Institute of Energy Economics at the University of Cologne
Exploring energy markets – enhancing decisions.

EWI STUDY

Hydrogen cluster Belgium, the Netherlands, and North-Western Germany

A projection and analysis of demand and production until 2030

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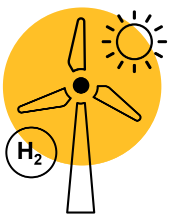
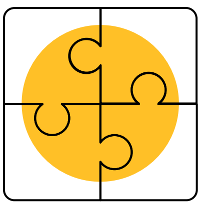
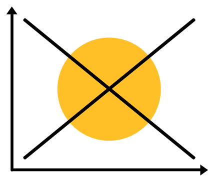
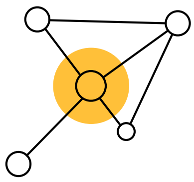
On behalf of Gesellschaft zur Förderung des Energiewirtschaftlichen Instituts an der Universität zu Köln e. V.









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Executive Summary

Phasing-out the use of unabated fossil fuels is one of the most urgent economic, social, and political challenges of the upcoming years. While direct electrification is an option to decarbonize a wide range of applications, low-carbon hydrogen will be required to tackle the emissions of sectors where electrification is not economically efficient or technically feasible. The chemical industry, primary steel production, or heavy-duty transport are primary examples of applications.

The region under study is of particular interest in the phase of the hydrogen market ramp-up since a hydrogen cluster has already been formed here today. Hydrogen clusters are characterized by a strong spatial concentration of production, distribution and demand and thus form a model region for a market ramp-up of hydrogen. This has many advantages for participating companies, authorities, and institutions since close cooperation creates network effects and synergies that can promote the development of a hydrogen economy.

The North Sea coastal region of mainland Europe—referring to Belgium, the Netherlands, and North-Western Germany—has a population of more than 60 million people and has several clusters of heavy industries. It is considered the center of the European chemical industry, has numerous large-scale industries such as steel mills and refineries, and has an extensive natural gas infrastructure. Today, the region consumes about one fifth of the conventional hydrogen produced in Europe. The resulting CO_2 emissions could be reduced by using low-carbon hydrogen from electrolysis ('green') or fossil-based hydrogen with carbon capture and storage ('blue'). High potentials for onshore and offshore wind production favour the production of green hydrogen, whereas abundant depleted offshore gas fields create the possibility for blue hydrogen projects. These conditions could allow the region to serve as a nucleus for the development of a large-scale, cross-border hydrogen network and market.

This study investigates the development of the region until the year 2030, conducting a bottom-up analysis of today's conventional hydrogen demand and a projection of future low-carbon hydrogen demand. Using different penetration rates for low-carbon hydrogen in the industry (ammonia, methanol, mineral oil refining, and steel production) and the transport sector (local public buses and heavy-duty transport) total low-carbon hydrogen demand in 2030 is estimated for a low and a high demand scenario in a high spatial resolution (NUTS 3). The potential future production capacity of low-carbon hydrogen is estimated through a review of operating, planned, and announced hydrogen projects within the region and by quantifying the amount of hydrogen produced as a by-product of chlor-alkali electrolysis.

For 2030, the region is projected to have a total low-carbon hydrogen demand of 25 TWh in the *low demand* and 50 TWh in the *high demand scenario*. Total production capacity amounts to 39 TWh in both scenarios. Hence, the region is self-sufficient in the low demand scenario. In the high demand scenario, additional projects would have to be commissioned, or, alternatively, low-carbon hydrogen has to be imported. The spatial analysis reveals that within the broader region, significant imbalances exist at the local (NUTS 3) level: low-carbon hydrogen demand is highly concentrated at large chemical plants and steel mills, whereas planned production facilities are more dispersed and situated mainly along the coast. Furthermore, imbalances between countries also exist, with the Netherlands showing a potential production surplus and Belgium as well as Germany having a supply shortage. These imbalances could be resolved through the development of a cross-border hydrogen network, which could simultaneously serve as the basis for a transnational hydrogen market.

A substantial share of the projected production capacity in the region is based on a few large-scale hydrogen production projects planned in the region. Hence, the realization of these projects will be a decisive factor in determining the total amount of low-carbon hydrogen production capacity available by 2030. Furthermore, it is unclear whether supply shortages up to 2030 can be offset by imports of low-carbon hydrogen. In the longer-term, the potential to directly import hydrogen-derived products, such as low-carbon ammonia or methanol, could put incumbent producers under pressure, potentially reducing the demand for pure hydrogen by these industries.

During the market ramp-up, security of supply plays a central role. Not only is a hydrogen network needed that connects hydrogen production and consumption, but also hydrogen storage. Especially for green hydrogen, a steady production cannot be guaranteed due to meteorological impacts. Further action is needed, particularly to reduce these uncertainties in order to incentivize more investments and bring companies to move planned projects to the final investment decision (FID) stage. Transnational initiatives, cross-border legislation, and information on supply and demand potentials could improve the investment environment and support the development of a large-scale low-carbon hydrogen supply chain in the region.

1 Introduction

Governments and corporations around the globe are seeking to push the decarbonization of energy systems forward using hydrogen. The benefits of hydrogen as an energy carrier have previously been highlighted in many studies, policy briefs, press statements, and public strategies. Hydrogen acts as an ideal element for sector-coupling and decarbonization through its broad range of potential end-use applications and low emission to emission-free production options. While conventional ('grey') hydrogen from fossil fuels is currently used as a feedstock in the (petro-)chemical industry, future applications envisage producing the gas using low or emission-free technologies. These are water electrolysis with electricity from renewable energy sources (RES; 'green'), steam methane reforming (SMR) with carbon capture and storage (CCS; 'blue'), or pyrolysis of hydrocarbons with the extraction of solid carbon ('turquoise'). Such low-carbon hydrogen projects are currently mostly at the demonstration or pilot stage, but commercialization and scaling up are getting started.

Figure 1: The region of Belgium, the Netherlands and North-Western Germany studied in this report

Source: Own illustration

In the early stage of a hydrogen market ramp-up, stakeholders expect that initially, local clusters with closed supply chains for low-carbon hydrogen will develop. These clusters will most likely emerge around large low-carbon hydrogen consumers, such as industrial plants, and close to favorable production locations. Gradually, the clusters will be connected by pipelines to form a growing hydrogen network (Schlund et al., 2021). Within this network, hydrogen supply and demand will be balanced to create the basis for a hydrogen market.

The North Sea coastal region of mainland Europe (Belgium, the Netherlands, and North-Western Germany with the federal states of North Rhine-Westphalia, Bremen, Hamburg, Lower Saxony, and Schleswig-Holstein (Figure 1)) represents a suitable area to form a nucleus for such a trans-regional pipeline grid and basis for a hydrogen market, due to several reasons. The region is home to large industrial clusters with substantial energy demand, high CO_2-emissions, and accordingly large decarbonization potentials through the utilization of low-carbon hydrogen. The distances between the clusters are appropriate for establishing a hydrogen pipeline network at reasonable costs, for example, by repurposing existing natural gas pipelines. Furthermore, regional low-carbon hydrogen production potentials are significant for both RES (particularly onshore and offshore wind) with electrolysis as well as SMR using depleted offshore gas fields as CO_2 storages. Numerous projects to produce low-carbon hydrogen are currently planned in the region, using different technologies and targeting different end-use purposes. Furthermore, the region is home to Europe's largest ports, such as Rotterdam, Antwerp, and Hamburg, which could potentially serve as hubs for the seaborne import of hydrogen or hydrogen-based synthetic energy carriers.

The region's potential of being a front-runner in developing a low-carbon hydrogen market has been acknowledged by a range of publications (e.g., Agora, 2021; IEA, 2021; Gas for Climate, 2020) as well as political and private initiatives. They strive to raise the potential and develop a cross-border pipeline network (e.g., PG, 2020; DECHEMA, 2020). This study aims to analyze the region of Belgium, the Netherlands, and North-Western Germany with respect to the potential for a low-carbon hydrogen cluster. For this purpose, detailed and spatially resolved supply and demand projections are calculated.

In this study, a bottom-up estimation of current hydrogen demand in the region is performed. It is assumed that until 2030, an increasing share of this hydrogen demand is supplied by low-carbon hydrogen. Additional demand for low-carbon hydrogen will arise from the steel industry, with plans to switch to hydrogen-based Direct Reduction of Iron Ore (DRI) in several of the region's steel mills. In the transport sector, an increasing share of heavy-duty vehicles (HDV) and public busses in local transport are likely to be fueled by low-carbon hydrogen as well. To assess the low-carbon hydrogen production capacities in the region, operating, planned, and announced low-carbon hydrogen projects are reviewed, including their installed production capacity and location. The European Hydrogen Backbone, an aspirational hydrogen pipeline network proposed by 23 European gas transmission system operators (TSOs) (Gas for Climate 2020), is overlayed to evaluate the potential role of such a network in linking production to consumption hubs.

2 Political strategies for low-carbon hydrogen

Political support for low-carbon hydrogen is often guided by official hydrogen strategies and roadmaps. In the region covered by this study, the Netherlands and Germany have issued official national hydrogen strategies, while in Belgium, strategies exist only on the regional level or published by industry-led initiatives. The following comparison refers to the Dutch hydrogen strategy published in 2019 (Government of the Netherlands, 2019) and the German hydrogen strategy from 2020 (BMWi, 2020). Table 1 presents an overview of key elements of the hydrogen strategies of the respective countries and regions.

Table 1: Summary of political hydrogen strategies for the Netherlands and Germany

Sources: BMWi (2020), Government of the Netherlands (2019); Van den Broeck et al. (2020), WEC LBST (2020) and Lambert et al., 2021

	The Netherlands	Germany
Supported type of hydrogen	Green and blue	Green
Planned electrolysis capacity [GW] and hydrogen production [TWh] by 2030	4 GW 15 TWh	5 GW 19 TWh
Import, export, or national production	National production, import, and role as energy hub	National production and import
Main targeted sectors	*Industry*: refineries, high temperature heat; *Transport*: aviation, shipping, busses, and trucks; *Power*	*Industry*: chemicals, refineries, and steel; *Transport*: aviation and shipping, busses, trucks
H_2 Transport strategy	Blending with natural gas grid, dedicated hydrogen grid, partially through repurposing	Blending with natural gas grid, dedicated hydrogen grid, partially through repurposing
Government support for H_2 strategies	Mainly R&D, regulatory and financial support	Mainly R&D, financial and governance support

2.1 Belgium

In 2020 the Belgian Integrated National Energy and Climate Plan 2021-2030 (ENCP Plan) was published by the European Commission discussing hydrogen utilization in Belgium until 2030 in general without defining specific targets for hydrogen production and usage (EC, 2020). The Belgian government has not yet published an official hydrogen strategy for the country, but several regional and private initiatives have issued hydrogen roadmaps, visions, or opinion papers (IEA, 2021).

For instance, an industry-led consortium published a hydrogen strategy for the Flanders region, suggesting a total installed electrolysis capacity of 550 MW in 2030, addressing hydrogen utilization in industry, transport, heating, and the power sector (Van den Broeck et al., 2020). The ministry of innovation of the Flanders region has also published a hydrogen vision envisaging to establish the region as the European leader in hydrogen technology (VARIO, 2020). For the

Wallonia region, an industrial consortium has published a hydrogen roadmap, setting capacity and sectoral demand targets for 2030 and 2050 (TWEED, 2018).

2.2 The Netherlands

For 2030, the Dutch national climate agreement (Government of the Netherlands, 2019) targets a greenhouse gas (GHG) emission reduction of 49 % against 1990 levels, focusing on decarbonizing the industry and transport sectors (WEC LBST, 2020). Furthermore, the agreement declares a hydrogen demand of 35 to 58 TWh for industrial applications in the coastal regions and between 7 and 11 TWh in the industrial region of Chemelot. Over 800 MW electrolysis capacity are planned to be built by 2025. In addition, the program aims to realize the establishment of 3 to 4 GW of capacity by 2030.

