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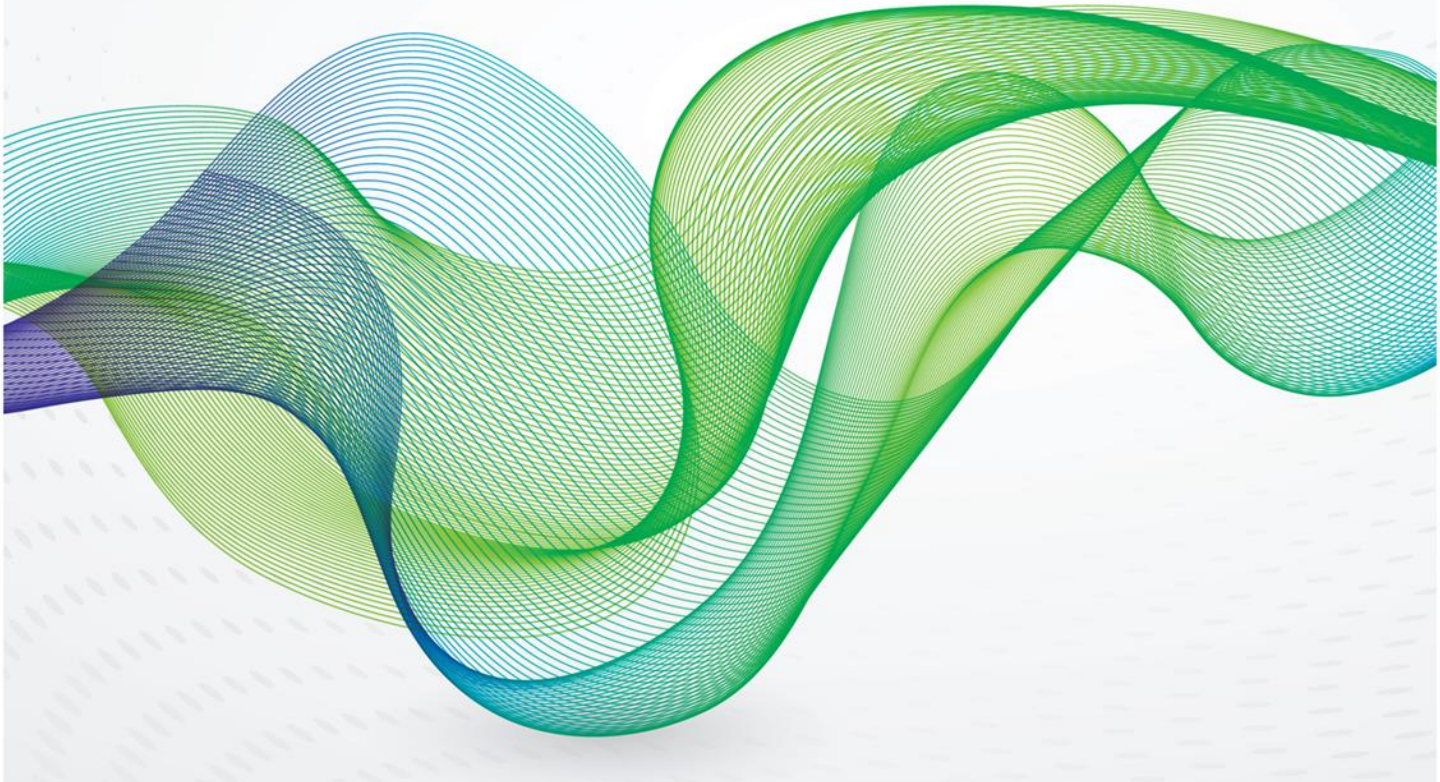
Contrasting European hydrogen pathways:

An analysis of differing approaches in key markets



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1. Introduction

The year 2020 will be remembered as the year when the Covid-19 pandemic swept the world, but it has also seen increasing momentum behind the urgency of tackling the longer-term global challenge of climate change, with more and more countries making pledges to achieve "net-zero" emissions. The UK and France started in mid-2019 with targets to achieve net-zero by 2050, but perhaps the most significant development in 2020 was the pledge by China to achieve net-zero by 2060.

In this context, there has also been growing momentum behind the view that low-carbon hydrogen will play a significant role in the decarbonisation of the energy system. Decarbonisation will certainly lead to a significant increase in the role of electricity, with it perhaps meeting over 50 per cent of final energy demand by 2050, compared with typically around 20 per cent today. Currently, the remaining 80 per cent of final energy demand is provided by molecules like oil, gas, and coal. There will still be a significant role for molecules as well as electrons in the future decarbonised world. Since the unabated use of fossil fuels will not be consistent with net-zero targets, low-carbon, or preferably zero-carbon, hydrogen will be required. Further details on the potential for hydrogen and some of the challenges, particularly around cost and scale, have been covered in previous OIES and EWI papers published during 2020.[1]

In Europe, the EU published its Hydrogen Strategy[2] in July 2020, closely linked to its Energy Sector Integration Strategy. Several European countries have also published their own hydrogen strategies during 2020 (e.g. Netherlands, Norway, Portugal, Germany, France, and Spain). While other countries (e.g. Italy and the UK) have not yet finalised formal strategies, they are actively developing plans for hydrogen to play a role in the energy transition. Outside Europe, several other countries have also published hydrogen strategies.[3]

While it is relatively straightforward to publish a document setting out a strategy, it is likely to be significantly more challenging to put in place the required budgets, incentives, and regulatory structures to enable the required investments to proceed within the aspired timetables. In this paper, we examine the intended hydrogen pathways in six key Western European markets and compare the approaches being developed in each of those countries. The selected countries are France, Germany, Italy, Netherlands, Spain, and the UK, chosen since they are all significant current natural gas markets and all are envisaging a significant role for hydrogen in the energy transition. It is notable that while all have similar ambitions and (apart from the UK) are all part of the EU, there are different approaches being developed in each country. It is likely that the use of molecules in the decarbonised energy system will vary by country and region, perhaps to a greater extent than the rather homogenous natural gas market across Europe today.

The paper is structured with an initial summary section (Section 2) with some overall themes and comparisons between the individual countries. This is followed by sections on each country arranged in alphabetical order, for those readers who would like more detail on each country. Each section is

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[1] Lambert (2020a) https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/Insight-66-Hydrogen-and-Decarbonisation-of-Gas.pdf , Dickel (2020): https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/06/Blue-hydrogen-as-an-enabler-of-green-hydrogen-the-case-of-Germany-NG-159.pdf, Barnes/Yafimava (2020) https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/09/Insight-73-EU-Hydrogen-Vision-regulatory-opportunities-and-challenges.pdf, Schlund/Schulte/Sprenger (2021) https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2021/03/EWI_WP_21-02_The_Whos_who_of_a_hydrogen_market_ramp-up_Schlund_Schulte_Sprenger.pdf, Brändle/Schönfisch/Schulte (2020) https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2020/11/EWI_WP_20-04_Estimating_long-term_global_supply_costs_for_low-carbon_Schoenfisch_Braendle_Schulte-1.pdf, Schulte/Lencz/Schlund/Baumgart/Berger/Mansius (2020) https://www.ewi.uni-koeln.de/en/news/policy-brief-regulation-hydrogen-networks/ and Schulte/Schlund (2020) https://www.ewi.uni-koeln.de/en/news/ewi-policy-brief-hydrogen-strategy/

[2] https://ec.europa.eu/commission/presscorner/api/files/attachment/865942/EU_Hydrogen_Strategy.pdf.pdf

[3] See, for example, https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_Executive-Summary_final.pdf for a summary description of the content of each strategy document.

structured with an initial consideration of relevant policy, followed by sections on current and potential hydrogen demand and then supply. Finally, Section 9 draws some overall conclusions.

2. Overview and Comparative Analysis

Sections 3 to 8 below review the current state of the hydrogen market and future plans for development of low-carbon hydrogen for each of the six selected countries. This section looks across countries to draw out some common themes and key differences between the countries.

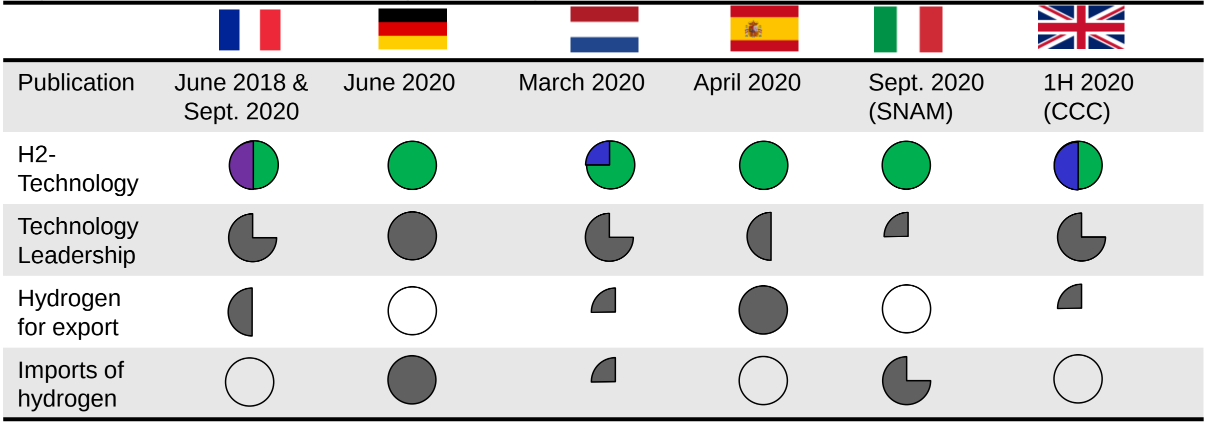
2.1. Policy drivers by country

While all six of the European countries considered have ambitions to grow production and use of low-carbon hydrogen, there are distinct differences between the policy drivers of each country. A more detailed comparison of the differences between international hydrogen strategies, both within and outside Europe has been published by the World Energy Council.[4] Figure 1 gives a high-level summary of some of the key differences between the six countries, and more details are provided in the Annex, but the paragraphs below explain the main policy drivers indicated in the diagram. Further details can be found in the policy section for each country.

Consistent with the EU hydrogen strategy, all countries see a significant long-term role for green hydrogen, made via electrolysis using renewable electricity. The UK, and to a lesser extent the Netherlands, are considering the use of blue hydrogen, using natural gas as a feedstock with carbon capture and storage, as an interim measure recognising the cost and scale-up challenges for green hydrogen. Germany, Spain, and Italy, however, see little if any role for blue hydrogen, although it remains to be seen whether this policy stance may have to soften as the challenges of production of green hydrogen at scale become apparent. France is unique in Europe for having a strong reliance on nuclear power generation (although many of its nuclear plants are now nearing end of life). Against that background, it is perhaps logical that it is also contemplating the potential production of hydrogen from electrolysis using nuclear electricity (sometimes referred to as “purple hydrogen”).

