realisation of connecting infrastructures, storages and the stimulation of demand in new applications; which in turn will strongly depend upon the adoption of supportive government policies.

The current policy landscape can create some momentum for this transformation approaching 2030. Under our Baseline scenario, hydrogen demand in the region will drop slightly from today's level, but a shift towards new applications in industry and mobility is expected, resulting in a new annual demand around 400 kt H_2 per year by 2030. However, current policies are not enough to ensure that this region taps into the full potential of hydrogen as an enabler of the energy and climate targets by 2030. Without further action, hydrogen production will remain based predominantly on unabated fossil fuels, accounting for 85% of dedicated production by 2030. The contribution from low-carbon production technologies increases only slightly as most projects in the pipeline struggle to reach FID. As a result, national targets and ambitions for low-carbon hydrogen production deployment in some countries within the region (France, Germany, the Netherlands and the United Kingdom) will not be met.

Successful implementation of supporting policies that are in line with the more ambitious climate and energy targets defined by the EU Green Deal or the UK Climate Change Act can drive a faster transformation. In our Accelerated scenario, total hydrogen demand in the region could grow by a third, reaching more than 8.5 Mt per year by 2030, and driven by hydrogen adoption in new industrial applications and mobility, but also in grid injection, heat or power generation. Moreover, a significant shift would happen in hydrogen production due to the deployment of the full existing pipeline of projects. More than half of the dedicated hydrogen production could come from low-carbon hydrogen technologies due to their successful deployment. Moreover, if the number and capacity of projects grow in tandem with national targets and ambitions for low-carbon hydrogen production, this contribution could reach two thirds of the total supply.

There are significant differences within the potential evolution of hydrogen demand and supply between countries in the region. Some countries show strong potential to expand hydrogen demand to new applications by 2030 but could find it difficult to meet this demand through national expansion of low-carbon hydrogen production. At the same time, other countries with more limited possibilities for new hydrogen demands show tremendous potential to expand low-carbon production capacity. This creates an opportunity for co-operation at a regional level, finding synergies and building on the best opportunities and complementarities across the region. Such co-operation would require development of an integrated hydrogen market and a supporting the creation regional infrastructure able to link production centres with final users, aiming to harness those countries with a potential to develop production capacities that exceed their national demand.

From the country strategies, we begin to recognise that decarbonisation based on electricity alone is difficult to achieve, and must be aided by a molecular energy carrier such as hydrogen for hard-to-abate emissions and efficient energy transport and storage and market balancing. Most countries also recognise the importance of feedstock decarbonisation using hydrogen and the potential for hydrogen to become an international tradeable commodity. Initiatives to repurpose natural gas pipeline networks (both transmission and distribution networks) at the EU level but also at the national level are on the agenda. Recognising catalyst opportunities in industry, in the slip stream hydrogen can be developed for new applications in mobility, power, steel making and low temperature heating where other technologies are sometimes harder to apply.

North-western European countries have already made significant progress developing their vision for the role that hydrogen should play in their long-term energy strategies. With their visions already defined, these countries face the next challenge of moving beyond the national discussions to establish a regional dialogue, which seems an indispensable condition in order to develop the fully integrated hydrogen market that the region needs. It is with the aim to inform this dialogue, that the IEA and CIEP have defined four priorities:

- Build on the large unused potential to co-operate on hydrogen in the north-western European region.
- Identify what is needed to develop an integrated regional market.
- Develop supporting schemes with a holistic view of the hydrogen value chain.
- Identify the best opportunities to simultaneously decarbonise current hydrogen production and deploy additional low-carbon supply.