The Dutch Government supports green and blue hydrogen projects. Hereby, the priority is green hydrogen, which is complemented by blue hydrogen to develop a national hydrogen industry. Deployment is already moving forward, with notable examples such as "NortH2", which plans to provide 3 to 4 GW of hydrogen production with offshore wind by 2030, and "Porthos", which is a large-scale CCS project in the Rotterdam area and planned to start production in 2023 (Lambert et al., 2021; Porthos, 2021).

The Northern Netherlands Hydrogen Investment Plan 2020 (PG, 2020) has proposed the following policy changes to promote green hydrogen production in the Netherlands. First, a supportive framework that requires green hydrogen to be produced using electricity from additional rather than existing renewable energy capacity. Second, to accelerate the scale-up, the Dutch government supports green hydrogen projects financially. Third, the investment plan envisages supporting the technical development of critical infrastructure required to operate a hydrogen economy, e.g., hydrogen pipelines and storage facilities. It was decided to implement mandates to accelerate green rather than grey hydrogen distribution in end-use applications.

2.3 Germany

The German Federal Ministry for Economic Affairs and Energy published the National Hydrogen Strategy in June 2020 (BMWi, 2020). The strategy assumes a current hydrogen consumption of 55 TWh for Germany – supplied mainly through SMR and to a small extent as a by-product of chlor-alkali electrolysis. The government projects the future demand to be between 90 and 110 TWh by 2030. Until 2050, this demand could increase significantly, with the National Hydrogen Strategy providing an estimated range of 110 to 380 TWh. Besides the national strategy, several hydrogen strategies for individual federal states or regions exist, e.g., the Hydrogen Roadmap North Rhine-Westphalia (MWIDE NRW, 2020), or the Hydrogen Strategy of North Germany for the states Bremen, Hamburg, Mecklenburg-Western Pomerania, Lower Saxony, and Schleswig-Holstein (NDWS, 2019).

The German National Hydrogen Strategy (BMWi, 2020) set a target of 5 GW of electrolysis capacity by 2030, which corresponds to an annual production of 14 TWh hydrogen[1] by water electrolysis, assuming an average of 4.000 full load hours and 70 % efficiency for the electrolyzers. A further 5 GW expansion is planned by 2040 at the latest.

The strategy further declares that the German government supports green hydrogen as the only long-term hydrogen option for decarbonization. While clearly defined commitments remain to be made, the German government plans to support hydrogen pilot projects through strategic investment grants and plans to introduce levy, tax, and surcharge exemptions for RES-based electrolysis.

According to the strategy, hydrogen will be used mostly in the industrial sector (mainly chemical industry, refineries, and steel production) and far less in the transport sector. It is not further specified to what extent this demand is to be met by low-carbon hydrogen (BMWi, 2020).

3 Determining current hydrogen demand and future low-carbon hydrogen production

The analysis builds upon three pillars: hydrogen demand, supply, and infrastructure, as illustrated in Figure 2. Historic demand is calculated through a bottom-up analysis of current hydrogen consumers. Potential new hydrogen consumers in the industry and transport sector are considered and analyzed accordingly. For the estimation of future demand for low-carbon hydrogen, end-use specific low-carbon hydrogen penetration rates are assumed. Low-carbon hydrogen production capacities are assumed to come from by-product hydrogen from chlor-alkali electrolysis in the industry sector and dedicated low-carbon hydrogen projects in the investigated region. Any unserved hydrogen demand is either implicitly supplied by existing conventional hydrogen

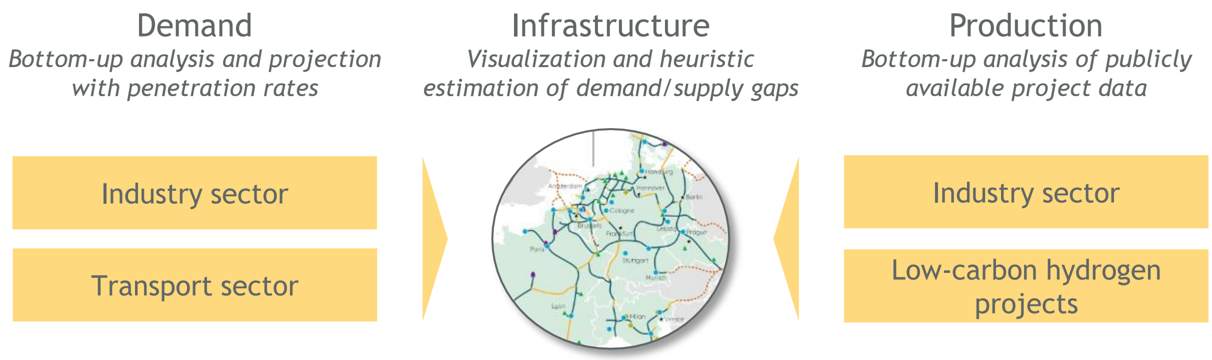


Figure 2: Methodology outline for the demand, supply, and infrastructure analysis

Sources: Own illustration and Gas for Climate (2020)

[1] In July 2021, the German Federal Minister of Economic Affairs and Energy Peter Altmaier announced an increase in the electricity consumption forecast for 2030 combined with increased hydrogen production of 19 TWh.

production or remains as a supply gap. Hydrogen demand and production data are spatially allocated to Nomenclature des Unités Territoriales Statistiques (NUTS) 3 regions[2], either by the location of facilities or by using adequate distribution keys, e.g., statistics on registered vehicles, freight traffic volume and population distribution. Regional low-carbon hydrogen demand and supply imbalances can be resolved by connecting consumption and production centers through pipelines. The European Hydrogen Backbone, proposed by the initiative Gas for Climate in 2020, updated in 2021, is used as a basis to assess the potential for inter-regional balancing.

The following sections describe the bottom-up analysis of hydrogen demand of industry and transport in more detail.

3.1 Hydrogen Demand

The study covers Belgium, the Netherlands, and North-Western Germany.[3] In order to determine the demand for hydrogen, plant locations, output quantities, company details, and other relevant information of all considered industries within this region are reviewed, as shown by the overview in Figure 3. These industries, cover the most relevant hydrogen consuming processes, which are predominantly using grey hydrogen: Mineral oil refining, ammonia, and methanol production. These three industries account for most of the current hydrogen demand (dena, 2016; Fraunhofer IEG, ISI, ISE, 2021).

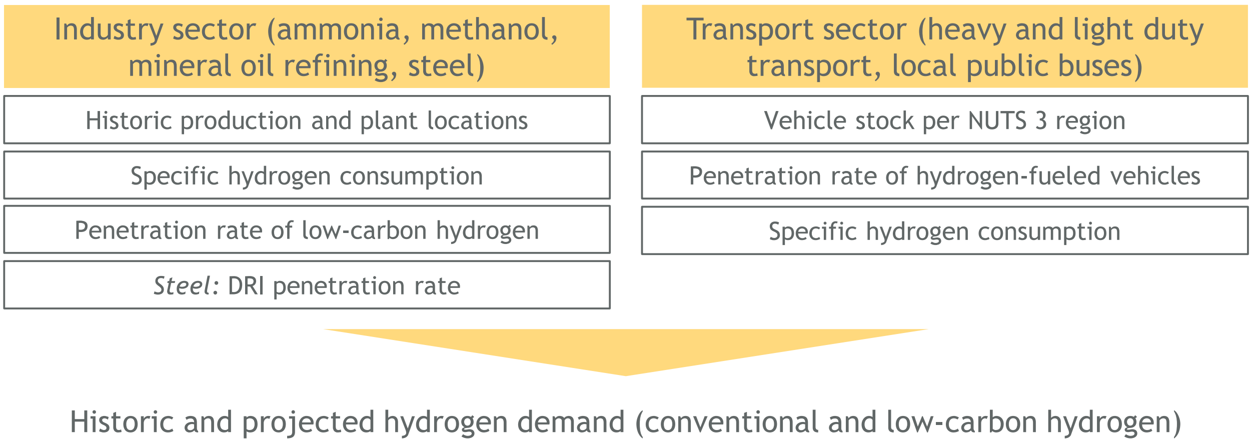


Figure 3: Overview of bottom-up hydrogen demand analysis

Source: Own illustration

To determine the future demand for low-carbon hydrogen, it is necessary to identify potential new consumption industries and sectors. In the industry sector, demand is expected to result from the shift to DRI in primary steel production. Also, HDV and local public transport are assumed to

[2] NUTS classifies geographical areas and regions within the European Union for the purpose of statistical analysis. NUTS 3 is the lowest hierarchical level with populations between 150,000 and 800,000 and corresponds in Germany to administrative districts and independent cities. In this study, NUTS 3 code projection 2021 is used from Eurostat database.

[3] In Germany, the following federal states are considered: Bremen, Hamburg, Lower Saxony, North Rhine-Westphalia, and Schleswig-Holstein.

generate considerable demand for low-carbon hydrogen in the transport sector (dena, 2016; Fraunhofer IEG, ISI, ISE, 2021). Since a large-scale hydrogen network and production capacity expansion will most likely be driven by large-scale applications with significant hydrogen demand in 2030, the demand analysis is focused on these consumers. Additional hydrogen demand could arise from, e.g., high-temperature heat, small-scale industry applications, the heating sector, aviation, shipping, trains, the power sector, and the production of synthetic fuels. However, it is assumed that these applications will not result in substantial hydrogen demand in 2030.

Most of the plants considered do not always operate at full capacity due to planned or unexpected maintenance or measures taken to prevent equipment breakdowns. Therefore, an average utilization factor for each industry is calculated using historical production volumes with data obtained from Eurostat (2021).[4] The calculated capacity factors are presented in Table 3 in the Appendix. In the next step, the annual production volumes [million tons] are translated into annual hydrogen demand [TWh] using process-specific input-output tables, which are introduced in the following section.

3.1.1 Industry sector

Mineral oil industry

There is a high demand for hydrogen in mineral oil refineries within the investigated region, especially in traditional mineral oil production processes, where hydrogen is often required in hydrotreating and hydrocracking processes.[5] The specific hydrogen consumption of mineral oil refineries for crude oil with hydrocracking is assumed as 0.94 PJ H_2/Mt output (gross) and 0.47 PJ H_2/Mt output (net) and without hydrocracking as 0.65 PJ H_2/Mt output and 0.18 PJ H_2/Mt output respectively (Self et al., 2000). The calculated capacity factor of mineral oil refineries amounts to 87 % in Belgium, 88 % in the Netherlands, and 81 % in Germany.

In general, a distinction is made between gross and net hydrogen demand in mineral oil refineries. Gross refers to the total hydrogen demand, including hydrogen from upstream processing units, e.g., hydrocracking and hydrogen from catalytic reforming processes. Net hydrogen demand implies the share of the hydrogen demand, which must be supplied by a dedicated hydrogen source, e.g., SMR. Hence, only net hydrogen demand can be replaced with low-carbon hydrogen (ENCON and LBST, 2018).

Chemical industry

In the chemical industry, ammonia and methanol production are the main consumers of hydrogen. In addition, hydrogen is widely used in many other chemical processes but in far smaller quantities. In terms of ammonia, the Haber-Bosch process is predominantly used, which allows

[4] As this data is in parts not publicly available for Belgium and the Netherlands, the capacity factors of ammonia and methanol plants calculated for Germany are used for these countries as well.

[5] Hydrotreating is a hydrogenation process that removes contaminants from liquid petroleum fractions. Hydrocracking is used to convert heavier hydrocarbon chains into lighter ones by the addition of hydrogen (Self et al., 2000).

for a substitution of conventional by low-carbon hydrogen. Therefore, it is an attractive option for low-carbon hydrogen usage. For ammonia plants, the specific hydrogen consumption is 21.36 PJ H_2 per Mt of ammonia (Bazzanella et al., 2017), and a calculated capacity factor of 82 % for all regions is applied[5].