For most countries, there is an element of wishing to develop hydrogen technologies to position the country as a centre of excellence to export the technology globally. Germany, in particular, will not wish to repeat its experience in the solar panel industry where its initial lead in technology was very quickly overtaken by China.[5] Perhaps as a result, Germany appears to have the strongest emphasis on technology leadership, while France, Netherlands and the UK also see it as an important element in their approaches to low-carbon hydrogen.

Figure 1: Comparison of hydrogen strategies and policy drivers by country



	🇫🇷	🇩🇪	🇳🇱	🇪🇸	🇮🇹	🇬🇧
Publication	June 2018 & Sept. 2020	June 2020	March 2020	April 2020	Sept. 2020 (SNAM)	1H 2020 (CCC)
H2-Technology	◑	●	◕	●	●	◑
Technology Leadership	◕	●	◕	◑	◔	◕
Hydrogen for export	◑	○	◔	●	○	◔
Imports of hydrogen	○	●	◔	○	◕	○

Source: Authors’ analysis

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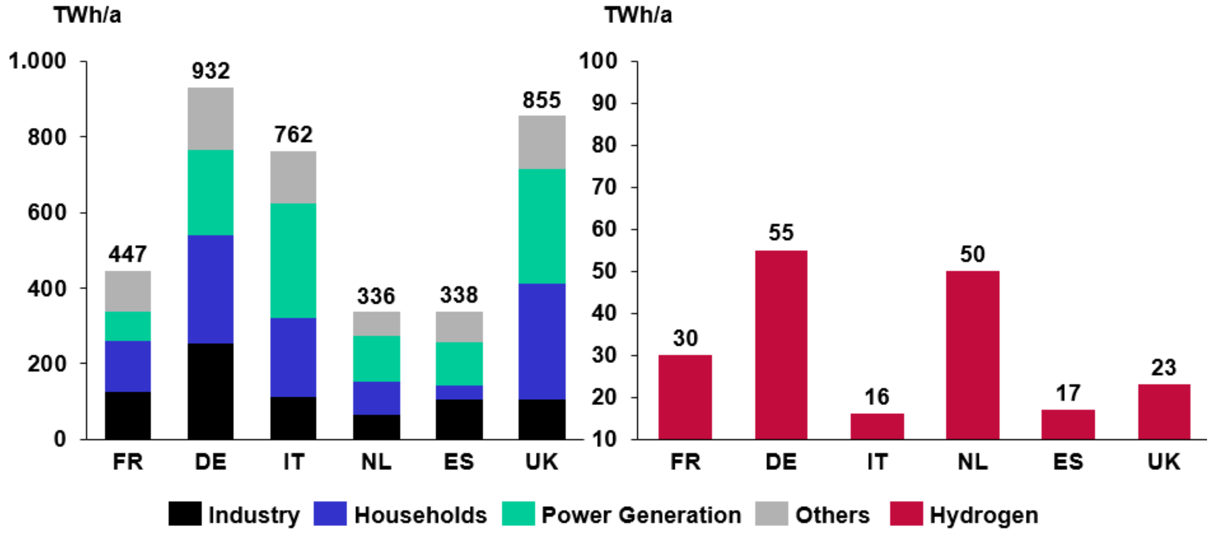
[4] https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_Executive-Summary_final.pdf
[5] http://large.stanford.edu/courses/2017/ph240/rojas1/

In terms of import/export, Germany is clear that it does not expect to be able to meet all of its demand for hydrogen from domestic production, so imports of low-carbon hydrogen will play a significant role. At the other extreme, Spain, with greater potential for large quantities of low-cost solar power sees itself as a potential significant exporter of hydrogen. Italy sees itself as a potential hub for imports into Europe from North Africa, although it is not clear at this stage the extent to which it envisages that there will be surplus hydrogen for further export northwards into the rest of Europe. The UK, with abundant offshore wind potential, and a more ready acceptance of CCS, sees a limited potential to export surplus hydrogen to neighbouring countries.

2.2 Hydrogen Demand

Current hydrogen demand, which is predominantly in the refining and ammonia industries, is summarised on the right-hand side of Figure 2. Germany and the Netherlands have the highest demand each in excess of 50 TWh hydrogen per year. Nearly all this production is currently grey hydrogen, so will need to be decarbonised or eliminated on the journey to net-zero. By contrast the left-hand side of Figure 2 shows the natural gas demand by sector in each country (note the left-hand y-axis scale is ten times the right-hand y-axis).

Figure 2: Current (2018) natural gas (left) and hydrogen (right) demand by country



Source: Authors' analysis of individual country data

In August 2020, the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) published a report reviewing the treatment of hydrogen in each Member State's (and the UK's) National Energy and Climate Plans.[6] These plans had been submitted to the EU by each country in late 2019/early 2020 with the next update due in 2025. The report then went on to develop low and high scenarios for renewable hydrogen production in 2030.

The development of these scenarios was made by calculating the penetration of low-carbon hydrogen as a percentage of total energy consumption in each key demand sector, under both low and high demand scenarios. The assumed penetration is given in Table 1. This shows that by far the largest percentage penetration is assumed to come from the refinery sector. This is logical, since the refinery sector (together with ammonia production) provides a readily available existing market for hydrogen. However, as can be seen from Table 1, the total energy demand of each sector has a significant impact in forecasting total hydrogen demand. Even though the transport sector is assumed to have only a 1 per cent (low case) or 2 per cent (high case) penetration in the demand forecasts, this translates into a

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[6] https://www.fch.europa.eu/publications/opportunities-hydrogen-energy-technologies-considering-national-energy-climate-plans

significant proportion (between 25-30 per cent) of the total low-carbon hydrogen demand in each country in 2030, particularly in the low scenario. Similarly in the building sector, an assumption of 0.75 per cent penetration in a low case and 7.5 per cent penetration in the high case (with the same value across all countries) appears somewhat questionable and leads to significant variation in demand projections. In each of the country sections, we give further information on the wide range of specific demand forecasts for those countries.

Our conclusion, however, is that there is limited value to be gained by placing undue emphasis on such demand forecasts. It will be more important to decarbonise the existing hydrogen production first and thereby increase the scale and reduce the costs of low-carbon hydrogen production. It is also important to explore the potential for new hydrogen demand in sectors where a significant new investment cycle will be taking place in the immediate future, for example in the steel industry in Germany. In parallel, research and development should continue to evaluate the use of hydrogen in other sectors, in particular to assess the extent and conditions under which hydrogen can provide a cost-effective pathway to decarbonisation in each sector, compared with alternatives such as electrification. For example, if hydrogen is to play a role in decarbonising buildings, it will be important to have early

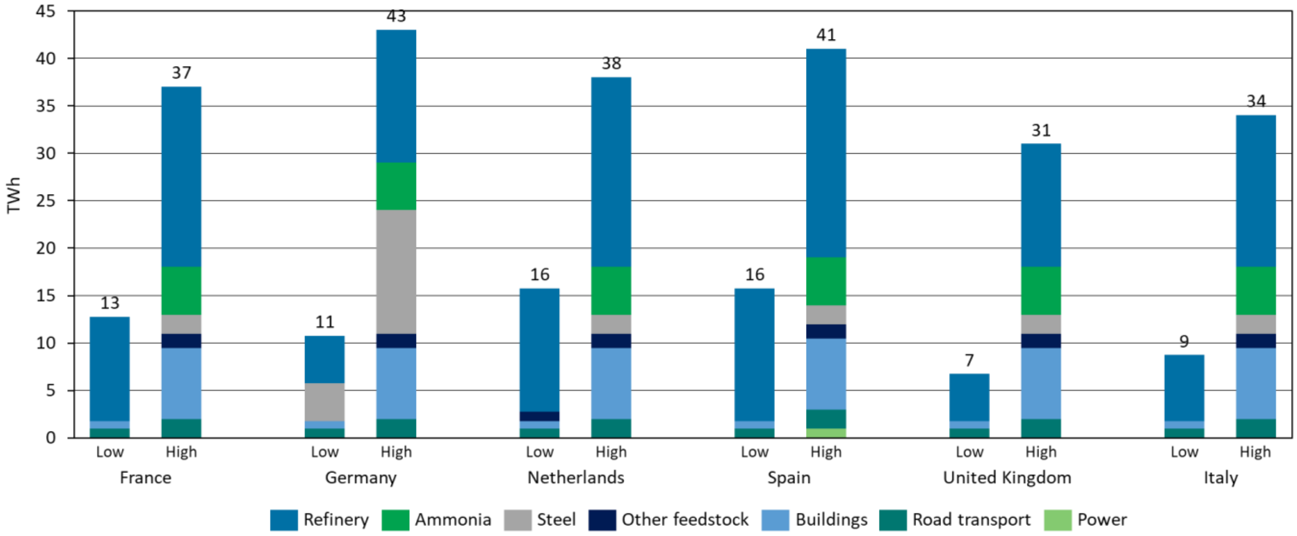
indications and associated policy of the relative merits of electric heat pumps and hydrogen boilers from an overall system perspective. It is also important that policy measures are developed to incentivise low-carbon hydrogen production. For the purpose of this study, it is clear that hydrogen demand is very unlikely to constrain low-carbon hydrogen production up to 2030.

Table 1: FCH JU assumed penetration in 2030 of low carbon hydrogen by country and sector

	Refinery	Ammonia	Steel	Other feedstock	Buildings	Road Transport	Power
Low scenario							
France	11%	0%	0		0,75%	1%	0%
Germany	5%	0%	4%		0,75%	1%	0%
Netherlands	13%	0%	0	1%	0,75%	1%	0%
Spain	24%	0%	0		0,75%	1%	0%
United Kingdom	5%	0%	0		0,75%	1%	0%
Italy	7%	0%	0		0,75%	1%	0%
High scenario							
France	19%	5%	2%	1,5%	7,5%	2%	0%
Germany	14%	5%	13%	1,5%	7,5%	2%	0%
Netherlands	20%	5%	2%	1,5%	7,5%	2%	0%
Spain	22%	5%	2%	1,5%	7,5%	2%	1%
United Kingdom	13%	5%	2%	1,5%	7,5%	2%	0%
Italy	16%	5%	2%	1,5%	7,5%	2%	0%

Source: Authors' analysis of FCH JU data

Figure 3: FCH JU low and high scenarios for 2030 hydrogen demand by sector and country



Source: authors' analysis of FCH JU data[6]

Given such a wide range of demand forecasts for 2030, it is not surprising that there is an even wider range of forecasts for 2050. For example (see individual sections for details), 2050 forecasts for the UK range from a low of 100 TWh to a high of 500 TWh and for Germany from 150 TWh to 550 TWh. At this stage, there is little value in trying to analyse the differences; the focus should be on the costs and scale of potential production and the policy drivers required to move along the pathway towards low-carbon hydrogen.

2.3 Hydrogen Supply

Today, hydrogen is predominantly produced from fossil fuels, accompanied by the generation of large amounts of CO_2, emitted into the atmosphere. Since it is produced close to consumption, there is no need for large-scale transportation. However, there are several options to replace this carbon-intensive hydrogen and expand production to make hydrogen available as an energy carrier. The leading low-carbon technologies targeted by European countries are electrolysis of water (using RES or nuclear power) and natural gas-based processes in combination with CCUS or pyrolysis. This chapter will focus on these technologies.