Annex

Pipeline of low-carbon hydrogen production projects

Belgium

Name	Year	Technology	Size	Status
HRS CMB Port of Antwerp	2021	Electrolysis	1 MW	Under Construction
Hyoffwind Zeebrugge, 1st phase	2023	Electrolysis	25 MW	FID
Hyport, 1st phase	2025	Electrolysis	50 MW	FID
Hyoffwind Zeebrugge, 2nd phase	2030	Electrolysis	1000 MW	Feasibility study
Power-to-Methanol Antwerp	2023 2030	Electrolysis	100 MW	Feasibility study
North CCU HUB, North-C Methanol Demo plant	2024	Electrolysis	63 MW	Feasibility study
Wallonia e-methane project	2025	Electrolysis	75 MW	Feasibility study
North CCU HUB, 2nd phase, North-C full scale	2028	Electrolysis	300 MW	Concept
North CCU HUB, 3rd phase	2030	Electrolysis	600 MW	Concept
Hyport, 2nd phase	2030	Electrolysis	300 MW	Concept

Denmark

Name	Year	Technology	Size	Status
H2RES – Orsted offshore wind	2021	Electrolysis	2 MW	FID
GreenLab Skive	2022	Electrolysis	12 MW	Under construction
HySynergy, 1st phase	2022	Electrolysis	20 MW	Under construction

Name	Year	Technology	Size	Status
AP Moller-Maersk-SAS-DSV Panalpina-DFDS-Copenhagen Airports-Orsted,	2023 2030	Electrolysis	1300 MW	Feasibility study
HySynergy, 2nd phase	2030	Electrolysis	1000 MW	Feasibility study
FUTURECEM		Electrolysis	100 MW	Concept

France

Name	Year	Technology	Size	Status
Hyport - Toulouse-Blagnac Airport	2021	Electrolysis	1.4 MW	FID
HyAMMED HD trucks refuelling station	2022	Electrolysis	2.1 MW	FID
Total's La Mède biorefinery	2024	Electrolysis	40 MW	FID
H2V Normandy	2022 2023	Electrolysis	200 MW	Feasibility study
H2V59	2022 2023	Electrolysis	200 MW	Feasibility study
Hygreen Provence	2025 2027	Electrolysis	435 MW	Concept
NEL-Lhyfe Agreement		Electrolysis	60 MW	FID

Germany

Name	Year	Technology	Size	Status
PtG-Fehndorf	2021	Electrolysis	2 MW	Under construction
Refhyne	2021	Electrolysis	10 MW	Under construction
Wunsiedel Energy Park, 1st phase	2022	Electrolysis	6 MW	Under construction
Linde Leuna Chemical Complex	2022	Electrolysis	24 MW	FID
SALCOS Salzgitter Clean Hydrogen project	2022	Electrolysis	2.2 MW	Feasibility study

	Name	Year	Technology	Size
RWE-Thyssenkrupp Duisburg steel plant	2022	Electrolysis	100 MW	Feasibility study
Element Eins	2022	Electrolysis	100 MW	Feasibility study
Bad Lauchstädt energy park	2022	Electrolysis	35 MW	Feasibility study
Westkuste 100, phase 1	2023	Electrolysis	30 MW	Feasibility study
Hybridge	2023	Electrolysis	100 MW	Feasibility study
Get H2 Nukleus	2023	Electrolysis	100 MW	Feasibility study
GreenHydroChem Central German Chemical Triangle	2024	Electrolysis	120 MW	Feasibility study
Lingen BP Refinery	2024	Electrolysis	50 MW	Feasibility study
Vattenfall's Moorburg plant	2025	Electrolysis	100 MW	Feasibility study
H2morrow	2030	SMR with CCS	256 kt H_2/y	Concept
Get H2 Lingen		Electrolysis	100 MW	Feasibility study
HySynGas		Electrolysis	50 MW	Feasibility study
STEAG-Thyssenkrupp Duisburg steel plant		Electrolysis	500 MW	Feasibility study
Westkuste 100, phase 2		Electrolysis	670 MW	Feasibility study