Methanol is mainly produced from synthesis gas containing carbon monoxide, carbon dioxide, and hydrogen. Therefore, if low-carbon hydrogen is provided independently, the carbon for the methanol synthesis would have to be provided from different sources. An alternative low-carbon production route is methanol synthesis via biomass gasification. Here, the specific hydrogen consumption amounts to 23.90 PJ H_2 per Mt of methanol (FutureCamp, 2019). A capacity factor of 94 % is calculated for methanol plans for the entire region.[5]

For various other chemicals, hydrogen is also used as a feedstock. However, the specific hydrogen volumes are hard to determine.[6] These products are mostly produced in integrated chemical parks with several companies and a wide range of produced chemicals. These sites are quite complex and take advantage of technical synergies, resulting in a very low net hydrogen demand. Therefore, this study focuses on today's large hydrogen consumers, such as ammonia, methanol, and refineries, as these require a dedicated hydrogen supply. In contrast, hydrogen required to produce other chemicals can be provided through own production or small-scale deliveries by truck and vessel.

Primary steel industry

While hydrogen is currently not a primary feedstock in the steel industry, DRI from natural gas or hydrogen is considered a promising pathway for the decarbonization of primary steel production in the future (WV Stahl, 2021; Bundesregierung, 2020; Tata Steel, 2021; ArcelorMittal, 2020). The specific hydrogen consumption for primary steel produced via DRI amounts to 8.19 PJ H_2 per Mt of primary steel (own calculations based on FfE, 2020 and Agora, 2019). For the primary steel industry, current production quantities per steel mill are used.

Steel mills located in the investigated region are assumed to switch from conventional primary steel production to DRI. The potential hydrogen demand by these production facilities is discussed later in the scenarios section, which considers future low carbon hydrogen penetration rates.

3.1.2 Transport sector

Hydrogen demand from the transport sector considered in this study comprises road freight transport by light-duty vehicles (LDV) and HDV and passenger transport by local public buses. These two are exclusively considered, as a significant hydrogen demand is expected by 2030 resulting from those vehicle types due to advantages in range and payload. Contrarily, no significant hydrogen demand is foreseen for trains and vessels by 2030 due to lacking technological

[6] An estimation of hydrogen demand in chemical parks was published by Agora (2021), indicating that the total hydrogen demand is rather low compared to ammonia, methanol, and refining processes.

readiness and market penetration under the short period of consideration. Therefore, hydrogen-fueled trains and vessels are not considered in this study.

For road freight transport, the following vehicle classes are considered, classified based on gross vehicle weight: vehicle type N1 (≤ 3,5 t), N2 (> 3,5 t and ≤ 12 t), N3 (> 12 t), and road tractors. Local public buses are not differentiated by vehicle types. In the calculations, only vehicles that are registered in the investigated region are considered.

The total hydrogen demand from the transport sector in 2030 is calculated based on today's national vehicle stocks with average annual mileages, forecasts for the development of freight traffic performance [tons*km] and passenger transport performance [person*km]. This allows for an estimation of the vehicle stock in 2030. Further, assuming market penetration rates and average specific fuel consumption for different types of hydrogen-fueled vehicles in 2030 yields the total hydrogen demand from road transport. The scenario section defines and presents the specific values of market penetration rates and freight traffic and passenger transport performances. Specific values for fuel consumptions and average annual mileages per vehicle type can be found in Table 4 in the Appendix.

For Germany, the vehicle stock and average annual mileage of LDV and HDV in 2019 are based on the published data of the respective registration districts taken from the annual report of the German Federal Motor Transport Authority (KBA, 2020a, 2020b), whereas for local public buses these figures are derived on federal state level from the German Federal Statistical Office (Destatis, 2020a, 2020b). In the Netherlands, the vehicle stock and average annual mileage of LDV and HDV and local public buses 2019 are provided by CBS Statistics Netherlands (CBS, 2020a, 2020b). For Belgium, the data on LDV and HDV is provided by the federal public service of Belgium (Mobilit, 2020). For local public buses, data from the three main public transport associations which are operating local public transport in Belgium is used.[7] For Germany and Belgium, the average annual mileage of local public buses is obtained by dividing the calculated total annual mileage of all buses registered in a certain federal state by the total bus stock quantity.

3.2 Hydrogen Production

Current hydrogen production can be separated into dedicated hydrogen production, e.g., using SMR or auto-thermal reforming, and by-product hydrogen, which is produced as a secondary output and either used in subsequent production steps of the same process (e.g., mineral oil refining) or unused in the same process (e.g., chlor-alkali electrolysis). Only the first type of hydrogen supply, the dedicated hydrogen production, can be replaced with low-carbon hydrogen.

In this study, only low-carbon hydrogen production is explicitly considered. This includes by-product hydrogen from chlor-alkali electrolysis using electricity from RES, which is already produced in significant amounts today, and low-carbon hydrogen from operational or planned

[7] For Wallonia: Annual report of TEC (TEC, 2020), Brussels-Capital: STIB (STIB, 2020), and Flanders: De Lijn (De Lijn, 2020).

dedicated hydrogen production facilities. Therefore, conventional hydrogen production from SMR without CCS is not considered.

Hydrogen from chlor-alkali electrolysis

In chlor-alkali processes, hydrogen is produced as a by-product and can therefore be used by other processes.[8] Assuming that electricity from RES is used for chlor-alkali electrolysis, the produced hydrogen is classified as low-carbon hydrogen. Euro Chlor (2020) contains a comprehensive list of plants and their production capacity. Using the production capacities and actual annual production volumes from Eurostat (2019), the capacity factors of chlor-alkali plants are calculated for Germany.

The same capacity factor is applied to both Belgium and the Netherlands, as the data for these are publicly not available. Finally, the actual amount of hydrogen as a by-product is calculated from the chlorine volumes produced. The calculation is based on Achtelik et al. (2019).

Low-carbon hydrogen project pipeline

Low-carbon hydrogen production in the current project landscape is mainly based on water electrolysis (using electricity from RES) and SMR with CCS. Few plants are currently in operation, with expansions in the megawatt to gigawatt scale expected to be commissioned in the upcoming years. In order to estimate the low-carbon hydrogen production capacity in 2030, operational, planned, and announced projects are reviewed and assessed. The final list includes hydrogen projects within Belgium, the Netherlands, and North-Western Germany. For each project, information on the technology used and its (planned) installed capacity, the end-use application, the location[9], and the commissioning year is retrieved from project websites, press releases, and reports. If relevant information cannot be obtained, the project is not further considered.

Although several projects do not have a final investment status yet, and thus uncertainties exist whether these projects will be realized, all announced projects are included in the production capacity. A list of considered projects and a helpful project database can be found in Table 5 in the Appendix. This table does not claim to be comprehensive.

Spatially resolved production capacities are calculated using the total installed capacity for low-carbon hydrogen. For the electrolysis of water, an efficiency of 70 % and full load hours of 4.000 per year are assumed to determine the total yearly production volume (BMWi, 2020).

[8] Today, the byproduct (grey) hydrogen is also used for heat applications. If it were to be used differently in the future, the energy quantities would have to be substituted by other energy carriers. This effect would have to be taken into account in an overall system analysis.

[9] If location was the only missing information, the most accurate data available such as city or region of construction is used. In the case of an entire lack of information, the company headquarter is used as location.

4 Defining hydrogen demand scenarios

Future hydrogen demand and supply developments are uncertain, and projections can only be point estimates for one discrete pathway. In order to cover a broader range of future developments, a low and a high hydrogen demand scenario are developed by assuming different penetration rates for low-carbon hydrogen in different sectors and end-use applications. While demand is varied between the two scenarios, supply is the same to ensure that the results are comparable. The assumed penetration rates are based on a review of existing energy system studies and stated political and company targets.[10] The following section introduces the scenarios in more detail.

The development of industrial production depends on various factors and shows multiple interdependencies, such as overall economic growth, technology readiness, and the political framework. For instance, the Projection Plan of the German Government (BMU, 2019) expects an overall economic growth until 2030 with almost constant production volumes in steel, ammonia, and methanol production.

The overall growth of mobility demand in the transport sector is expected to be positive, whereas refinery production could be declining in the upcoming years due to increasing electrification. Therefore, expanding battery electric vehicle penetration rates could partially offset a declining demand for refinery products. For reasons of simplification, the production level in the considered industry sectors is therefore assumed to be constant until 2030. Consequently, hydrogen demand from the (petro-)chemical industry is assumed to remain constant, with an increasing share of low-carbon hydrogen. Additionally, low-carbon hydrogen demand is assumed to emerge from the steel industry, which partially switches to DRI until 2030.

The hydrogen demand of the transport sector is assumed to increase until 2030, with some of the LDV & HDV and local public buses switching to fuel cell drive. The growth of freight traffic volume of LDV and HDV is expected to be 1.5 % per year until 2030 and remains the same across borders in Belgium, Netherlands, and North-Western Germany. For local public buses, the passenger traffic volume in 2030 is assumed to be at today's level.

4.1 Low demand scenario

The low demand scenario represents a pathway where the penetration rate of low-carbon hydrogen in existing applications and the switching rate to hydrogen in new applications in industry and transport is comparatively low. Table 2 shows key parameters for the development of transport and industrial production and the penetration rates of low-carbon hydrogen.

[10] The hydrogen demand and supply projections should not be misunderstood as results of an energy system optimization, but rather as rough estimates based on available data and previous systems studies.

It is assumed that the hydrogen demand of new applications, i.e., in the transport sector and steel industry, is fully covered by low-carbon hydrogen. Conventional hydrogen demand of the chemical industry is substituted with low-carbon hydrogen at a fixed penetration rate. The DRI production route in the steel industry also works with natural gas as reduction agent, already reducing emissions significantly. Hence, when low-carbon hydrogen is still scarce in the transition period, the DRI plants are assumed to run partially on natural gas.

Forecasting market penetration of fuel cell vehicles is very challenging as the development of vehicle fleets depends on numerous technological, economic, and political parameters. Economically, several studies identify the acquisition costs of vehicles as the decisive factor for market penetration of fuel cell vehicles. The key economic components of a fuel cell system are the fuel cell stack and the high-pressure tank for hydrogen storage. In addition, the hydrogen fuel price will also be a decisive factor in the future. From a technical point of view, the maturity of the fuel cell systems for LDV and HDV is seen in studies as the major impact for the future market penetration of fuel cell vehicles, as it determines the point in time of market entry. Besides this, political factors such as taxes, subsidies, and the cost of CO_2 pricing have a significant influence on the market share of a particular vehicle technology. The assumptions on market penetration rates in 2030 in the individual vehicle classes are therefore based on literature, own estimates, and expert assessments (dena, 2018, Schlund et al., 2021, Öko-Institut, 2014 b, Fraunhofer ISI, IML, 2017). Fuel cell trucks are predicted to have their main application in the long-distance and heavy load transport sector. The major market launch of such vehicles is not expected before 2025. Therefore, the penetration rate of hydrogen-fueled HDV is assumed to be twice as high as the penetration rate of LDV. In general, the market shares of hydrogen-fueled LDV and HDV are kept low in this study, as larger shares are not expected by 2030 due to today's rather low technological maturity.

For local public buses, the main driver of the increasing uptake of hydrogen-fueled vehicles is the Clean Vehicle Directive of the European Commission (EC, 2019). It regulates procurement quotas for low- and zero-emission vehicles for public tenders. The Netherlands is often referred to as the European front-runner in emission-free local public bus transport. By 2030, or even earlier in some locations, the entire bus fleet will be emission-free (RVO, 2019). Therefore, the penetration rate of hydrogen-fueled local public buses in the Netherlands is assumed to be higher than in Germany and Belgium.