2.3.1. Electrolysis of water

Hydrogen derived from water electrolysis accounts for less than one per cent of the hydrogen production in the six countries considered. However, due to decarbonisation ambitions accompanied by the expansion of RES, the future production potential is high. In general, two electricity sourcing options can be distinguished: electricity supply from dedicated plants (off-grid), for example offshore wind, and electricity supply from the grid. While in the former case electrolysis is directly supplied with the electricity from the dedicated low-carbon power plant, the latter option's carbon-intensity depends on the electricity market and the supply mix of each of the six countries under consideration. Hybrid systems, dedicated plants with a connection to the grid or market, are not considered in detail in this discussion.[7]

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[7] In liquid markets without grid bottlenecks as well as levies and surcharges, they would converge to the second option, (the electricity supply from the grid) since the dedicated RES plant would have the opportunity to sell its electricity to the market.

2.3.1.1. Electricity supply from dedicated plants

When considering electricity supply from dedicated plants, these plants need to be low-carbon electricity generation. The most discussed options for the large-scale electricity generation of low-carbon hydrogen are RES-based plants, namely photovoltaics, onshore and offshore wind energy or nuclear power plants.[8] While the latter can provide a constant and predictable electricity supply, the RES-based electricity supply is characterized by dependence on the weather and higher volatility.

The main advantage of electricity supply from dedicated plants is that no electricity grid connection is necessary. Hydrogen production from dedicated plants may help reduce bottlenecks within the electricity grid from volatile RES feed-in. This is, for example, the case in Germany, where RES potential is in the windy areas in northern Germany, and industrial demand is located in southern Germany. The main disadvantage is the high production costs or the levelized hydrogen costs (LCOH), especially for RES-based hydrogen generation. The costs comprise two aspects: the levelized cost of electricity generation (LCOE) and costs for the electrolysis (OPEX + CAPEX). Since capacity factors of RES are low, the full load hours of the electrolysis would be as well, resulting in high CAPEX impact on the LCOH. Hence, hydrogen production based on water electrolysis from dedicated RES plants is not currently competitive.

Costs of both RES and electrolysis plants are expected to decline, especially when production occurs at a large scale. Brändle et al. (2020)[9,10] estimate that learning curve effects are leading to a further decline of RES-based hydrogen costs. Figure 4 depicts the cost reduction potential identified by Brändle et al. (2020)[10] by 2030 under baseline assumptions for different RES technologies in selected European regions relevant for the six countries analysed. Figure 4 illustrates hydrogen-based production on photovoltaics in Southern[11] Europe, onshore wind in Western[12] and Northern[13] Europe, and offshore wind in the North Sea.[14] The LCOH vary between EUR 3-5/kg, depending on the technology and region. Onshore wind-based hydrogen in well-positioned areas with high-capacity factors (> 0.3) has comparably good production potential from a cost perspective. However, since this type of production is limited, it would account for a total capacity of around 19 million tonnes per year (Mtpa) of hydrogen production. Since this onshore wind potential will compete with direct use for the electricity sector's decarbonisation, it is unlikely to be available for hydrogen generation on a large scale.[15] For lower capacity factors (<0.3) the onshore wind potential of the six considered countries is more extensive (100 Mtpa).

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[8] It is important to mention that not only the electricity produced by the plant is low-carbon but also the plant itself, on a life cycle assessment basis.

[9] Brändle et al. (2020): Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen, EWI Working Paper 20/04, https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2020/11/EWI_WP_20-04_Estimating_long-term_global_supply_costs_for_low-carbon_Schoenfisch_Braendle_Schulte-1.pdf

[10] EWI provides an Excel tool that allows hydrogen production and import costs to be calculated for different countries: https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2020/12/Global_H2_Cost_Tool_v2.xlsx

[11] Average costs for Italy, Spain and Portugal.

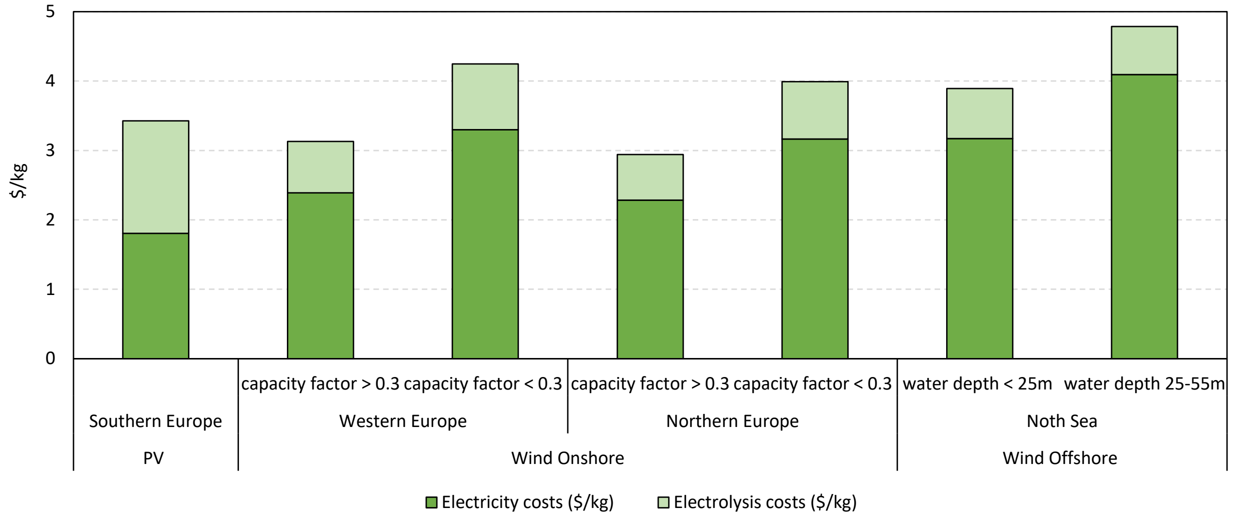
[12] Average costs for Spain, France, the Netherlands, Germany, Italy and the UK.

[13] Average costs for Norway, Denmark, Sweden and Finland.

[14] Average costs for North Sea neighbors Norway, Denmark, the Netherlands and the UK.

[15] See also Dickel (2020): https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/06/Blue-hydrogen-as-an-enabler-of-green-hydrogen-the-case-of-Germany-NG-159.pdf

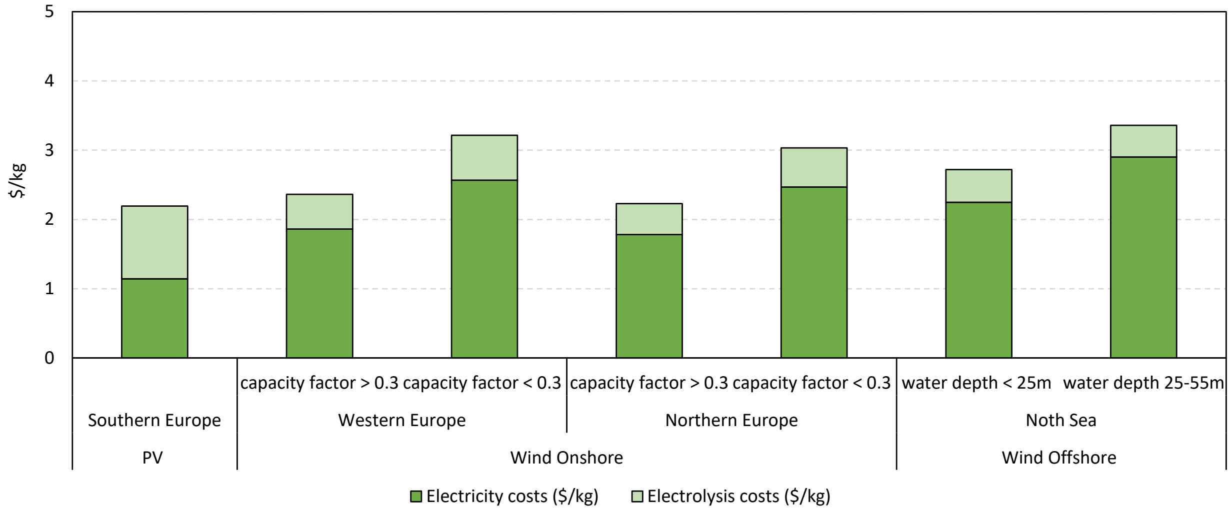
Figure 4: LCOH for green hydrogen production for selected RES technologies and regions by 2030



Source: Brändle et al, 2020

The same applies to PV-based hydrogen. While the potential in regions with higher capacity factors is limited (7 Mtpa), it is larger for lower capacity factors (0.125 - 0.2). For the Southern European countries of Spain and Italy, it amounts to 550 Mtpa hydrogen production. The potential for offshore wind-based hydrogen lies primarily in the North Sea, putting the neighbouring countries in a good position. While production costs for offshore wind-based hydrogen are higher, the technology has the advantage of higher capacity factors and contiguous area potential for large-scale electricity and hence hydrogen production. The hydrogen cost shares underline this observation for PV-based hydrogen and wind-based hydrogen. While the LCOE is expected to be lower for PV, it accounts for a large percentage of the LCOH of wind. However, due to higher wind capacity factors, especially offshore wind, electrolysis can be utilized more intensively in combination with wind-based electricity, resulting in higher full-load hours and lower capital costs for electrolysis.

Figure 5: LCOH for green hydrogen production for selected RES technologies and regions by 2050



Source: Brändle et al, 2020

By 2050, further cost reduction potential is likely for both RES technologies and electrolysis. According to Brändle et al., under baseline assumptions, the LCOH in Europe may vary between EUR 2/kg to more than EUR 3/kg hydrogen, as shown in Figure 5.

Hence, Southern European countries like Spain and Italy have the best potential to become large-scale producers of RES-based hydrogen, due to a large and comparable low-cost PV-potential. In Central European countries such as Germany, the Netherlands and the UK, PV plays only a minor role, due to limited capacity factors. While these countries have some good locations for onshore wind, the area potential is limited, especially for low-cost locations. Offshore wind potential in the North Sea benefits from high capacity factors and considerable area potential. It could be an option for countries bordering the North Sea such as Germany, the Netherlands, and the UK. However, the LCOH of offshore-based hydrogen is high, compared to other options. Among the countries considered within this paper, France has the largest onshore wind potential, with high capacity factors. Furthermore, with its large nuclear power plant fleet, France may benefit from low-cost, nuclear-based hydrogen production.

2.3.1.2. Electricity supply from the grid

The second important electricity supply option for large-scale hydrogen production using water electrolysis is supply from the grid or the electricity wholesale market. The main advantage of this option is that running the electrolysis does not depend on RES capacity factors. Hence, the electrolysis can run at higher full load hours, resulting in lower unit capital costs. Furthermore, hydrogen production can take place near to demand centres, such as large industrial clusters, avoiding hydrogen transportation costs.