The Netherlands

Name	Year	Technology	Size	Status
H2GO, 1st phase	2021	Electrolysis	2.5 MW	Under construction
Duwaal	2021	Electrolysis	2 MW	Under construction
Hysolar Green on Road	2021	Electrolysis	2 MW	Under construction
Hydrogenpilot Oosterwolde	2021	Electrolysis	1 MW	Under construction
GreenH2UB (1st hub)	2021	Electrolysis	3 MW	Under construction
Alliander Oosterwolde	2021	Electrolysis	1.4 MW	Under construction
Multiphly	2022	Electrolysis	2.6 MW	FID
Hollandse Kust (noord)	2023	Electrolysis	200 MW	FID
GZI next	2022	Electrolysis	10 MW	Feasibility study

Name	Year	Technology	Size	Status
DJEWELS Chemiepark	2022 2023	Electrolysis	100 MW	Feasibility study
H_2 Air Base Leeuwarden	2022	Electrolysis	5 MW	Feasibility study
GldH2	2023	Electrolysis	1 MW	Feasibility study
H2ermes	2023	Electrolysis	100 MW	Feasibility study
Centrale Vlissingen	2023	Electrolysis	25 MW	Feasibility study
HyNetherlands	2023 2028	Electrolysis	1000 MW	Feasibility study
Deltaurus 1	2024	Electrolysis	150 MW	Feasibility study
H2.50	2025	Electrolysis	250 MW	Feasibility study
Curthyl	2025	Electrolysis	100 MW	Feasibility study
Yara Sluiskil	2025	Electrolysis	100 MW	Feasibility study
Maasvlakte	2025	Electrolysis	100 MW	Feasibility study
H-Vision	2026 2030	ATR with CCS	300 kt H_2/y	Feasibility study
Deltaurus 3	2027	Electrolysis	700 MW	Feasibility study
H2M	2027	NG with CCUS	294 kt H_2/y	Feasibility study
NortH2, 1st phase	2027 2030	Electrolysis	3000 MW	Feasibility study
GreenH2UB (9 hubs)	2030	Electrolysis	27-90 MW	Feasibility study
H2GO, 2nd phase		Electrolysis	26 MW	Concept
Hydrogen Delta - Zeeland		Electrolysis	900 MW	Feasibility study
Westereems Wind Farm		Electrolysis	100 MW	Feasibility study
Hemweg hub Amsterdam		Electrolysis	100 MW	Feasibility study

Norway

Name	Year	Technology	Size	Status
HAEOLUS	2020	Electrolysis	2.5 MW	Under construction
Carbon Recycling International methanol plan	2023	Electrolysis	110 MW	Feasibility study
Statkraft-CELSA-Mo green H_2 for steel production	2023	Electrolysis	40-50 MW	Feasibility study

Name	Year	Technology	Size	Status
Green fertilizer project Porsgrunn, 1st phase	2023	Electrolysis	5 MW	Feasibility study
Kvinnherad Power-to-Gas	2023	Electrolysis	30-60 MW	Feasibility study
Norsk-E fuel	2023	Electrolysis	22 MW	Feasibility study
HyDEMO	2025	SMR with CCS	218 kt H_2/y	Feasibility study
Green fertilizer project Porsgrunn, 2nd phase		Electrolysis	20 MW	Feasibility study
Glomfjord Hydrogen AS		Electrolysis	2 MW	Feasibility study

United Kingdom

Name	Year	Technology	Size	Status
Northern Irish hydrogen project	2021	Electrolysis	1 MW	Under construction
Tyseley Energy Park refuelling hub	2021	Electrolysis	3 MW	FID
Green Hydrogen for Glasgow	2022	Electrolysis	10 MW	Feasibility study
Hynet Northwest	2025 2030	ATR with CCS	900 kt H_2/y	Feasibility study
H2H Saltend	2026	ATR with CCS	150 kt H_2/y	Feasibility study
Gigastack-Hornsea 2		Electrolysis	100 MW	Feasibility study
Centurion		Electrolysis	100 MW	Feasibility study

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H2 HYDROGEN
CLEAN ENERGY