Table 2: Penetration rate of low-carbon hydrogen in the industry and transport sector in the low and high demand scenario

Source: Own assumptions based on EWI (2021)

Parameter	Low demand scenario			High demand scenario		
	DE	NL	BE	DE	NL	BE
DRI in steel industry	30 %	50 %	50 %	30 %	50 %	50 %
Low-carbon hydrogen share in DRI	50 %	50 %	50 %	100 %	100 %	100 %
Low-carbon hydrogen share in ammonia production	15 %	15 %	15 %	30 %	30 %	30 %
Low-carbon hydrogen share in mineral oil refining (net demand)	15 %	15 %	15 %	30 %	30 %	30 %
Low-carbon hydrogen share in methanol production	15 %	15 %	15 %	30 %	30 %	30 %
Development of freight traffic performance	1.5 %	1.5 %	1.5 %	1.5 %	1.5 %	1.5 %
Development of passenger traffic performance	0 %	0 %	0 %	0 %	0 %	0 %
Share of fuel cell drives in light duty vehicles	1 %	1 %	1 %	2 %	2 %	2 %
Share of fuel cell drives in heavy duty vehicles	2 %	2 %	2 %	4 %	4 %	4 %
Share of fuel cell drives in local public buses	7.5 %	10 %	7.5 %	15 %	20 %	15 %

4.2 High demand scenario

In the high demand scenario, the uptake of low-carbon hydrogen in existing and new applications is following a more ambitious trajectory. Table 2 shows key parameters for the transport and industrial production development and the assumed penetration rates of low-carbon hydrogen.

The DRI penetration in steel production equals the low demand scenario; however, it is assumed that DRI plants are fully supplied with low-carbon hydrogen instead of natural gas. The low-carbon hydrogen penetration in the chemical industry doubles compared to the low demand scenario.

In the transport sector, freight and passenger traffic volume developments remain the same as in the low scenario. The penetration shares of hydrogen-fueled LDV, HDV, and local public buses are doubled in the high scenario.

5 Results

The results have been calculated by applying the sector-specific penetration rates for low-carbon hydrogen demand on the underlying production output and transport demand, respectively. The production potentials are based on a review of low-carbon hydrogen projects and hydrogen production as a by-product from chlor-alkali electrolysis. For the year 2030, the total low-carbon hydrogen demand is compared with the production potentials on an aggregate and regional level.

Comparison of total and low-carbon hydrogen demand and supply in 2030

For both scenarios, the total hydrogen demand is calculated using the bottom-up analysis introduced in the previous sections. Low-carbon hydrogen production is assumed to be identical in both scenarios. Furthermore, the total hydrogen demand from the (petro-)chemical industry is stable. Therefore, additional hydrogen demand in 2030 arises from the steel industry and the transport sector.

In the **low demand scenario**, total hydrogen demand in Belgium, the Netherlands, and North-Western Germany increases from 63 TWh today to 81 TWh in 2030. Thereof, 16 TWh is consumed in the steel industry and 2 TWh by the transport sector. Ammonia production accounts for 27 TWh, mineral oil refining for 26 TWh, and methanol synthesis for 10 TWh. Figure 4 illustrates the distribution of low-carbon hydrogen demand and supply on NUTS 3 regional level. Regions with high demands are coloured in dark red; the green circles display low-carbon hydrogen production locations. The map shows that low-carbon hydrogen demand is highly concentrated in regions where chemical industry and steel mills are located. Areas with the highest absolute hydrogen demand are Duisburg with 6 TWh, Ijmond with 4 TWh, and Ghent with almost 3 TWh. Steel mills are located in all of these areas. Mineral oil refining and the chemical industry create significant demand for low carbon hydrogen in the regions Zeeland (1.5 TWh), Antwerp (1 TWh), and the county of Dithmarschen (0.6 TWh). Regions with little industry, smaller populations and lower transport activity tend to have negligible hydrogen demand, visible on the maps as white and light red colored regions.

Projects to produce low-carbon hydrogen are distributed over the entire region. However, most are located along the North Sea coast or close to large consumption centers in the German interior, like the Rhine-Ruhr or the Hamburg metropolitan region. The largest planned low-carbon hydrogen production projects can be found along the northern coastline of the Netherlands, around the Groningen area, with a total project production volume of more than 15 TWh. “NorthH2” is the largest considered green hydrogen project with a total installed electrolysis capacity of 4 GW. Other regions with significant production capacities are Rotterdam (5 TWh), Dithmarschen[11] (3 TWh), and Duisburg (2 TWh).

[11] Dithmarschen is identified as a potential landing point for a hydrogen pipeline from the AquaVentus project around Helgoland. Therefore, the hydrogen quantities produced in Helgoland are included in the hydrogen balance of Dithmarschen.

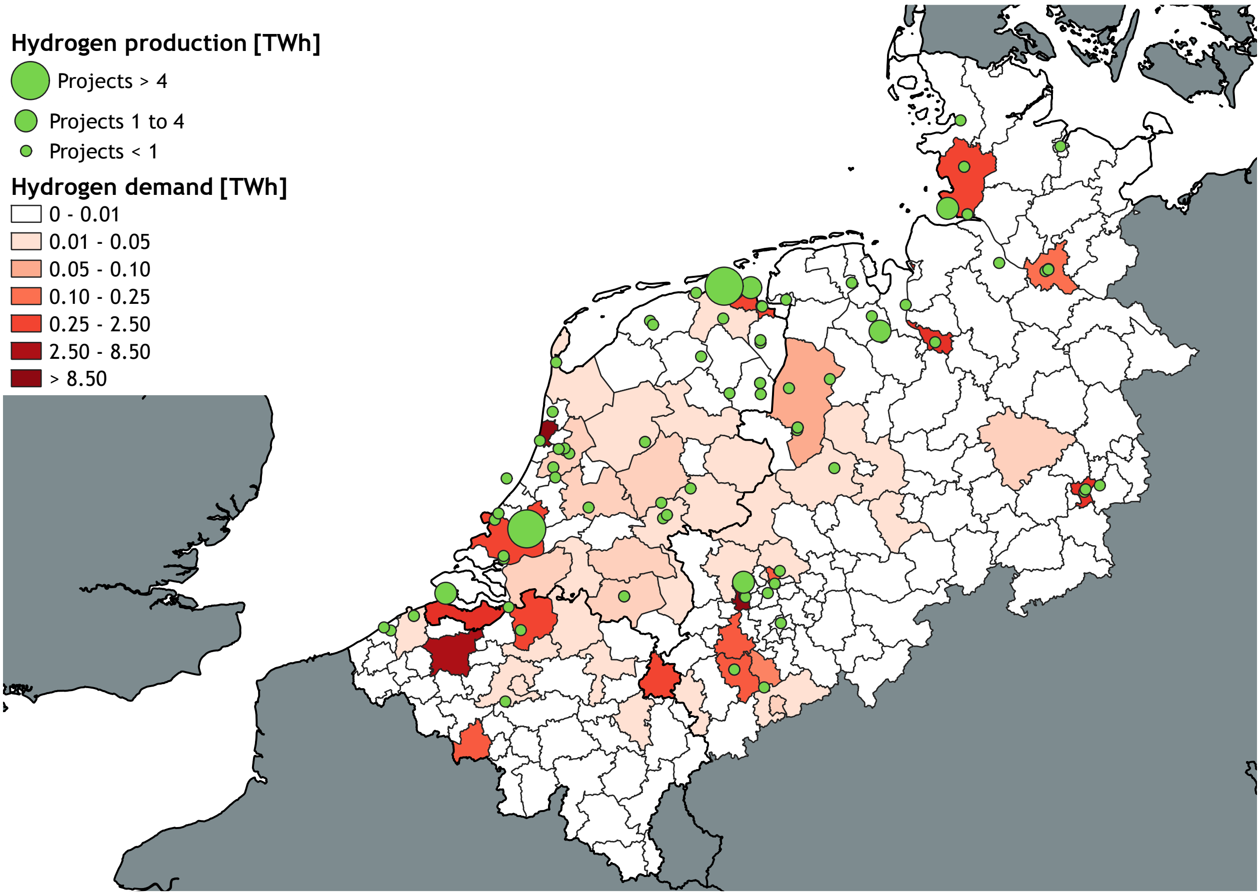


Figure 4: Low demand scenario with hydrogen demand and production by NUTS 3 regions

Source: Own illustration

The **high demand scenario** is characterized by more ambitious penetration rates of low-carbon hydrogen in the different sectors. Total hydrogen demand amounts to 99 TWh in 2030 – 18 TWh more than in the low demand scenario. The regional distribution is visualized in Figure 5. This scenario also shows a concentration in a few areas but with higher absolute demand volumes. Due to the higher hydrogen demand in the transport sector, more regions show notable hydrogen demands compared to the low demand scenario. Regions with the highest absolute hydrogen demands remain the same, but with a doubling of the absolute hydrogen demand in the steel industry: Duisburg with 12 TWh, Ijmond with 8 TWh, and Ghent with nearly 6 TWh. Regions with the highest demand for low-carbon hydrogen from the (petro-)chemical industry are Zeeland (3 TWh), Antwerp (1.7 TWh), and the county of Dithmarschen (1.2 TWh). The transport sector has the highest demand for hydrogen in the densely populated areas around Rotterdam, Hamburg, and Antwerp; however, demand is still below 0.5 TWh in each of these regions.

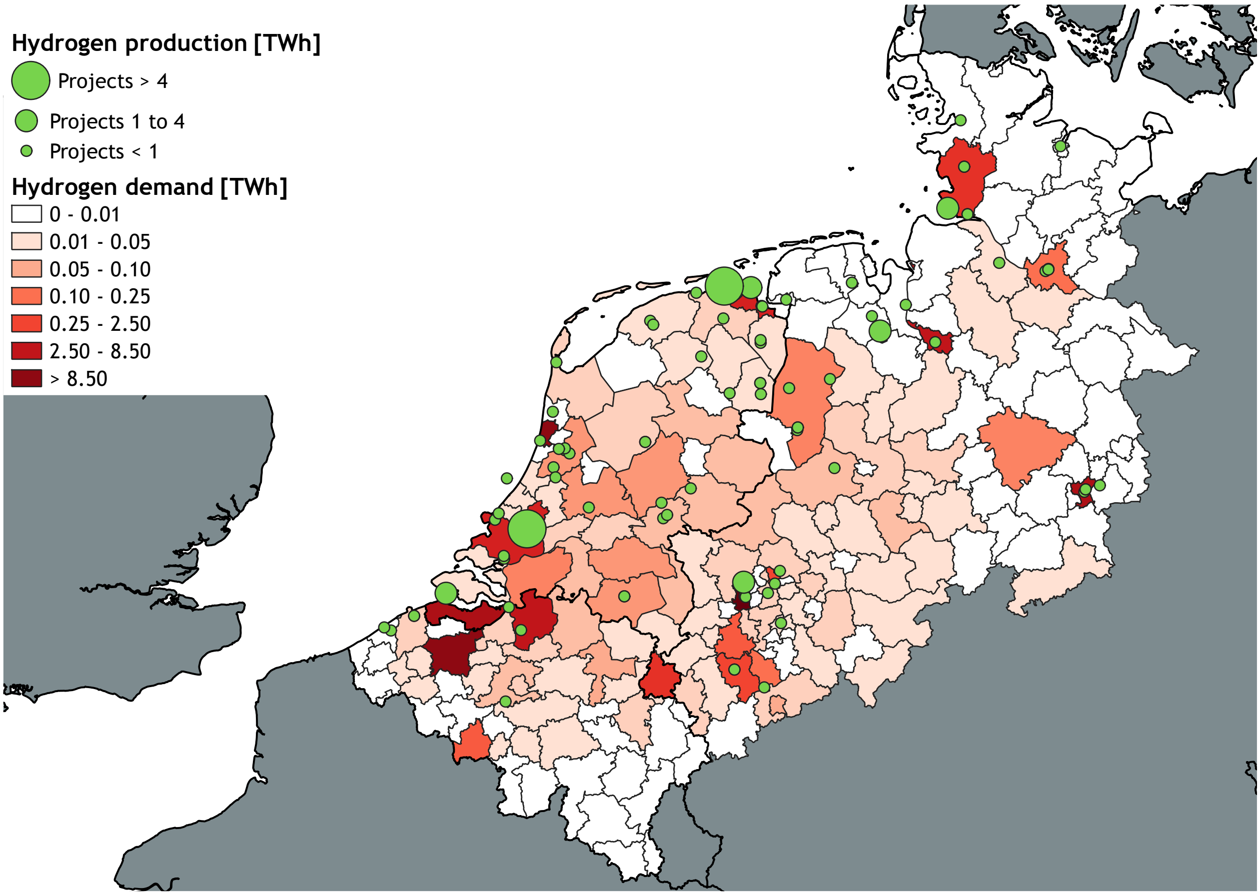
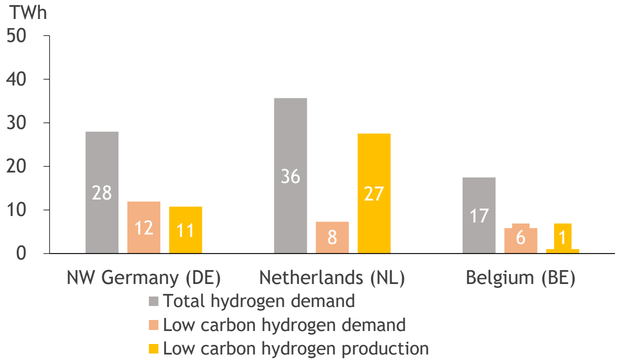