However, while producing hydrogen near to demand areas saves on hydrogen transportation, it creates a need for electricity transportation, which has a lower energy density. For countries like Germany, where RES production and industrial demand are far apart, the increasing need for electricity close to demand centres may cause additional bottlenecks in the electricity grid infrastructure. Furthermore, it is necessary to ensure that grid electricity supply has low carbon intensity, which is not the case for most of the countries under consideration (see Table 2). With its extensive nuclear power plant fleet, France has a low carbon intensity electricity mix, while by contrast, the German and Dutch electricity mixes are characterized by large shares of coal- and gas-fired generation, resulting in higher carbon intensity. However, the average annual electricity mix provides only a rough estimation of the electricity supply's carbon intensity for water electrolysis in the respective countries. The determining factor is the marginal supply source at the relevant time, including electricity imports and the neighbouring country's marginal supply source. Thus, electrolysis should only operate when enough RES-based or low-carbon electricity is available. Ramping up coal, oil or natural gas-fired power plants to produce electricity to satisfy the additional need for water electrolysis should be avoided. Table 2 shows the occurrence of hours with negative prices in each of the countries, which can be interpreted as hours with excess electricity, which could be stored by transformation into hydrogen. However, with an increase of negative electricity prices, competition for these prices will increase, too. The more low-carbon electricity sources enter a country's electricity system, the less carbon-intensive supply sources will determine the marginal supply.

Table 2: Electricity system characteristics of individual countries

	DE	ES	FR	IT	NL	UK
Average CO_2 emission factor in electricity mix in 2019 (g CO_2e/kWh)[16]	338	207	52	233	390	228
Average electricity wholesale price 2019 (day-ahead) (euro/MWh)[17]	37.7	47.7	39.4	41.2	51.2	48.9
Number of occurrences of negative day-ahead prices in 2019[18]	211	0	27	0	3	1

Source: Authors' analysis

Today, taxes and levies imposed on electricity for water electrolysis vary from country to country. An exemption from levies could help to make production competitive. If a plant is placed in the right region to help reduce congestion in the electricity grid, it reduces the need for grid expansion. Under these conditions, it is reasonable to exempt such plants from grid tariffs. If electrolysis also supports the integration of surplus electricity and avoids curtailments, there is an argument for exempting these plants from renewable surcharges.

In some European countries, the electricity used for hydrogen production is already exempt from certain taxes and levies. In Germany, for example, the electricity used for electrolysis is free of grid charges for twenty years. There are also plans to reduce the renewable energy surcharge. In France, operators of electrolysis plants do not have to pay electricity tax. However, to create a level playing field within Europe and to guarantee that the electricity used by electrolysis comes from RES or is low-carbon, exemptions should be harmonized and linked to specific requirements, which are similar to those mentioned in the Renewal Energy Directive (REDII)[19], namely additionality, temporal, and geographical correlation.

2.3.2. Natural gas-based hydrogen with carbon capture

In all six countries considered in this paper, natural gas is currently the predominant hydrogen production source. However, transformation by steam methane reforming is accompanied by large amounts of CO_2 emitted into the atmosphere. To capture, transport, and store the CO_2, additional facilities and infrastructure are necessary.

As shown in Figure 6, the costs of natural gas-based hydrogen are very sensitive to natural gas prices. The figure shows LCOH for low-carbon hydrogen, RES-based (based on section 2.2.1) and natural gas-based production. It becomes clear that, particularly until 2030, RES-based hydrogen will not be

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[16] European Environment Agency (2020): Greenhouse gas emission intensity of electricity generation, https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6#tab-googlechartid_googlechartid_chart_111_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7B%22pre_config_date%22%3A%5B2018%5D%7D%3B%22sortFilter%22%3A%5B%22ugeo%22%5D%7D

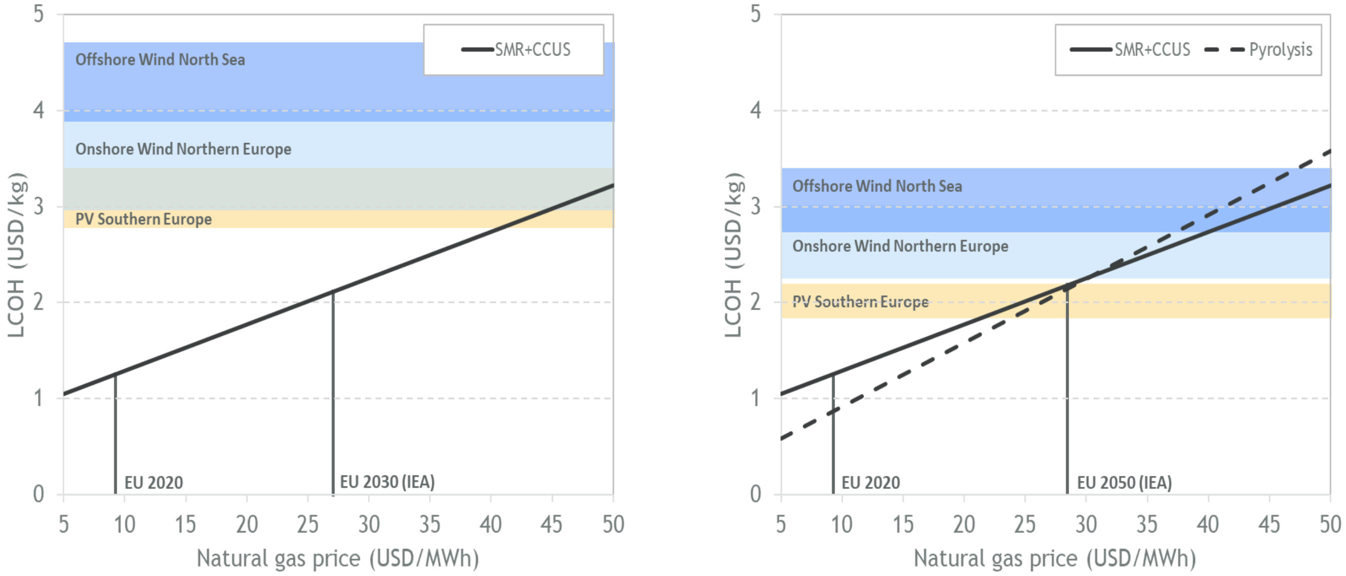
[17] ACER (2020), ACER Market Monitoring Report 2019, p. 19, https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Market%20Monitoring%20Report%202019%20-%20Electricity%20Wholesale%20Markets%20Volume.pdf

[18] ACER (2020), ACER Market Monitoring Report 2019, p. 23, https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Market%20Monitoring%20Report%202019%20-%20Electricity%20Wholesale%20Markets%20Volume.pdf

[19] Directive (EU) 2018/2001 of the European Parliaments and of the Council, p. 14, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

competitive if natural gas prices increase as predicted by the IEA.[20] In the long-run, only PV-based hydrogen production in Italy and Spain would be competitive with gas-based, low-carbon hydrogen, under the baseline estimations of Brändle et al (2020).[21]

Figure 6: Comparison of natural gas-based and RES-based hydrogen production in 2030 (left) and 2050 (right) based on Brändle et al.[22]



Since hydrogen transport needs additional or retrofitted infrastructure, the import of natural gas and conversion close to demand is more competitive. Infrastructure for import, transportation, and storage is sufficient within Europe, as shown in Table 3 and additionally some of the countries under consideration have domestic natural gas production. However, there is also an existing infrastructure for hydrogen transport.

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[20] IEA (2020) The Future of Hydrogen, p.2, https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf

[21] Brändle et al. (2020): Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen, EWI Working Paper 20/04, https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2020/11/EWI_WP_20-04_Estimating_long-term_global_supply_costs_for_low-carbon_Schoenfisch_Braendle_Schulte-1.pdf

[22] Brändle et al. (2020): Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen, EWI Working Paper 20/04, https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2020/11/EWI_WP_20-04_Estimating_long-term_global_supply_costs_for_low-carbon_Schoenfisch_Braendle_Schulte-1.pdf

Table 3: Comparison of the CO_2, natural gas and hydrogen infrastructure of the selected European countries

		DE	ES	FR	IT	NL	UK
CO_2 storage potential ($MtCO_2$)[23, 24]	**Onshore**	14,180	3,679	8,692	6,317	1,622	-
	Offshore	2,900	3,500	-	233	718	14,400
Domestic natural gas production (bcm/a)[25]		5	-	-	5	28	40
Natural gas import capacity (bcm/a)	**Pipeline[26]**	285	32	77	113	67	97
	LNG[27]	-	57	26	15	12	48
Natural gas transmission grid (km)		40,000[28]	11,000[29]	32,000[30]	9,590[31]	11,700[32]	7660[33]
Natural gas storage capacity (bcm)[34]		23	3	13	20	14	1
H_2 grid (km)[35]		390	-	303	8	237	40

Source: Authors' analysis

The world's largest hydrogen grid connects the Port of Rotterdam in the Netherlands with Belgium and France, while industrial gas suppliers Air Liquide and Linde also operate hydrogen transport infrastructure in Germany. However, these pipelines are predominantly used to connect industrial clusters that use hydrogen as a feedstock. The total length of hydrogen pipelines in Europe is less than 2000 km[36] compared with over 200,000 km of natural gas transmission pipelines (plus over 1 million km of natural gas distribution pipelines).[37] Compared to the transport of energy in the natural gas grid, hydrogen infrastructure is negligible.

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[23] Navigant Consulting (2019), Gas for Climate. The optimal role for gas in a net-zero emissions energy system, p.156, https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

[24] EU GeoCapacity (2009), Assessing European Capacity for Geological Storage of Carbon Dioxide, p. 21, https://ec.europa.eu/clima/sites/clima/files/docs/0028/geocapacity_en.pdf

[25] BP (2020), Statistical Review 2020, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-natural-gas.pdf, p.5

[26] ENTSOG (2019), Capacity Map 2019, https://www.entsog.eu/maps#, assumed calorific value: 11.11 kWh/m³

[27] GIE (2019), LNG Map 2019, https://www.gie.eu/download/maps/2019/GIE_LNG_2019_A0_1189x841_FULL_Final3.pdf

[28] FNB Gas (2021), Überregionaler und regionaler Gastransport bis zum Verbraucher, https://www.fnb-gas.de/gasinfrastruktur/marktteilnehmer/gasnetzbetreiber/

[29] Enagás S.A. (2016), Leader in natural gas infrastructures, p. 6, https://www.enagas.es/stfls/ENAGAS/Transporte%20de%20Gas/Documentos/CAT_English.pdf

[30] ENGIE S.A. (2021), Transportation, https://www.engie.com/en/activities/infrastructures/transportation

[31] Snam Rete Gas (2017), Ten-year network development plan of the natural gas transmission network 2017-2026, p.12, http://pianodecennale.snamretegas.it/static/upload/201/2017-2026-decennale-web_eng.pdf

[32] Gasunie Deutschland Transport Services GmbH (2021), The Gasunie network, https://www.gasunie.de/en/infrastructure/gasunie-netzwerk

[33] https://www.nationalgrid.com/uk/gas-transmission/

[34] AGSI (2021), https://agsi.gie.eu/#/, GCV 10kWh/m³

[35] H_2Tools (2021), Pipeline Infrastructure, https://h2tools.org/

[36] https://h2tools.org/hyarc/hydrogen-data/hydrogen-pipelines

[37] https://www.ceer.eu/documents/104400/-/-/0261ad33-6b06-f708-354b-5adf04683129

For gas-based hydrogen with CCS, long-term CO_2 storage in specific geological formations is necessary, with storage taking place in saline aquifers or depleted oil and gas fields. CO_2 is already injected into the latter for enhanced oil and gas recovery. While the acceptance of CO_2 storage is low in some European countries, e.g. Germany, storage potential is high. Table 3 shows the potential for CO_2 storage in the six countries considered in this paper. Because onshore storage faces acceptance issues, offshore storage in the North Sea is the most likely option, at least for the foreseeable future. In addition to the countries covered in this report, other North Sea neighbours like Norway (29,188 $MtCO_2$) or Sweden (14,900 $MtCO_2$) have enormous, identified CO_2 offshore storage potential that European countries could use.[38,39] However, a CO_2 infrastructure would be necessary to transport the CO_2 to storage.

Another option to produce low-carbon hydrogen from natural gas is pyrolysis, whereby natural gas is split into hydrogen and solid carbon and therefore no CO_2 escapes into the atmosphere. There are different pyrolysis technologies (e.g. thermal or plasma-based), but all technologies are at an early stage of development (Technical Readiness Level (TRL) 3 to 5), and production costs are very uncertain. Nonetheless, companies within Europe, especially Germany (e.g. BASF[40]) are currently researching pyrolysis. Brändle et al. (2020) estimated that pyrolysis is even more sensitive to the natural gas price than steam methane reforming (Figure 6). Like gas-based hydrogen with CCS, pyrolysis could take place close to demand, using the existing gas import infrastructure. There would be no need for CO_2 storage since the hydrogen by-product, the solid carbon (ca. 3.3 kg carbon per 1 kg hydrogen[41]), could be stored or used as a feedstock.

2.4. Summary Conclusion

Government policy remains the key driver in the growth of low-carbon hydrogen production. While the aspiration of each country is becoming clearer, there is as yet little clarity on the precise policy mechanisms which will be put in place to enable the required investments leading to significant low-carbon hydrogen production. It is expected that in the course of 2021 further clarity on such mechanisms will be provided by further EU directives and policy publications from individual country governments. OIES and EWI intend to follow such developments and provide further commentary as appropriate.

There is a very wide range of hydrogen demand forecasts in each of the countries being considered. This broad spectrum is largely based on widely varying assumptions of the extent to which different sectors will become significant for hydrogen consumption. In particular, space heating and transport show large variations depending on assumptions on the extent to which consumers will adopt electric solutions (heat pumps and BEVs respectively). A larger uptake of electrical solutions, which, where they are possible, typically have a higher efficiency, will lead to a smaller role for low-carbon hydrogen. The use of hydrogen to decarbonise industry is a common theme in projections for all countries and provides a solid baseline for potential hydrogen demand, until at least 2030. Longer term, there is a possibility that heavy industry may relocate to those regions, both within and outside Europe, with large and low-cost renewable energy potential, but that should not constrain initial development of low-carbon hydrogen supply within Europe.

On the supply side, even over the six countries considered in this study, there is a wide variety of different approaches being considered with different rationales. Blue hydrogen is only being considered in the Netherlands and the UK, where public and government opinion regarding carbon capture and storage, at least as a transition solution, is more favourable. Green hydrogen is favoured in the southern European countries of Spain and Italy, perhaps with some justification as the higher incidence of solar

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[38] Navigant Consulting (2019), Gas for Climate. The optimal role for gas in a net-zero emissions energy system, p.156, https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

[39] A project that is currently taking place is “Northern Lights”, a joint project of Equinor, Shell and Total (https://northernlightsccs.com/en/about)

[40] A. Bode. New process for clean hydrogen - BASF research press conference 2019. Technical report, 2019.

[41] Oeko-Instiut (2020), Wasserstoff sowie wasserstoffbasierte Energieträger und Rohstoffe, p. 52, https://www.oeko.de/fileadmin/oekodoc/Wasserstoff-und-wasserstoffbasierte-Brennstoffe.pdf

irradiation leads to lower cost solar PV electricity. Germany is also focused on green hydrogen mainly because of the societal unacceptability of carbon capture and storage. We remain unconvinced of the logic for significant investment in hydrogen from electrolysis as long as marginal incremental power generation is provided by fossil fuels. It would be more logical to focus on blue hydrogen initially, until around 2030 when there should be sufficient large-scale renewable power generation to justify significant investment in electrolysis. France is perhaps the outlier among the countries under consideration, on account of its high share of nuclear power generation. While it remains uncertain to what extent France will continue to rely on nuclear power in the future, at this stage consideration is being given to hydrogen production using nuclear electricity to drive electrolysers at times of low electricity demand.

Comparing supply and demand projections, it is clear that at least until 2030 total low-carbon hydrogen supply (both blue and green) will be lower than the existing industrial use of grey hydrogen. Thus, there is scope for the production of low-carbon hydrogen to be accelerated, without any limitation on demand. That statement, however, ignores pricing considerations, since without clear policy drivers, existing users of grey hydrogen will have little incentive to switch to higher cost low-carbon hydrogen.

3. France

3.1. Policy Framework

In 2018, France published its national hydrogen plan,[42] the first European country to do so. The plan, developed by the Ministry for Ecological Transition, targeted the launch of a hydrogen sector in France with the country aiming to become the world leader in hydrogen technologies. It addressed the entire energy system, in particular hydrogen and electricity storage. Two years later, the French government, supported by the Ministry for Ecological Transition and the Ministry of Economics and Finance, published a further hydrogen development strategy as part of its COVID-19 recovery plan. This strategy highlights the role of decarbonised or carbon-free hydrogen. It defines decarbonised hydrogen as hydrogen which uses RES-based or carbon-free electricity. While not explicitly mentioned, the latter option includes electricity generated by nuclear power stations.

In its action against COVID-19, the French government is providing financial support for a market ramp-up of carbon-free hydrogen to support the economic recovery. Investment support of EUR 7 bn until 2030 should strengthen the French industry and generate up to 150,000 jobs in the hydrogen sector. About half of this financial support will be provided in the first phase (through to 2023), and will address the following three priorities: industry (54 per cent), transport and trade (27 per cent), research and development (19 per cent). The financial support does not address the heating sector.

The government has set a target for an installed electrolysis capacity of 6.5 GW by 2030, the most ambitious target within the EU so far. However, since electrolysis in France can use carbon-free nuclear electricity, which has low variable costs and high full load hours, hydrogen production could be competitive with other RES-dependent regions or countries. By 2022, the financial support for large-scale industrial electrolysis will have amounted to EUR 1.5 bn with the research and development and industrialization taking place in close cooperation with Germany.

Measures defined in the National Hydrogen Strategy

On the supply side, the government is aiming for a reduction in electrolyser costs. Unit cost reduction can be achieved by a high number of full load hours and when the electrolysis is powered by electricity from the grid, the strategy assumes that 4,000-5,000 full load hours are possible. In France, around one-third of the electricity price comprises taxes and surcharges. However, while the operator of an electrolysis system has to pay network charges (TURPE), they are exempted from taxes (specifically

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[42] Ministère de la Transition écologique et Solidaire (2018), Plan de déploiement de l’hydrogène pour la transition énergétique, https://www.ecologie.gouv.fr/sites/default/files/Plan_deploiement_hydrogene.pdf

the contribution to the public electricity service, known as CSPE), which reduces electricity supply costs by EUR 22.5/MWh.[43] Compared to other European countries, French electricity prices are low, due to the above-mentioned large share of nuclear power generation.

The French hydrogen plan from 2018 defines specific hydrogen targets for the industrial and transport sectors on the demand side but does not address the household heating sector. The industrial sector has the highest priority for carbon-free hydrogen application, and here, the government plans to replace carbon-intense hydrogen consumption by carbon-free hydrogen. By 2023, the national hydrogen plan sees a replacement of 10 per cent (around 90 thousand tonnes per year), rising to 20-40 per cent (180 to 360 thousand tonnes per year) by 2028.

The second priority is the mobility sector, especially heavy-duty vehicles and the government is pursuing an ambitious strategy to decarbonise this sector. Its Energy Transition Law for Green Growth (LTECV) introduced a clean mobility strategy and the Climate Plan notably foresees the end of diesel and petrol car sales by 2040. Individual French cities are also actively reducing local emissions (for example, Paris has a stated ambition to end the use of diesel cars by 2024 and petrol cars by 2030).[44] Financial public support is provided for pilot projects for river shuttles and hydrogen-powered vessels and the aviation sector. Furthermore, targets have been set for FCEV (5,000 by 2023, 20,000-50,000 by 2028) and fuel cell trucks (200 by 2023, 800-2,000 by 2028) as well as hydrogen filling stations (100 by 2023, 400-1,000 by 2028). The French strategy aims to support FCEV for captive fleets with predictable driving and refuelling patterns and regular visits to a depot to address the lack of infrastructure in the transport sector.[45] Examples are light commercial vehicles, heavy-duty vehicles, buses, or household waste disposal trucks.

3.2. Hydrogen Demand

In France, hydrogen demand accounts for around 0.9 million tonnes per year (30 TWh energy equivalent).[46] Almost all consumption occurs in the industrial sector, especially in refining, the chemical industry, fertiliser production, and metallurgy. By contrast, French natural gas demand in 2018 is shown in Table 4.

Table 4: Final energy consumption for natural gas in 2018

Sector	Gas Consumption (TWh)
Households	137
Industry	124
Services	92
Mobility	3
Power Generation	75
Energy Industry – Other	17
Total	**447**

Source: Eurostat (2020)

Until 2050, hydrogen demand is projected to grow by a factor of six in France, according to a study by the French Association for Hydrogen and Fuel Cells (AFHYPAC). The association includes all major hydrogen stakeholders, such as Air Liquide, Alstom, EDF, Engie, and Total. It estimates a demand of

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[43] RTE (2020), La transition vers un hydrogène bas carbone, p.59, http://www.avere-france.org/Uploads/Documents/1584099723ff44570aca8241914870afbc310cdb85-rapport_hydrogene_RTE.pdf

[44] L'Association Française pour l'Hydrogène et les Piles à Combustible (AFHYPAC) (2018), Développons l'Hydrogène pour l'économie française, p.8, https://www.afhypac.org/documents/actualites/pdf/Afhypac_Etude%20H2%20Fce_VDEF.pdf

[45] Mobilité Hydrogène France (2019), Hydrogen Mobility in France, https://www.tresor.economie.gouv.fr/Articles/120903c7-34bc-49b1-a324-b1f6ba0dbf53/files/5828cf4a-96d5-4eb5-9966-c3cfff882fe2

[46] Ministère de l'Écologie, du Développement durable et de l'Énergie and Ministère de l'Économie, de l'Industrie et du Numérique (2015), Filière hydrogène-énergie, p.14, https://www.economie.gouv.fr/files/files/directions_services/cge/filiere-hydrogene-energie.pdf

5.5 million tonnes in 2050, which would correspond to a share of about 20 per cent of the country's final energy demand, [47] a lower forecast for hydrogen penetration than some other European countries, such as Germany. The French energy system is already characterised by a large share of electrification, due to the high proportion provided by nuclear which offers low-carbon and stable electricity generation at a low cost. However, electrification is not possible for all processes and sectors, even with a reliable and low-cost electricity supply, so the potential for hydrogen demand varies by sector.