Figure 5: High demand scenario with hydrogen demand and production by NUTS 3 regions

Source: Own illustration

Low-carbon hydrogen supply gap

The regionally resolved hydrogen demand and production volumes can be aggregated on a national level to reveal potential hydrogen supply gaps in 2030. This illustrates whether planned hydrogen projects are sufficient to meet the entire demand from industry and transport or whether hydrogen imports are necessary, e.g., from countries with surpluses within the investigated region or other prospective exporting countries. Figure 6 and Figure 7 show the country-specific results of total hydrogen production and resulting differences for the low and high demand scenario, respectively.



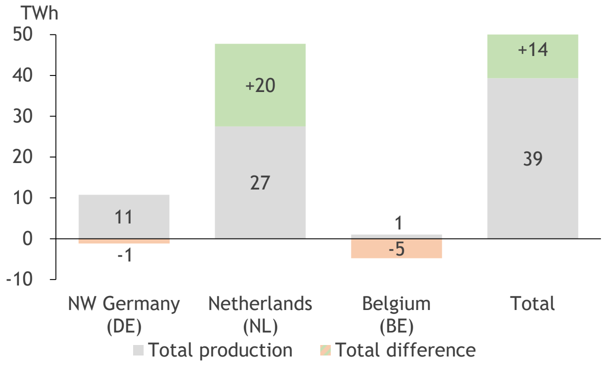


Figure 6: Low demand scenario 2030 - country-specific hydrogen demand and production (left) and total low-carbon hydrogen production and difference (right)

Source: Own illustration

The low-carbon hydrogen production reflects the status-quo of by-product hydrogen from chlor-alkali electrolysis as well as operating, planned, and announced projects within the region and sums up to 39 TWh in 2030. Green hydrogen projects represent most of the low-carbon production capacities with a total of 31 TWh. Blue hydrogen projects amount to 5 TWh, and hydrogen as a by-product of chlor-alkali electrolysis account for 4 TWh. The low demand scenario shows a supply surplus of 14 TWh of low-carbon hydrogen in 2030. This results from the hydrogen production surplus in the Netherlands of approximately 20 TWh due to its numerous and large-scale planned hydrogen projects. The hydrogen balances of Belgium and North-Western Germany, by contrast, exhibit supply shortages of 5 and 1 TWh, respectively. Germany could almost completely cover its total hydrogen demand, while Belgium would have to import a considerable amount of hydrogen. The Netherlands, with a clear surplus of hydrogen, could become an export country of low carbon hydrogen with the opportunity to fill the supply gaps of Germany and Belgium in 2030. Nevertheless, this should be treated with caution since the production capacity reflects the current project pipeline, of which probably not the entire capacity will be commissioned. Furthermore, the Dutch project “NorthH2” with an annual hydrogen output of more than 11 TWh alone could be the decisive factor in determining whether the Netherlands will achieve a hydrogen surplus in 2030 and thus becoming a potential exporting country or not.

In the high demand scenario, the total surplus of low-carbon supply turns negative because hydrogen production remains constant, whereas total demand increases by 18 TWh. As a result, North-Western Germany’s supply gap grows to 13 TWh and Belgium’s to 11 TWh. In this scenario, the Dutch supply surplus would not be sufficient to close the gaps within Germany and Belgium.

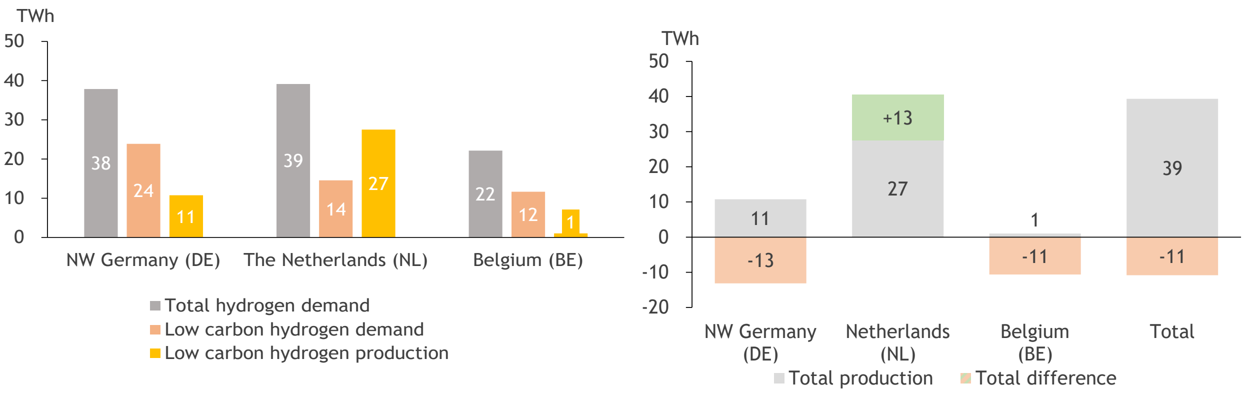


Figure 7: High demand scenario 2030 - country-specific hydrogen demand and production (left) and total low-carbon hydrogen production and difference (right)

Source: Own illustration

Regional supply-demand gaps

Figure 8 visualizes the hydrogen balance of each NUTS 3 region, with shortages displayed in red and surpluses in blue for the high demand scenario.[12] The map reveals that in some regions, significant imbalances exist. These shortages and surpluses also occur in the low demand scenario (see Figure 9 in the Appendix) and have various reasons. First, demand is highly concentrated in regions with large industrial plants. In particular, steel mills with DRI can create an extraordinarily high demand for hydrogen. Consequently, regions with the highest shortage in low-carbon hydrogen are Duisburg (10 TWh), Ijmond (8 TWh), Ghent (6 TWh), and Salzgitter (3 TWh) in the high demand scenario. However, ambitious penetration of low-carbon hydrogen in the chemical industry and mineral oil refining also creates deficits in some regions, for instance, in Zeeland (6 TWh), Limburg (3.3 TWh), Antwerp (3 TWh), and Delfzijl (3 TWh).

Furthermore, low-carbon hydrogen production facilities tend to be planned in areas with good RES potentials or, in the case of SMR with CCS, access to suitable CO_2 storage sites. Good RES potentials for green hydrogen production are often found onshore near the coastline or offshore, whereas blue hydrogen from SMR with CCS is usually planned in close proximity to depleted offshore gas fields. Therefore, the highest regional surpluses in the high demand scenario can be found in the regions around Groningen (16 TWh), Rotterdam (4 TWh), Zeeland (3 TWh), and Dithmarschen (2 TWh). The latter is focused on blue hydrogen production and the former advancing green hydrogen projects. The spatially resolved hydrogen balances show that low-carbon hydrogen demand and supply do not necessarily coincide spatially. Some regions with low-carbon hydrogen gaps and surplus are close to each other and could therefore form local clusters, e.g., the region around Hamburg, Groningen, Rotterdam, and Antwerp. Others are further apart

[12] The map only shows supply shortages and surpluses of more than 0.1 TWh. Smaller demand and supply imbalances do mostly occur due to either small-scale projects or exclusive hydrogen demand from the transport sector.

from production facilities and could require access to a hydrogen grid, for instance, Duisburg, Salzgitter, and Limburg (BE) (see chapter 7 for details).

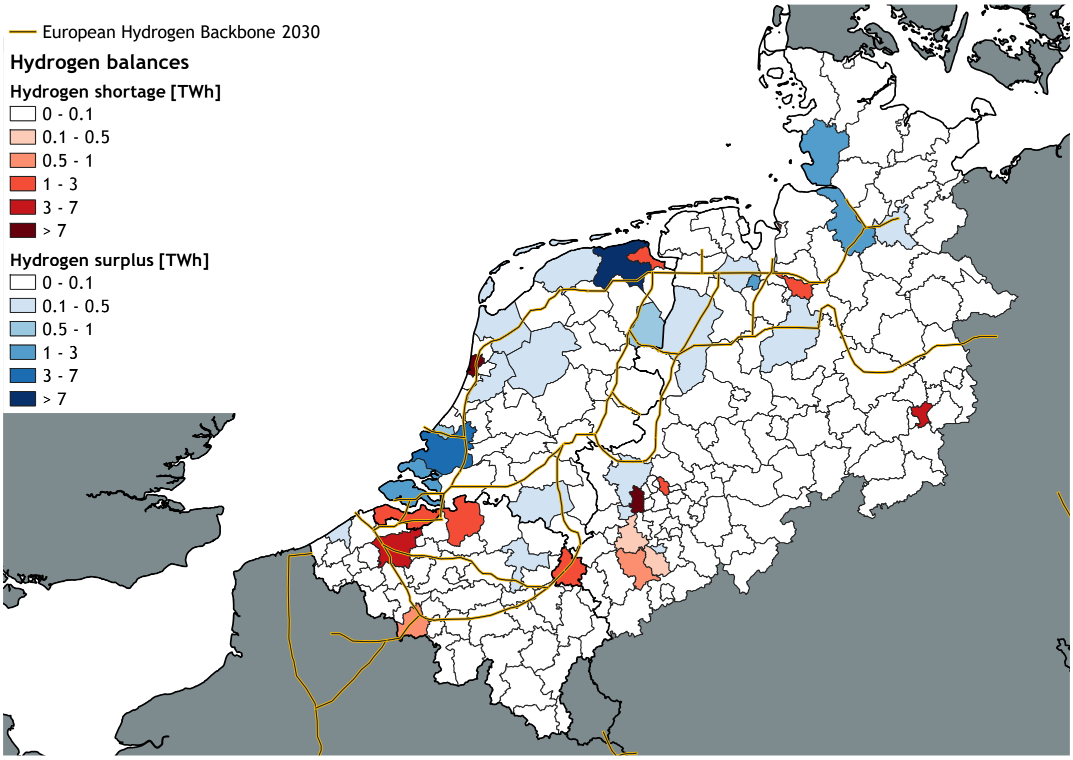


Figure 8: High demand scenario with hydrogen balance by specific NUTS 3 regions

Sources: Own illustration and Gas for Climate (2020)

It should also be considered that the demand analysis has focused explicitly on large industrial plants and those parts of the transport sector, where electrification is more complicated. Whereas these consumers will be the driver for a cross-border hydrogen grid and the scaling of production facilities, additional demand for low-carbon hydrogen could emerge locally, e.g., from smaller industrial plants or the heating sector. This could widen the supply gap, thus, require additional action.

6 Implications for the region as a future hydrogen cluster

The results show that an ambitious utilization of low-carbon hydrogen in the high demand scenario will most likely cause a gap between production and demand, considering the current projects for hydrogen production. Potential measures against a supply gap and the impact on the development of the region as a hydrogen cluster are discussed in this chapter.