In France, half of the hydrogen consumption within the industrial sector[48] occurs in ammonia production, a base material for fertilizer production.[49] France has one of the largest agriculture sectors within Europe, and fertiliser production is correspondingly large. In 2018, the country consumed 2.1 million tonnes of fertiliser or around 21 per cent of the EU27 consumption.[50] Seven of the fifty one major fertilizer plants in Europe are located in France.[51] Refineries also account for a large share and consume more than one-third of the country's hydrogen production.[49] Currently, hydrogen consumption is mainly covered by so-called grey hydrogen, natural gas-based hydrogen that releases carbon emissions to the atmosphere. Hence, low-carbon hydrogen could be used to decarbonise the existing feedstock within the chemical and refining industries. Since the French ammonia and refining markets are mature, demand growth is limited apart from substitution of grey by low-carbon hydrogen.

The French steel industry paints a different picture, with high demand growth potential for low-carbon hydrogen. Here, low-carbon hydrogen could serve as a reducing agent to produce carbon-free steel. In 2019, France produced around 14 million tonnes of crude steel, making the country the third-largest steel producer within the EU27.[52] Since the processes required to produce carbon-free steel are at an early stage of development, hydrogen penetration in this sector needs time and financial support without which low-carbon steel will not be competitive in the global market.

Besides using hydrogen as a feedstock for industrial processes, low-carbon hydrogen may play an essential role in decarbonizing industrial energy, mainly by replacing natural gas consumption to generate high-temperature process heat. In 2016, industrial natural gas consumption for heat was around 90 TWh in France.[53] However, CO_2-abatement by using low-carbon hydrogen for heating is expensive compared to natural gas and a minimum price for CO_2 would be necessary to make hydrogen competitive. However, the level of this required CO_2-price will depend on the levies and surcharges of electricity used for hydrogen generation as well as individual industrial applications. If natural gas-based heating is the benchmark, a high CO_2-price would be necessary. Therefore, apart from initial large-scale demonstration projects, significant penetration is unlikely before 2030.[54]

Demand growth potential is also seen in France's transport sector. The country has a robust automotive industry, including two of the world's ten largest car manufactures. Both of these (the PSA Groupe and

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[47] L'Association Française pour l'Hydrogène et les Piles à Combustible (AFHYPAC) (2018), Développons l'Hydrogène pour l'économie française, p.9, https://www.afhypac.org/documents/actualites/pdf/Afhypac_Etude%20H2%20Fce_VDEF.pdf

[48] https://cefic.org/our-industry/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/

[49] Ministère de l'Écologie, du Développement durable et de l'Énergie and Ministère de l'Économie, de l'Industrie et du Numérique (2015), Filière hydrogène-énergie, p.32, https://www.economie.gouv.fr/files/files/directions_services/cge/filiere-hydrogene-energie.pdf

[50] Eurostat (2020), Consumption of inorganic fertilizers, https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=aei_fm_usefert&lang=en

[51] Fertilizers Europe (2020), Industry facts and figures, p.8, https://www.fertilizerseurope.com/wp-content/uploads/2020/07/Industry-Facts-and-Figures-2020-spreads.pdf

[52] European Steel Association (Eurofer) (2020), European Steel in Figures, p.14, https://www.eurofer.eu/assets/Uploads/European-Steel-in-Figures-2020.pdf

[53] J. Oriol (2020), Barometer Wärmeverbrauch in Frankreich, Deutsch-französisches Büro für die Energiewende (DFBEW), p.5, https://energie-fr-de.eu/files/ofaenr/04-notes-de-synthese/02-acces-libre/05-efficacite-chaleur/2020/DFBEW_Barometer_Waerme_Frankreich_2011.pdf

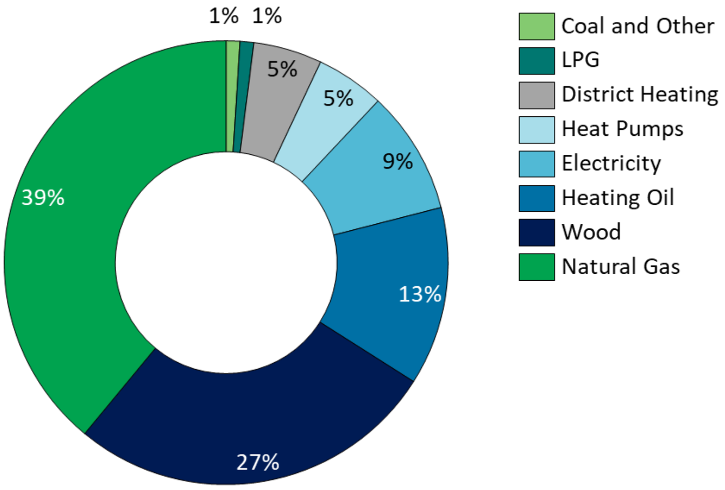
[54] Ministère de l'Écologie, du Développement durable et de l'Énergie and Ministère de l'Économie, de l'Industrie et du Numérique (2015), Filière hydrogène-énergie, p.14, https://www.economie.gouv.fr/files/files/directions_services/cge/filiere-hydrogene-energie.pdf

Renault[55]) support the development of FCEV. The same applies to the two sizeable automotive suppliers Faurecia and Michelin, which have started a joint venture to develop and produce fuel cells on a large scale.[56] However, the country lacks hydrogen filling stations so far, with currently only fifteen stations in use.[57]

Despite these ambitions, only around 300 light-duty FCEVs were registered in France in 2019, mainly in Paris and the Île-de-France region. Around one third belong to "Hype", the world's first zero-emission taxi fleet, a project launched at the COP21 in Paris in 2015, with the company planning to operate 600 hydrogen taxis by the end of 2020.[58] Additionally, more than 80 fuel cell-based buses are in the process of being developed all over the country.[59]

Further demand potential is evident in the aviation sector, as this is a sector which is hard to electrify. Hydrogen is one option for decarbonising the aerospace industry, while another is the use of hydrogen-based synthetic fuels. The industry is one of France's key export industries with Airbus SE, Europe's largest aerospace corporation, located in Toulouse. In 2020, Airbus launched a concept for a hydrogen-fuelled commercial aircraft, which could enter service by 2035.[60]

Figure 7: French heating sector by source[61]



In the French household heating sector, natural gas heating systems are the prevailing technology. In 2018, 39 per cent of energy consumption for heating was provided by natural gas (Figure 7). Around 27 per cent of the household heating systems were fuelled by wood. However, at 13 per cent, the share of electricity in the French heating system is already high, compared to other European countries.

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[55] FuelCellWorks (2019), Renault Introduces Hydrogen into its Light Commercial Vehicles Range, https://fuelcellsworks.com/news/renault-introduces-hydrogen-into-its-light-commercial-vehicles-range/

[56] Autovista Group (2019), New hydrogen venture to develop vehicle systems in France, https://autovistagroup.com/news-and-insights/new-hydrogen-venture-develop-vehicle-systems-france

[57] European Alternative Fuels Observation (2020), France - H2 Filling Stations, https://www.eafo.eu/countries/france/1733/infrastructure/hydrogen

[58] Zefer (2019), Kouros Invests In Zero-emission Hydrogen Taxis Hype, https://zefer.eu/uncategorised/kouros-invests-in-zero-emission-hydrogen-taxis-hype/

[59] Mobilité Hydrogène France (2019), Hydrogen Mobility in France, p. 8, https://www.tresor.economie.gouv.fr/Articles/120903c7-34bc-49b1-a324-b1f6ba0dbf53/files/5828cf4a-96d5-4eb5-9966-c3cfff882fe2

[60] Airbus (2020), Airbus reveals new zero-emission concept aircraft, https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html

[61] J. Oriol (2020), Barometer Wärmeverbrauch in Frankreich, Deutsch-französisches Büro für die Energiewende (DFBEW), p.3, https://energie-fr-de.eu/files/ofaenr/04-notes-de-synthese/02-acces-libre/05-efficacite-chaleur/2020/DFBEW_Barometer_Waerme_Frankreich_2011.pdf

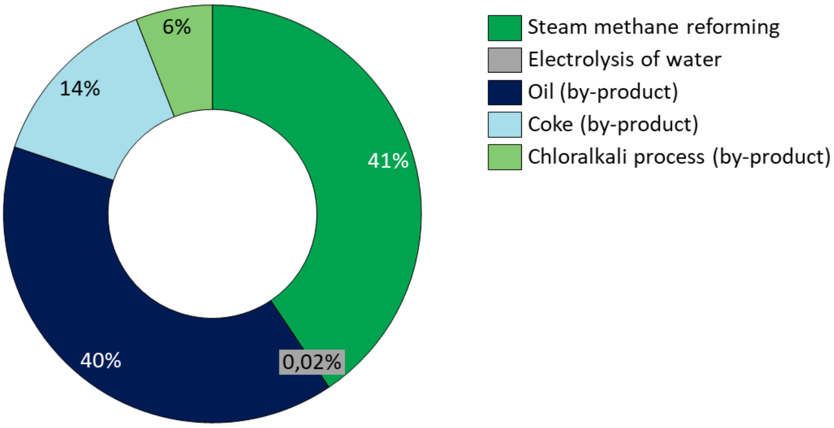
However, most of these are inefficient electric heating systems (nine per cent), due to low French electricity prices. Since a new regulation on thermal insulation was launched in 2012, more efficient heat pump systems have become the prevailing heating technology for new single-family houses and heat pumps now account for five per cent of the installed heating systems in France. Around thirteen per cent of systems are still fuelled by oil. District heating systems provided around five per cent of the household heat supply and they play an essential role in the area around Paris (Ile-de-France) and Auvergne-Rhône-Alpes.[62]

Low electricity prices and public funding for the expansion of renewable energy sources in the heating sector (biomass, geothermal, solar thermal, and district heating) will further suppress inefficient oil and gas boilers, and inefficient electric heating systems in the household sector.[63] However, efficient gas condensing boilers have the advantage that they could use a limited share (up to around 20 per cent) of hydrogen without modification. Hence, a proportion of natural gas demand could be replaced by hydrogen in the long term.

3.3. Hydrogen Supply

As in the other countries, natural gas is the dominant source for current hydrogen production in France. Currently, 41 per cent of the hydrogen produced is based on steam methane reforming (SMR). The remaining 59 per cent is produced as a by-product, for example coming from oil in refineries or chloralkaline processes. Water electrolysis-based hydrogen production currently plays a minor role in overall French hydrogen production (Figure 8).[64] However, the 0.9 mt hydrogen produced annually emits approximately 10 million tonnes of CO_2, around two to three per cent of total French carbon emissions.[65]

Figure 8: Current hydrogen production by technology in France [66]



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[62] J. Oriol (2020), Barometer Wärmeverbrauch in Frankreich, Deutsch-französisches Büro für die Energiewende (DFBEW), p.3, https://energie-fr-de.eu/files/ofaenr/04-notes-de-synthese/02-acces-libre/05-efficacite-chaleur/2020/DFBEW_Barometer_Waerme_Frankreich_2011.pdf

[63] J. Oriol (2020), Barometer Wärmeverbrauch in Frankreich, Deutsch-französisches Büro für die Energiewende (DFBEW), p.6, https://energie-fr-de.eu/files/ofaenr/04-notes-de-synthese/02-acces-libre/05-efficacite-chaleur/2020/DFBEW_Barometer_Waerme_Frankreich_2011.pdf

[64] Ministère de l'Écologie, du Développement durable et de l'Énergie and Ministère de l'Économie, de l'Industrie et du Numérique (2015), Filière hydrogène-énergie, p.14, https://www.economie.gouv.fr/files/files/directions_services/cge/filiere-hydrogene-energie.pdf

[65] RTE (2020), La transition vers un hydrogène bas carbone, p.14, http://www.avere-france.org/Uploads/Documents/1584099723ff44570aca8241914870afbc310cdb85-rapport_hydrogene_RTE.pdf

[66] Ministère de l'Écologie, du Développement durable et de l'Énergie and Ministère de l'Économie, de l'Industrie et du Numérique (2015), Filière hydrogène-énergie, p.14, https://www.economie.gouv.fr/files/files/directions_services/cge/filiere-hydrogene-energie.pdf

In France, the industrial gas producer Air Liquide operates a hydrogen transmission network close to the Belgium border, which connects several hydrogen sources and sinks in France, Belgium, and the Netherlands, comprising large industrial clusters, such as the ports of Rotterdam and Antwerp. In total, it accounts for 1,103 km which makes it the world's largest hydrogen pipeline network.[67] The privately-owned network is not regulated, and hydrogen is marketed through bilateral contracts. In comparison, the regulated French natural gas network comprises 232,000 km of pipelines.[68]

3.3.1 Electrolysis of water

French RES-based hydrogen production, using water electrolysis, currently accounts for less than one per cent of total hydrogen production. The current electrolysis capacity amounts to around 1 MW with an additional 900 MW currently planned or under construction.[69] According to its hydrogen strategy, France plans an installed capacity of 6.5 GW by 2030, the highest target within the EU27.[70]

The technical potential for RES-based electricity is high in France, estimated at more than 2,000 TWh/yr, of which around 1,500 TWh/y

r is from onshore wind.[71] Electricity generation is currently dominated by nuclear power, with an installed nuclear power capacity of 60 GW in 2017 which produced 75 per cent of French electricity.[72] By 2035, the government plans to reduce nuclear generation to 50 per cent and replace it by RES.[73] Nonetheless, over the next fifteen years, nuclear power plants could help to ramp-up France's hydrogen economy: due to low variable costs and stable generation, water electrolysis could benefit from high full load hours, fuelled by 'excess' nuclear energy. This relatively low-cost, nuclear-based hydrogen could help grow the French hydrogen market and necessary infrastructure in the mid-term.

3.3.2 Natural gas-based hydrogen with carbon capture

A further option to produce low-carbon hydrogen is the combination of steam methane reforming with carbon capture and storage (CCS) or utilization. France's potential for CCS is limited due to the limited CO_2 storage potential, which amounts to around 8,000 $MtCO_2$,[74] mainly in onshore saline aquifers in Central and Southwest France.[75] Furthermore, the societal acceptance for CCS is unclear and a CO_2 transport infrastructure is necessary. French industrial gas producer Air Liquide operates a carbon capture facility in Port Jerome, Northern France.[76] The facility consists of a steam methane reformer that supplies up to 40,000 tonnes of hydrogen a year to a nearby refinery.[77] Since 2015, the facility has been expanded to capture the remaining carbon dioxide for utilization in the food and beverage industry, capturing around 100,000 tonnes of CO_2 a year.[78]

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[67] F. Ausfelder et. al (2017), Energy Storage as Part of a Secure Energy Supply, ChemBioEng Reviews, p.31, https://onlinelibrary.wiley.com/doi/full/10.1002/cben.201700004

[68] Engie (2021) https://www.engie.com/en/activities/infrastructures/transportation

[69] IEA (2020), Hydrogen Projects Database, https://www.iea.org/reports/hydrogen-projects-database

[70] RTE (2020), La transition vers un hydrogène bas carbone, http://www.avere-france.org/Uploads/Documents/1584099723ff44570aca8241914870afbc310cdb85-rapport_hydrogene_RTE.pdf

[71] T. Hubert and E. Vidalenc (2012), Renewable Electricity Potentials in France: A Long Term Perspective, Energy Procedia, p.253, https://www.sciencedirect.com/science/article/pii/S1876610212007552

[72] World Nuclear Association (2020), Nuclear Power in France, https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx

[73] J. Stones (2020), French strategy boasts largest 2030 electrolyser hydrogen capacity, ICIS, https://www.icis.com/explore/resources/news/2020/09/11/10551839/french-strategy-boasts-largest-2030-electrolyser-hydrogen-capacity

[74] EU GeoCapacity (2009), Assessing European Capacity for Geological Storage of Carbon Dioxide, p. 21, https://ec.europa.eu/clima/sites/clima/files/docs/0028/geocapacity_en.pdf

[75] IEA (2020), ETP: Special Report on Carbon Capture Utilisation and Storage, p. 136.

[76] D. Pichot et al. (2017), Start-up of Port-Jérôme CRYOCAP™ Plant: Optimized Cryogenic CO2 Capture from H2 Plants, Energy Procedia, https://www.sciencedirect.com/science/article/pii/S1876610217317265

[77] CertiHy (2020), Pilot project, https://certifhy.eu/project-description/pilot-projects.html

[78] IEA (2020), Hydrogen Projects Database, https://www.iea.org/reports/hydrogen-projects-database

4. Germany

4.1. Policy Framework

To support the development of hydrogen within Germany, the government published its "National Hydrogen Strategy" in June 2020.[79] Initially, the plan was to publish the document in December 2019, and the delay highlights the discrepancy between the ministries involved, namely the Federal Ministry for Economic Affairs and Energy (BMWi), the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU), and the Federal Ministry of Education and Research (BMBF). Besides the German National Hydrogen Strategy, several regional strategies have been published, including those for North-Rhine Westphalia,[80] Bavaria,[81] Eastern and Northern Germany.[82]

To speed up the hydrogen market rollout within Germany the government is making EUR 7 bn available for hydrogen and hydrogen-related projects or instruments. Financial support of a further EUR 2 bn will be provided for international partnerships. The federal government believes that only RES-based hydrogen will be sustainable in the long term. Hence, only this kind of hydrogen is addressed and supported by the national strategy. It does recognise that other forms of low-carbon hydrogen will be an option in other countries, and therefore contemplates other forms of low-carbon hydrogen imports (e.g. natural gas-based blue hydrogen), at least initially.

The government strategy includes a two-stage plan of action. The first ‘ramp-up’ phase lays the foundation for a well-functioning domestic hydrogen market through to 2023. To this end, the strategy outlines 38 measures, addressing supply and the different demand sectors. The second phase will strengthen this market ramp-up and provide a basis for European and international cooperation.

The strategy also sets a target for electrolysis capacity. By 2030, the strategy aims for a cumulative electrolysis capacity of 5 GW. A further 5 GW is planned between 2035 and 2040. However, this target emphasises the need for imports. The strategy projects hydrogen demand of 90-110 TWh in 2030. Assuming 4,000 full load hours (FLH) for electrolysis,[83] the targeted capacity of 5 GW generates 14 TWh of domestically produced RES-based hydrogen. Hence, according to the strategy, there is a domestic supply gap of 76-96 TWh by 2030. Beyond that date, according to the scenario mentioned above, the gap will be still higher.

To close the gap the government plans to import RES-based hydrogen from other EU member states, in particular those states that generate hydrogen from offshore wind in the North and Baltic Sea, or PV in southern Europe. Furthermore, cooperation with non-European countries is planned. However, if other European countries pursue similar hydrogen strategies, it is questionable if there will be enough RES-based hydrogen available to meet the projected demand. Additionally, many European countries still have a high share of fossil fuels in their electricity generation sector. It would be more efficient for them to use their domestic RES to decarbonise their own electricity generation instead of producing hydrogen and exporting it to Germany.[84]

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[79] BMWi (2020), Die Nationale Wasserstoffstrategie, https://www.bmbf.de/files/die-nationale-wasserstoffstrategie.pdf

[80] MWIDE NRW (2020), Wasserstoff Roadmap Nordrhein-Westfalen, https://broschuerenservice.land.nrw/files/5/d/5d2748f42f6b926ea2f21b529b968a47.pdf

[81] StMWi (2020), Bayerische Wasserstoffstrategie, https://www.stmwi.bayern.de/fileadmin/user_upload/stmwi/Publikationen/2020/2020-07-20_Wasserstoffstrategie_Broschuere-BF.pdf

[82] Wirtschafts- und Verkehrsministerien der norddeutschen Küstenländer (2019), Norddeutsche Wasserstoff Strategie, https://www.hamburg.de/contentblob/13179812/f553df70f865564198412ee42fc8ee4b/data/wasserstoff-strategie.pdf

[83] Assumed electrolysis efficiency is 70 per cent.

[84] Schulte & Schlund (2020), Hintergrund Nationale Wasserstoffstrategie [05/2020] https://www.ewi.unikoeln.de/cms/wpcontent/uploads/2020/05/EWI_Policy_Brief_Wasserstoffstrategie_20200519.pdf

Measures defined in the National Hydrogen Strategy

To promote RES-based hydrogen, the German government plans to check if it is possible to exempt the electricity used for electrolysis from taxes, surcharges, and levies. However, measures in the Climate Action Programme 2030, which is mentioned in the strategy, are not sufficient to make hydrogen production from water electrolysis competitive. The programme introduces carbon prices into the non-EU ETS sectors of mobility and heating and brings in a reduction of the renewable surcharge (Erneuerbare-Energien-Gesetz or EEG). While the carbon price will increase only slightly over time, to EUR 35/tonne by 2025, the EEG surcharge reduction is set at EUR 0.625/kWh in 2023 (a reduction of less than 10 per cent of the surcharge which was EUR 0.641/kWh in 2019). With the amendment of the EEG surcharge in 2021, there will be a further reduction for electrolysis plants which fulfil specific requirements, namely which ensure the electricity used for hydrogen generation is based on RES. However, the exact amount of the reduction and the conditions surrounding it have not been published yet but are expected during 2021.

Furthermore, the government will examine business cases or cooperation options between the operators of regulated electricity and gas networks. Here, investments in electrolysis could be an option to reduce bottlenecks in the electricity infrastructure. One open question is how the hydrogen that regulated entities will produce can find a way onto the market without creating market distortions.