Measures to reduce or close the demand and supply gap

The analysis points out a potential supply gap of low-carbon hydrogen if the development of demand follows an ambitious path (exemplarily shown in the high demand scenario). As the production capacities in the analysis only reflect the current project pipeline, **additional projects for hydrogen production** could be incentivized. Also, the calculated hydrogen supply must be carefully interpreted. The production capacities are based on a review of operating, planned, and announced hydrogen projects. It is uncertain to what extent the considered projects will be realized until 2030. For a realistic estimation of the production capacities, it is of great importance that the projects reach their final investment decision in the near term. This applies especially to projects with high installed capacities, such as the Dutch “NortH2” project with an installed electrolysis capacity of 4 GW or the “AquaVentus” project with 1 GW, which accounts for around one-third of the total projected installed capacity in North-Western Germany. The realization of such large projects could become a decisive factor during the market ramp-up. Additionally, using a technology mix for low-carbon hydrogen production could widen the potential and ensure economic efficiency.

Low-carbon hydrogen could be **imported from close neighbors**, which invest in hydrogen production facilities, in particular Denmark, Norway[13], and the United Kingdom[14]. However, it is uncertain whether these countries would be willing to export hydrogen from the very beginning, especially if there is no domestic surplus available for export. Besides importing hydrogen from neighboring countries, long-distance imports are an often-discussed option to fill supply gaps. Belgium, the Netherlands, and Germany have arranged several memoranda of understanding with other countries (e.g., Portugal, Morocco, Egypt, Australia) with the objective to establish bilateral trade in hydrogen. However, such projects require significant investments in transport infrastructure and production equipment, challenging the implementation of long-distance hydrogen supply chains by 2030.

The long-distance import of hydrogen is more cost-efficient using liquid energy carriers than highly pressurized gaseous or liquid hydrogen transport (Brändle et al., 2020). Suitable energy carriers are, for instance, Ammonia or Liquid Organic Hydrogen Carriers (LOHC), where hydrogen is transported in a chemically bound form. However, this raises the question of whether Ammonia should be manufactured within the region of Belgium, the Netherlands, and North-Western Germany at all, instead of producing it overseas with subsequent seaborne imports. Although this case will become relevant in the long run, it sets incumbent producers of Ammonia and other chemical commodity suppliers under very high pressure.

Most promising seems to be a combination of all presented options, which can be realized in the short- to mid-term. Currently, a major obstacle for final investment decisions is the risk investors face due to uncertainties regarding costs, volumes, and legislation. Actions should be taken to reduce those risks in order to incentivize private investments, which ultimately leads to a scaling of the technologies.

[13] In the case of Norway, the government takes the view that during the market ramp-up only natural gas will be exported to produce hydrogen with CCS close to the consumer with CO_2 being transported back to Norway. Large-scale hydrogen export pipelines are rather seen as an option in the long-term future (Norw. Government, 2020).

[14] The United Kingdom focuses on the establishment of a domestic market for hydrogen production and supply, especially during the market ramp-up. In the long-term, the government plans to export low-carbon hydrogen, its derivatives (e.g., Ammonia), and production and transportation equipment (HM Government, 2021).

Implications for a cross-border hydrogen grid

Transporting hydrogen enables a balancing of demand and supply between regions. For large volumes and distances, pipeline transport is particularly suitable. The European Hydrogen Backbone, as suggested by some European gas TSOs, is included in Figure 8 (and Figure 9 in the Appendix) as a reference for a potential hydrogen network in 2030.[15] The visualization shows that the suggested network covers most of the regions with large hydrogen supply shortages or surpluses. The development of infrastructure is an essential step in fostering hydrogen trade and developing a prospective hydrogen market.

Low-carbon hydrogen can be produced where it is economically optimal, e.g., close to carbon storage sites or at locations with good RES potentials, and transported to consumers, where low-carbon hydrogen production would be more costly. Thus, the pipeline network creates the foundation for a potential future hydrogen market.

Furthermore, prospective hydrogen imports by ship from overseas could land at import terminals and be fed directly into the pipeline grid—similar to LNG-terminals today. Since ports are often populated with industrial plants, they are usually well connected to the gas network and could therefore be connected to a future hydrogen grid with little effort.

During the market ramp-up, hydrogen is expected to be very scarce and pipeline supply could be unstable, if only few producers feed small quantities into the network. This raises questions regarding the utilization and the financing of an early hydrogen grid. By partially repurposing existing gas pipelines, the cost for a hydrogen grid can be substantially reduced. Nevertheless, high upfront investments under great uncertainty of off-take quantities are required. In the early phase of a cross-border hydrogen network, these costs must be carried by a low number of network users—challenging the overall economic attractiveness of low-carbon hydrogen. Recently, a discussion has started on the necessity to regulate an early hydrogen grid and to what extent the network should be financed only by hydrogen network users or also by gas grid users, or even by all energy consumers. The financing mechanism will be a crucial determinant of an early hydrogen grid to be established and will have a significant impact on the incentives to build a network at a reasonable cost and with appropriate capacities.

In addition, interruptible production could hamper security of supply, which could be a risk, particularly for consumers who rely on stable supply. Hydrogen storage might be needed from the very beginning to balance supply and demand and ensure a minimum security of supply. Additionally, consumers could require fallback options in the case of supply interruptions, for instance, the DRI process can also be run on natural gas (with corresponding CO_2 emissions). However, in the long-term, when supply and storage capacities have been established, a pipeline grid is a powerful instrument for ensuring security of supply.

The cross-border hydrogen network sets the basis for a trans-national hydrogen market. Since hydrogen is a homogeneous commodity from a physical perspective—provided that the purity is standardized—, a virtual differentiation of production sources is needed using certificates. These

[15] Note that this map roughly shows pipeline routes based on the published network by Gas for Climate (2020) and should not be understood as representation of real pipeline maps. Therefore, geographical deviations from the published map as well as from real pipeline routes are unavoidable.

guarantees of origin ensure that hydrogen can be physically traded independently of the production technology while the indirect emissions from hydrogen production are traceable. Particularly in the region of Belgium, the Netherlands, and North-Western Germany, a certification scheme should be implemented from the very beginning of a cross-border hydrogen grid, as different political objectives regarding the favored hydrogen production technology should not impede transnational cooperation and trade.

Potential synergies in the hydrogen cluster region

The North-Western European hydrogen cluster has the potential to create significant positive spill-over effects. The development of a large-scale hydrogen supply chain creates substantial learning and scaling effects, which do not only reduce the cost within the region but for the entire hydrogen economy. Therefore, the region could become a global front-runner of large-scale hydrogen applications. The cross-border pipeline network ensures scaling of production and supply and enables to connect new market entrants flexibly.

While the network will integrate large production and consumption centers in the first place, it also offers the chance to connect with other small-scale hydrogen consumers. After the network has been established, small industrial consumers and the heating sector could also get access to low-carbon hydrogen supply and decarbonize their energy consumption. Gas distribution grids could either blend hydrogen with existing natural gas streams or repurpose whole gas networks. Therefore, the cluster could become the first region to develop a full hydrogen ecosystem across all sectors with a large decarbonization potential.

Environment of uncertainties inhibits investments

Throughout this report, several reasons for uncertainties have been addressed, which occur at all stages of the hydrogen supply chain. For the market development, uncertainties create additional costs due to higher risks or lack of information. Reducing uncertainties is therefore an important requirement to support the market ramp-up. Politics need to put comprehensive cross-border policies and regulations in place so that potentials and synergies of a transnational approach can be realized. Partially, financial support will also be needed, but the mechanisms should be designed to minimize market distortions. Private actors, e.g., companies, should start investing in technologies and commit to announced projects to ensure a realistic view on the demand and supply capacities. Research can support the process by showing transformation pathways, creating new information to improve transparency, and analyzing new emerging issues. This study has also shown that reliable and transparent information on hydrogen production and consumption is the basis for a realistic projection of future scenarios. Since this information is largely missing, data gathering and official statistics for the hydrogen sector should be initiated to provide a sound basis for different types of analyses.

7 Conclusions

The region of Belgium, the Netherlands, and North-Western Germany[16] has significant potential to serve as a nucleus for a European cross-border hydrogen infrastructure and market. The region has strong economic activity and is home to large industries with high CO_2 emissions that could be abated by using low-carbon hydrogen as a feedstock and energy carrier. The geological and climatic characteristics of the region are a solid foundation to develop both green and blue low-carbon hydrogen production. Good onshore and offshore wind energy potentials can be harvested to produce hydrogen from electrolysis. Abundant depleted offshore gas fields could be used as CO_2 storage, providing the prerequisite to produce hydrogen from natural gas reforming with carbon capture and storage (CCS). Furthermore, hydrogen or hydrogen-derived products could be imported from overseas through existing ports, e.g., Antwerp, Rotterdam, or Hamburg. Finally, the existence of a dense natural gas network provides an opportunity to repurpose pipelines to form a hydrogen network and thus save costs.

This study performs a bottom-up and scenario-based estimation of the potential development of low-carbon hydrogen demand and production in the considered region until 2030. It is assumed that low-carbon hydrogen is first consumed by currently existing hydrogen consumers, which replace conventional with low-carbon hydrogen. New demand arises from the steel industry, heavy-duty transport, and the public transport sector. Future production capacities are derived from a detailed review of operating, planned, and announced low-carbon hydrogen projects in the region and chlor-alkali electrolysis, which produces carbon-free hydrogen as a by-product if electricity is produced from renewable energy sources (RES). Two scenarios are defined and characterized by low and high penetration rates of low-carbon hydrogen in the consumption sectors.

The results show that a transnational hydrogen pipeline network could partially resolve regional imbalances of demand and supply. Assuming moderate growth of low-carbon hydrogen demand, the current project pipeline is sufficient for self-supply—provided that all projects are going to be realized. However, the high demand scenario illustrates a more ambitious demand growth which lead to a supply shortage. In order to fill a supply gap, either more projects need to be initiated or imports of low-carbon hydrogen from neighboring states, such as Norway, the United Kingdom or Denmark, or from overseas are required. Furthermore, the stated production capacities are very sensitive to some single large-scale projects, whose realization could be decisive for a sufficient hydrogen supply.

Further action is needed to tap these potentials. Establishing a hydrogen market requires additional measures, such as hydrogen storage, certification schemes, transparent information, and a suitable legislative framework. To succeed, private and public actors need a transnational approach and further commitment to set the development of a hydrogen market on track.

[16] Referring to the federal states of North Rhine-Westphalia, Bremen, Hamburg, Lower Saxony, and Schleswig-Holstein.

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List of abbreviations

CCS	Carbon Capture and Storage
DRI	Direct Reduced Iron
FID	Final Investment Decision
GHG	Greenhouse Gas
HDV	Heavy Duty Vehicle
LDV	Light Duty Vehicle
LOHC	Liquid Organic Hydrogen Carriers
NUTS	Nomenclature des Unités Territoriales Statistiques
RES	Renewable Energy Sources
SMR	Steam Methane Reforming
TSO	Transmission System Operator

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Appendix

A.1 Assumptions

Table 3: Specific hydrogen consumption per output unit and calculated capacity factor of investigated industries

Sources: Eurostat (2021), Bazzanella et al. (2017), Future Camp (2019), FfE (2020), Agora (2019), Self et al. (2020), own calculation and expert estimates

Type of product	Specific hydrogen consumption [PJ H_2/Mt output]	Calculated capacity factors [%]
Ammonia	21.36	82 %
Methanol	23.90	94 %
Primary steel (via DRI)	8.19	n/a[17]
Mineral oil refining: crude oil With hydrocracking (gross/net) Without hydrocracking (gross/net)	 0.94 / 0.47 0.65 / 0.18	BE: 87 % NL: 88 % DE: 81 %

Table 4: Vehicle specific assumptions of fuel consumption and average annual mileage

Sources: KBA (2020 a, b), Destatis (2020 a, b), CBS (2020 a, b), Mobilit (2020) and own calculations

Vehicle category	Specific fuel consumption 2030 [kg H_2/100 km]	Specific average annual milage [km/year]		
		Germany	The Netherlands	Belgium
Vehicle category N1 (≤ 3.5 t)	2.3	19,343	14,280	16,798
Vehicle category N2 (≤ 12 t)	3.5	21,615	23,127	19,932
Vehicle category N3 (> 12 t)	6.1	38,158	46,862	19,932
Road tractors	6.1	93,136	70,454	63,323
Local public buses	8.0	72,037	72,704	59,373

[17] For primary steel production, annual production quantities per steel mill are determined, therefore no capacity factors are needed.

Table 5: Considered hydrogen production projects until 2030[18]

Hydrogen production Project name	Country	Color	Annual hydrogen production [GWh_{th}]
3Emotion	BE	Green	2.8
4 H2 wind turbines	NL	Green	28
4 H2 wind turbines	NL	Green	28
AquaVentus	DE	Green	2800
Battolyser pilot plant	NL	Green	0.04
Bio Energy Netherlands	NL	Blue	-
Blue Hydrogen Den Helder	NL	Blue	280
Carbon2Chem	DE	Green	0
Clean Hydrogen Coastline	DE	Green	1120
CO2RRECT	DE	Green	0.84
Cyrus Smith	NL	Green	0.06
D4	NL	Green	280
Delfzijl - Hystock	NL	Green	2.9
DJEWELS 1 Chemiepark - Delfzijl	NL	Green	-
DJEWELS 2 Chemiepark - Delfzijl	NL	Green	224
DNV Kema/DNV GL	NL	Green	0.03
Don Quichote	BE	Green	0.84
DRIBE2	DE	Green	280
Duwaal	NL	Green	5.6
EemsHydrogen	NL	Green	280
Electrolyzer including storage	NL	Green	4.2
ElementEins	DE	Green	280
Get H2 (Nukleaus)	DE	Green	280
GldH2	NL	Green	2.8
Green MeOH	DE	Green	784
GreenH2UB (1st hub, Noord Brabant)	NL	Green	28
GreenH2UB (9 hubs of 3-10 MW)	NL	Green	252
GreenMotionSteel	DE	Green	336
GrInHy2.0 (1. Stufe SALCOS)	DE	Green	2.02
Grüner Wasserstoff für grünen Stahl aus Duisburg	DE	Green	1400
GZI Next Emmen scale-up	NL	Green	560
GZI Next Phase 1	NL	Green	28
GZI Next Phase 2	NL	Green	196
H? Air Base Leeuwarden	NL	Green	14
H2 wind turbine	NL	Green	7
H2-based residential area in Van der Veen	NL	Green	-
H2BrakeCO2	DE	Green	0
H2CAST Etzel	DE	Green	16.8
H2-Fifty	NL	Green	700

[18] This project list does not claim to be comprehensive, as projects with uncertain project status or missing information are excluded.

Hydrogen production Project name	Country	Color	Annual hydrogen production [GWh_{th}]
H2GO - 1st phase	NL	Green	7
H2GO - 2nd phase	NL	Green	65.8
H2Herten	DE	Green	2.8
H2-Modellregion Düsseldorf - Wuppertal - Rhein-Kreis Neuss	DE	Green	2.8
H2Ships Platform	BE	Green	140
HEAVENN (Hydrogen Energy Applications for Valley	NL	Green	2.8
Hemweg	NL	Green	280
HPEM2Gas	DE	Green	0.84
HRS CMB	BE	Green	2.8
H-Vision	NL	Blue	4233.73
Hydrogen Delta - Zeeland	NL	Green	2800
Hydrogen Plant for Westereems Wind Farm (RWE Eemshaven)	NL	Green	280
Hydrogenpilot Oosterwolde	NL	Green	2.8
HyFLEET:CUTE, Amesterdam	NL	Green	0.84
HyNetherlands, 1st phase	NL	Green	280
HyNetherlands, 2nd phase	NL	Green	1820
HyNetherlands, 3rd phase	NL	Green	700
Hyoffwind Zeebrugge, 1st phase	BE	Green	2.8
Hyoffwind Zeebrugge, 2n phase	BE	Green	67.2
Hyport	BE	Green	140
Hysolar Green on Road - Nieuwegein	NL	Green	5.6
HySynGas	DE	Green	140
HyWindBalance	DE	Green	0.84
Ijmuiden project	NL	Green	280
Lingen BP Refinery	DE	Green	140
MefCO2	DE	Green	2.8
Norddeutsches Reallabor	DE	Green	215.6
NorthH2 green hydrogen phase 1	NL	Green	11200
Nouryon 200 MW electrolyzer	NL	Green	560
P2P IPKW	NL	Green	2.8
Pilotprojekt Power-to-Gas Ibbenbüren	DE	Green	0.42
Port of Rotterdam BP refinery	NL	Green	700
PosHYdon	NL	Green	2.8
Power 2 Metal	DE	Green	0
Producing Hydrogen by Gasification of Biomass in 'het Groene	NL	Blue	3.36
Project H2ermes	NL	Green	280
REEFUEL (Kiwi AG & Alternoil)	DE	Green	16.8
REFHYNE	DE	Green	28
Regenerativer Energiepark Ostfalia	DE	Green	0.01
RH2-WKA	DE	Green	2.8
Rozenburg Power2Gas Phase 2	NL	Green	0.02
Shell - Port of Rotterdam	NL	Green	560
TF_Energiewende	DE	Green	0
Wasserstoffelektrolyse-Anlage	DE	Green	14

Hydrogen production Project name	Country	Color	Annual hydrogen production [GWh_{th}]
Wasserstoffverbund Hamburg	DE	Green	280
Westküste100	DE	Green	84
wind2gas energy / WindWasserstoff Bunsbüttel	DE	Green	6.72
WindGas Hamburg	DE	Green	2.8
Zuidwending	NL	Green	2.8

A.2 Results

Table 6: Hydrogen production and demand by NUTS 3 regions

Region	Nuts 3 Code	Hydrogen production [TWh]	Hydrogen demand industry [TWh]		Hydrogen demand mobility [TWh]	
			High	Low	High	Low
Bremen, Stadt	DE501	0.28	2.457	1.229	0.032	0.016
Bremerhaven, Stadt	DE502	0	0	0	0.007	0.004
Hamburg	DE600	0.51	0.134	0.067	0.121	0.061
Braunschweig, Stadt	DE911	0	0	0	0.014	0.007
Salzgitter, Stadt	DE912	0	3.279	1.639	0.006	0.003
Wolfsburg, Stadt	DE913	0	0	0	0.005	0.003
Gifhorn	DE914	0	0	0	0.009	0.004
Goslar	DE916	0	0	0	0.010	0.005
Helmstedt	DE917	0	0	0	0.006	0.003
Northeim	DE918	0	0	0	0.009	0.004
Peine	DE91A	0	0	0	0.008	0.004
Wolfenbüttel	DE91B	0	0	0	0.006	0.003
Göttingen	DE91C	0	0	0	0.025	0.012
Diepholz	DE922	0.16	0	0	0.025	0.012
Hameln-Pyrmont	DE923	0	0	0	0.008	0.004
Hildesheim	DE925	0	0	0	0.014	0.007
Holzminden	DE926	0	0	0	0.005	0.002
Nienburg/Weser	DE927	0	0	0	0.014	0.007
Schaumburg	DE928	0	0	0	0.010	0.005
Region Hannover	DE929	0	0.004	0.002	0.063	0.031
Celle	DE931	0	0	0	0.011	0.006
Cuxhaven	DE932	0	0	0	0.012	0.006
Harburg	DE933	0	0	0	0.017	0.009
Lüchow-Dannenberg	DE934	0	0	0	0.004	0.002
Lüneburg	DE935	0	0	0	0.012	0.006
Osterholz	DE936	0	0	0	0.006	0.003
Rotenburg (Wümme)	DE937	0	0	0	0.022	0.011

Region	Nuts 3 Code	Hydrogen production [TWh]	Hydrogen demand industry [TWh]		Hydrogen demand mobility [TWh]	
			High	Low	High	Low
Heidekreis	DE938	0	0	0	0.010	0.005
Stade	DE939	1.81	0	0	0.016	0.008
Ülzen	DE93A	0	0	0	0.005	0.003
Verden	DE93B	0	0	0	0.010	0.005
Delmenhorst, Stadt	DE941	0	0	0	0.004	0.002
Emden, Stadt	DE942	0	0	0	0.003	0.001
Oldenburg, Stadt	DE943	1.12	0	0	0.008	0.004
Osnabrück, Stadt	DE944	0	0	0	0.012	0.006
Wilhelmshaven, Stadt	DE945	0.09	0	0	0.003	0.001
Ammerland	DE946	0.28	0	0	0.012	0.006
Aurich	DE947	0	0	0	0.014	0.007
Cloppenburg	DE948	0	0	0	0.021	0.011
Emsland	DE949	0.44	0.065	0.033	0.034	0.017
Friesland	DE94A	0	0	0	0.006	0.003
Grafschaft Bentheim	DE94B	0	0	0	0.011	0.005
Leer	DE94C	0	0	0	0.014	0.007
Oldenburg (Oldenburg)	DE94D	0	0	0	0.011	0.005
Osnabrück	DE94E	0	0	0	0.033	0.016
Vechta	DE94F	0	0	0	0.024	0.012
Wesermarsch	DE94G	0	0	0	0.008	0.004
Wittmund	DE94H	0.02	0	0	0.004	0.002
Düsseldorf, Stadt	DEA11	0	0	0	0.029	0.014
Duisburg, Stadt	DEA12	1.74	12.169	6.084	0.026	0.013
Essen, Stadt	DEA13	0	0	0	0.027	0.014
Krefeld, Stadt	DEA14	0.16	0	0	0.009	0.005
Mönchengladbach, Stadt	DEA15	0	0	0	0.016	0.008
Mühlheim a.d. Ruhr, Stadt	DEA16	0	0	0	0.007	0.003
Oberhausen, Stadt	DEA17	0	0	0	0.009	0.005
Remscheid, Stadt	DEA18	0	0	0	0.006	0.003
Solingen, Stadt	DEA19	0	0	0	0.007	0.003
Wuppertal, Stadt	DEA1A	0	0	0	0.017	0.009
Kleve	DEA1B	0	0	0	0.023	0.011
Mettmann	DEA1C	0	0	0	0.027	0.013
Rhein-Kreis Neuss	DEA1D	0.30	0.512	0.256	0.042	0.021
Viersen	DEA1E	0	0	0	0.025	0.012
Wesel	DEA1F	0.14	0	0	0.031	0.016
Bonn, Stadt	DEA22	0	0	0	0.052	0.026
Köln, Stadt	DEA23	0	0.118	0.059	0.055	0.027
Leverkusen, Stadt	DEA24	0.25	0	0	0.009	0.005
Düren	DEA26	0	0	0	0.020	0.010
Rhein-Erft-Kreis	DEA27	0.19	0.957	0.478	0.034	0.017
Euskirchen	DEA28	0	0	0	0.015	0.007
Kreis Heinsberg	DEA29	0	0	0	0.018	0.009

Region	Nuts 3 Code	Hydrogen production [TWh]	Hydrogen demand industry [TWh]		Hydrogen demand mobility [TWh]	
			High	Low	High	Low
Oberbergischer Kreis	DEA2A	0	0	0	0.019	0.009
Rheinisch-Bergischer Kreis	DEA2B	0	0	0	0.013	0.006
Rhein-Sieg-Kreis	DEA2C	0.05	0	0	0.033	0.017
Städteregion Aachen	DEA2D	0	0	0	0.033	0.017
Bottrop, Stadt	DEA31	0	0	0	0.006	0.003
Gelsenkirchen, Stadt	DEA32	0	1.067	0.533	0.016	0.008
Münster, Stadt	DEA33	0	0	0	0.017	0.008
Borken	DEA34	0	0	0	0.035	0.018
Coesfeld	DEA35	0	0	0	0.018	0.009
Recklinghausen	DEA36	0	0	0	0.033	0.016
Steinfurt	DEA37	0.05	0	0	0.038	0.019
Warendorf	DEA38	0	0	0	0.019	0.010
Bielefeld, Stadt	DEA41	0	0	0	0.018	0.009
Gütersloh	DEA42	0	0	0	0.037	0.018
Herford	DEA43	0	0	0	0.017	0.009
Höxter	DEA44	0	0	0	0.011	0.006
Lippe	DEA45	0	0	0	0.024	0.012
Minden-Lübbecke	DEA46	0	0	0	0.027	0.014
Paderborn	DEA47	0	0	0	0.024	0.012
Bochum, Stadt	DEA51	0	0	0	0.018	0.009
Dortmund, Stadt	DEA52	0	0	0	0.030	0.015
Hagen, Stadt	DEA53	0	0	0	0.012	0.006
Hamm, Stadt	DEA54	0	0	0	0.012	0.006
Herne, Stadt	DEA55	0	0	0	0.007	0.003
Ennepe-Ruhr-Kreis	DEA56	0	0	0	0.020	0.010
Hochsauerlandkreis	DEA57	0	0	0	0.023	0.011
Märkischer Kreis	DEA58	0	0	0	0.027	0.014
Olpe	DEA59	0	0	0	0.010	0.005
Siegen-Wittgenstein	DEA5A	0	0	0	0.020	0.010
Soest	DEA5B	0	0	0	0.020	0.010
Unna	DEA5C	0	0	0	0.022	0.011
Kreisfreie Stadt Flensburg	DEF01	0	0	0	0.003	0.001
Kreisfreie Stadt Kiel	DEF02	0.08	0	0	0.014	0.007
Lübeck, Hansestadt	DEF03	0	0	0	0.007	0.003
Kreisfreie Stadt Neumünster	DEF04	0	0	0	0.003	0.002
Kreis Dithmarschen	DEF05	3.08	1.223	0.611	0.005	0.002
Kreis Herzogtum Lauenburg	DEF06	0	0	0	0.006	0.003
Kreis Nordfriesland	DEF07	0	0	0	0.007	0.004
Kreis Ostholstein	DEF08	0	0	0	0.005	0.003
Kreis Pinneberg	DEF09	0	0	0	0.010	0.005
Kreis Plön	DEF0A	0	0	0	0.004	0.002
Kreis Rendsburg-Eckernförde	DEF0B	0	0	0	0.008	0.004
Kreis Schleswig-Flensburg	DEF0C	0	0	0	0.009	0.004

Region	Nuts 3 Code	Hydrogen production [TWh]	Hydrogen demand industry [TWh]		Hydrogen demand mobility [TWh]	
			High	Low	High	Low
Kreis Segeberg	DEF0D	0	0	0	0.007	0.004
Kreis Steinburg	DEF0E	0	0	0	0.004	0.002
Kreis Stormarn	DEF0F	0	0	0	0.006	0.003
Oost-Groningen	NL111	0.01	0	0	0.017	0.008
Delfzijl en omgeving	NL112	0.30	1.693	0.847	0.008	0.004
Overig Groningen	NL113	15.54	0	0	0.030	0.015
Noord-Friesland	NL124	0.29	0	0	0.024	0.012
Zuidwest-Friesland	NL125	0	0	0	0.014	0.007
Zuidoost-Friesland	NL126	0	0	0	0.020	0.010
Noord-Drenthe	NL131	0	0	0	0.016	0.008
Zuidoost-Drenthe	NL132	0.78	0	0	0.019	0.010
Zuidwest-Drenthe	NL133	0	0	0	0.014	0.007
Noord-Overijssel	NL211	0	0	0	0.038	0.019
Zuidwest-Overijssel	NL212	0	0	0	0.012	0.006
Twente	NL213	0	0	0	0.042	0.021
Veluwe	NL221	0	0	0	0.059	0.029
Zuidwest-Gelderland	NL224	0	0	0	0.030	0.015
Achterhoek	NL225	0	0	0	0.037	0.019
Arnheim/Nijmegen	NL226	0	0	0	0.042	0.021
Flevoland	NL230	0.28	0	0	0.034	0.017
Utrecht	NL310	0.01	0	0	0.059	0.029
Kop van Noord-Holland	NL321	0.28	0	0	0.031	0.015
Ijmond	NL323	0.28	8.531	4.266	0.011	0.005
Agglomeratie Haarlem	NL324	0	0	0	0.006	0.003
Zaanstreek	NL325	0	0	0	0.011	0.006
Het Gooi en Vechtstreek	NL327	0	0	0	0.008	0.004
Alkmaar en omgeving	NL328	0.01	0	0	0.011	0.005
Groot-Amsterdam	NL329	0.56	0	0	0.062	0.031
Agglomeratie's-Gravenhage	NL332	0	0	0	0.022	0.011
Delft en Westland	NL333	0.56	0	0	0.023	0.011
Agglomeratie Leiden en Bollenstreek	NL337	0	0	0	0.022	0.011
Zuidoost-Zuid-Holland	NL33A	0	0	0	0.029	0.015
Oost-Zuid-Holland	NL33B	0	0	0	0.022	0.011
Groot-Rijnmond	NL33C	5.47	1.567	0.783	0.131	0.065
Zeeuwsch-Vlaanderen	NL341	0	2.778	1.389	0.012	0.006
Overig Zeeland	NL342	2.80	0	0	0.024	0.012
West-Noord-Brabant	NL411	0.06	0	0	0.066	0.033
Midden-Noord-Brabant	NL412	0	0	0	0.039	0.019
Noordoost-Noord-Brabant	NL413	0	0	0	0.056	0.028
Zuidoost-Noord-Brabant	NL414	0.28	0	0	0.055	0.028
Noord-Limburg	NL421	0	0	0	0.039	0.019
Midden-Limburg	NL422	0	0	0	0.023	0.011
Zuid-Limburg	NL423	0	1.608	0.804	0.035	0.017

Region	Nuts 3 Code	Hydrogen production [TWh]	Hydrogen demand industry [TWh]		Hydrogen demand mobility [TWh]	
			High	Low	High	Low
Bruxelles-Capitale	BE100	0	0	0	0.031	0.016
Antwerpen	BE211	0.32	1.686	0.843	0.094	0.047
Mechelen	BE212	0	0	0	0.033	0.016
Turnhout	BE213	0	0	0	0.045	0.022
Tongeren	BE223	0	0	0	0.017	0.008
Hasselt	BE224	0.25	0	0	0.046	0.023
Maaseik	BE225	0	0	0	0.025	0.012
Aalst	BE231	0	0	0	0.020	0.010
Dendermonde	BE232	0	0	0	0.017	0.008
Eeklo	BE233	0	0	0	0.008	0.004
Gent	BE234	0	5.688	2.844	0.058	0.029
Oudenaarde	BE235	0	0	0	0.012	0.006
Sint-Niklaas	BE236	0	0	0	0.027	0.013
Halle-Vilvoorde	BE241	0	0	0	0.042	0.021
Leuven	BE242	0	0	0	0.024	0.012
Brugge	BE251	0.07	0	0	0.031	0.015
Diksmuide	BE252	0	0	0	0.006	0.003
Ieper	BE253	0	0	0	0.015	0.007
Kortrijk	BE254	0	0	0	0.024	0.012
Oostende	BE255	0.28	0	0	0.012	0.006
Roeselare	BE256	0	0	0	0.021	0.011
Tielt	BE257	0	0	0	0.022	0.011
Veurne	BE258	0	0	0	0.005	0.003
Nivelles	BE310	0	0	0	0.022	0.011
Mons	BE323	0	0.585	0.292	0.013	0.007
Tournai-Mouscron	BE328	0	0	0	0.013	0.006
La Louviere	BE329	0	0	0	0.018	0.009
Ath	BE32A	0	0	0	0.005	0.002
Charleroi	BE32B	0	0	0	0.021	0.010
Soignies	BE32C	0	0	0	0.008	0.004
Thuin	BE32D	0	0	0	0.005	0.002
Huy	BE331	0	0	0	0.008	0.004
Liege	BE332	0	0	0	0.033	0.016
Waremme	BE334	0	0	0	0.003	0.002
Verviers - commune francophones	BE335	0	0	0	0.012	0.006
Verviers - deutschsprachige Gemeinde	BE336	0	0	0	0.004	0.002
Arlon	BE341	0	0	0	0.004	0.002
Bastogne	BE342	0	0	0	0.005	0.003
Marche-en-Famenne	BE343	0	0	0	0.005	0.002
Neufchateau	BE344	0	0	0	0.005	0.003
Virton	BE345	0	0	0	0.003	0.001
Dinant	BE351	0	0	0	0.009	0.005
Namur	BE352	0.11	0	0	0.018	0.009

Region	Nuts 3 Code	Hydrogen production [TWh]	Hydrogen demand industry [TWh]		Hydrogen demand mobility [TWh]	
			High	Low	High	Low
Philippeville	BE353	0	0	0	0.003	0.002

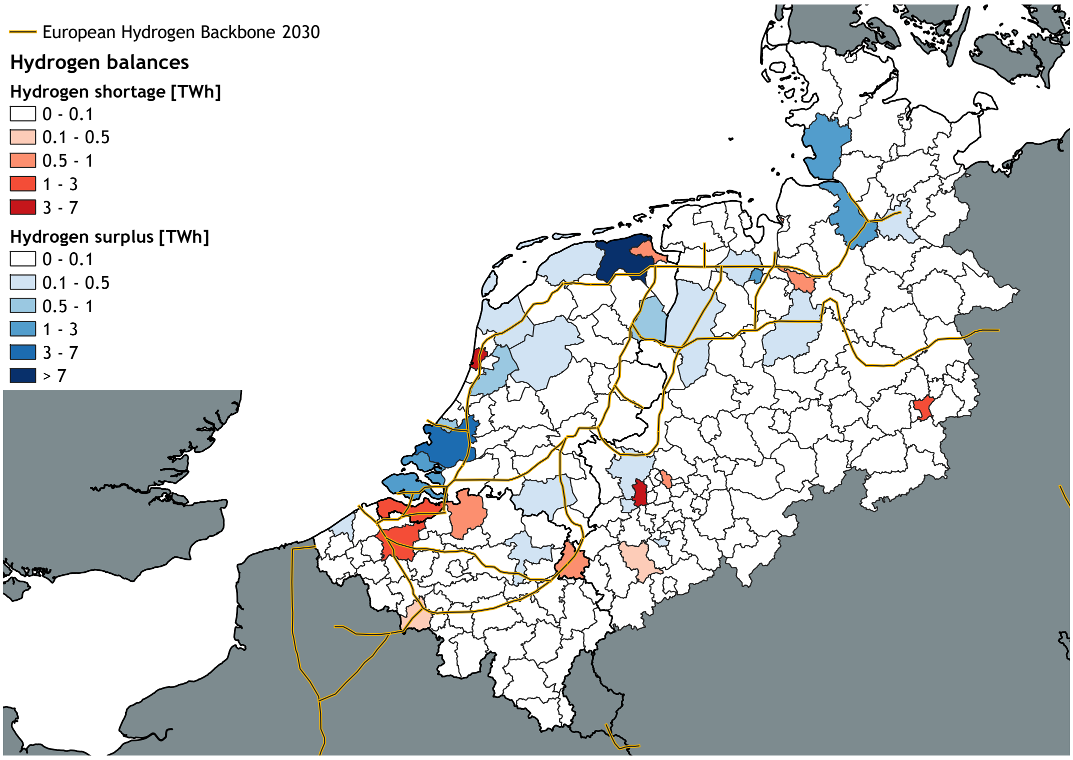

Figure 9: Low demand scenario with hydrogen balance by specific NUTS 3 regions

Sources: Own illustration and Gas for Climate (2020)