On the demand side, the strategy defines measures for each sector. Strong support is primarily intended for the industrial and transport sectors. Energy-intensive industry that acts in an internationally competitive environment will benefit from investment grants for pilot projects for the switch-over from fossil-based technologies to climate-neutral ones. The focus will be on processes with inherent emissions in the chemical or steel industry (e.g. direct reduced iron). To support the supply of green hydrogen, the government will use carbon contracts for differences as a financial instrument to provide investment security for the industry, at least for the uncertain development of the carbon price. Because low-carbon production technologies are not competitive internationally, the government wants to explore solutions to protect the domestic industry.

To support green hydrogen in the transport sector, the EU Renewable Energy Directive II (REDII) will be implemented into national law in 2021. Furthermore, additional funds will be provided to continue incentives for the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP). These involve EUR 0.9 bn in purchase grants for utility vehicles powered by alternative, climate-friendly driveline technology and EUR 0.6 bn to purchase buses with alternative drivelines. Not explicitly addressed by the National Hydrogen Strategy but mentioned in an official document of the Federal Ministry of Transport and Digital Infrastructure (BMVI) are targets to ramp-up the number of refuelling-stations for FCEV.[85] Numbers are expected to increase from 100 stations in 2020 to 400 in 2025 and 1,000 in 2030. According to the National Hydrogen Strategy, further grants will be provided to develop these refuelling stations, especially for heavy-duty road haulage vehicles, public transport, and local passenger rail services. To facilitate the cross-border transport of FCEV within Europe, similar advocacy is planned at an EU level.

Measures for the heating sector fall short in the National Hydrogen Strategy. The necessity for hydrogen-based applications in the industrial sector, especially for the provision of high-temperature heat, are either not addressed at all or only in the long-term. Within the building sector, support for highly efficient fuel-cell heating systems will be continued and possibly expanded. Regarding combined heat and power generation, the government is looking to provide funding for 'hydrogen readiness' installations.

The motivation behind Germany’s National Hydrogen Strategy is to reduce carbon emissions in order to achieve the Paris Agreement's targets. On the supply side, it provides support for an industrial ramp-

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[85] Bundesministerium für Verkehr und digitale Infrastruktur: Nationaler Strategierahmen über den Aufbau der Infrastruktur für alternative Kraftstoffe [2014/94/EU]
https://www.bmvi.de/SharedDocs/DE/Anlage/G/MKS/mks-nationaler-strategierahmen-afid.pdf?__blob=publicationFile p. 30

up of RES-based hydrogen, while on the demand side, the focus lies on developing and commercialising low-carbon and hydrogen-based technologies. While this support may position German industry as a future leader and exporter of low-carbon technologies, domestic carbon emission reductions will not directly result from the strategy in the medium-term (the next ten years). However, if technologies become competitive in the long-term, large-scale adoption may lead to substantial emission reductions. The chicken-and-egg problem could be better addressed by technology-neutral support of low-carbon hydrogen technologies (including natural gas reforming or pyrolysis) to allow a faster ramp-up on the supply side. This would make more low-carbon hydrogen available at a lower cost for a quicker uptake in demand. Furthermore, more robust support on the demand side for all sectors would allow a better utilization and hence financing of the transport and storage infrastructure. As a result, decarbonisation of the energy system could take place by 2030.

4.2. Hydrogen Demand

Data on current hydrogen consumption in Germany is scarce. According to the National Hydrogen Strategy, hydrogen consumption amounted to 55 TWh[86] or around 1.65 Mt[87] in 2019. Almost all hydrogen consumption took place in the industrial sector, predominately in the chemical industry. Within this industry, around 85 per cent[88] of hydrogen demand can be assigned to two different sub-industries: (1) the base chemical industry (for example, ammonia and methanol production), and (2) refineries. Consumption by other sectors such as transport is insignificant. In comparison, German natural gas demand in 2018 is shown in Table 5.

Table 5: Final energy consumption for natural gas in Germany in 2018

Sector	Gas Consumption (TWh)
Households	287
Industry	253
Services	138
Mobility	10
Power Generation	224
Energy Industry – Other	20
Total	**932**

Source: Eurostat (2020)

There is considerable potential for hydrogen demand growth in Germany. Future scenarios from various studies that assume a substantial reduction of CO_2 emissions (a 95 per cent reduction by 2050 compared to 1990) see a high penetration of hydrogen (Figure 9). While studies like the Klimaschutzszenarien ("Climate Action Scenarios") by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety see moderate increases in hydrogen demand of up to 110 TWh in 2050, optimistic studies like the hydrogen study by the regional government of North-Rhine Westphalia projects increases of up to 643 TWh in 2050. The large range results from assumptions regarding the penetration of hydrogen in various sectors, which are discussed below.

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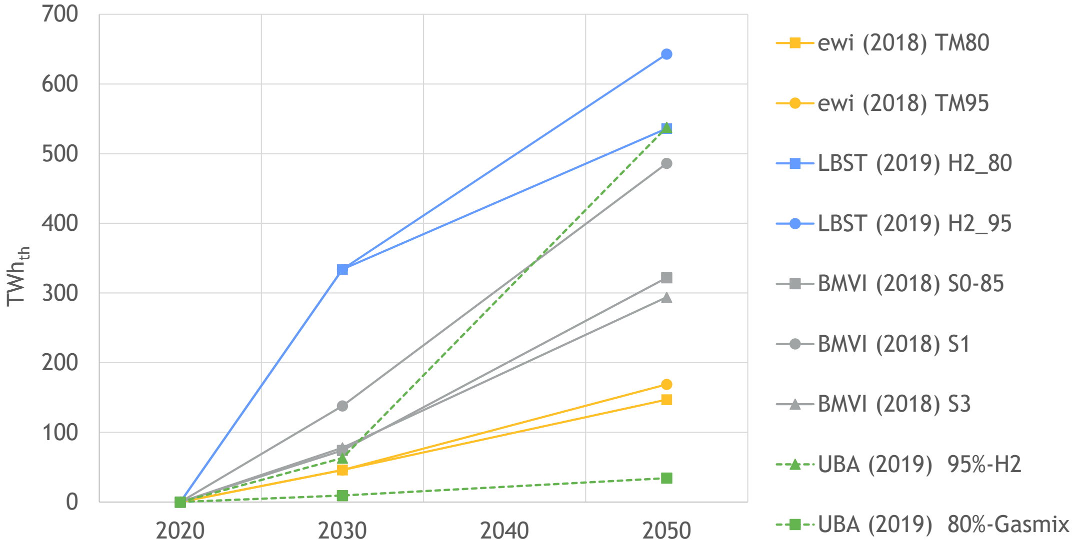
[86] The Federal Government 2020: The National Hydrogen Strategy. The number is based on a study of the Prognos AG, which is itself based on an ad-hoc-committee of the Federal Ministry of Education and Research from 1988 (*BMFT*, *Ad-hoc-Ausschuß* (Hrsg.) (1988b): *Solare Wasserstoff-Energiewirtschaft*. Gut achten und *wissenschaftliche Beiträge*, Bonn.). There are no statistics on the current hydrogen demand in Germany. https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6

[87] Heating value 33,3 kWh/kg.

[88] MWV & IG BCE (Marz2018): Potentialatlas für Wasserstoff https://www.innovationsforum-energiewende.de/fileadmin/user_upload/Potentialstudie-fuer-gruenen-Wasserstoff-in-Raffinerien.pdf

At 33 per cent, Germany has the largest share of the EU27's industrial gross value added (GVA). The German industrial sector makes up 25 per cent of the country's GVA[89] and this underlines how important the industrial sector is for the country's wealth. In terms of CO_2, German industry generates 23 per cent of total German emissions and 26 per cent of total European industrial emissions.[90] Hence, the industrial sector's potential for decarbonisation is substantial, and hydrogen could play an essential role in this. Within industry, the potential for low-carbon hydrogen demand can be separated between processes where hydrogen is a feedstock and in processes where it is used especially for high temperature process heat. Feedstock demand currently accounts for the lion's share of hydrogen consumption.

Figure 9: German hydrogen consumption as estimated in different scenario studies



In the base chemical industry and refineries, large volumes of hydrogen are used as a feedstock. German refineries consume around 440 kt of hydrogen per year, of which about 263 kt results from the crude oil steam reforming process of the refinery process itself. Only around 177 kt is produced from by additional sources, mainly from steam methane reforming (SMR). These 177 kt could be replaced by low-carbon hydrogen, for example by using water electrolysis, resulting in a carbon dioxide emission reduction of around 1.7 Mt CO_2-equivalent, at relatively low CO_2 abatement costs.[91]

Potential sources for additional hydrogen demand as a feedstock can be found in the German iron and steel industry. In 2017, 42 million tonnes of iron and steel were produced, resulting in 57 million tonnes of CO_2.[92] The use of low-carbon hydrogen and the direct reduction process instead of the metallurgical coke-based blast furnace technology could also reduce process-related carbon dioxide emissions (18 million tonnes). Because investments in new technologies are necessary to reduce process-related emissions, the CO_2 abatement costs within the iron and steel industry are high. On the upside, many blast furnaces are depreciated, and the industry is facing a significant reinvestment cycle within the next few years. On the downside, the new technologies are not ready for market yet (TRL 4-5), and

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[89] Eurostat (2020), Gross value added and income by A*10 industry breakdowns, https://ec.europa.eu/eurostat/databrowser/product/view/NAMA_10_A10?lang=en

[90] EEA (2020), EEA greenhouse gas – data viewer, https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer

[91] MWV & IG BCE : Potentialatlas für Wasserstoff [03/2018] https://www.innovationsforum-energiewende.de/fileadmin/user_upload/Potentialstudie-fuer-gruenen-Wasserstoff-in-Raffinerien.pdf

[92] Agora Energiewende: Klimaneutrale Industrie [2019] https://www.agoraenergiewende.de/fileadmin2/Projekte/2018/Dekarbonisierung_Industrie/164_A-EW_Klimaneutrale-Industrie_Studie_WEB.pdfp.4

products will not be competitive in the global market.[93] However, reinvestment cycles in the industry are more than fifty years, so a timely solution is necessary.[94] By 2050, the German national hydrogen strategy projects a hydrogen demand in the iron and steel sector of 80 TWh.

The German industrial sector also has immense potential for the use of hydrogen as an energy source.[95] In 2016, fossil fuel-based generation of industrial process heat generated 126 million tonnes CO$_2$-equivalent. High-temperature process heat (>500°C), which accounts for 75 per cent of total process heat, is particularly hard to decarbonise with RES-based electricity processes, high-temperature heat pumps or electric boilers, although direct-electric methods such as electric furnaces in the aluminium foundry can decarbonise some high-temperature processes. It is estimated that demand for high-temperature heat generated by combustion processes, for example hydrogen or hydrogen derivate fired, will be 200 TWh in 2050.[96]

In the transport sector, there is a chicken-and-egg problem between the provision of infrastructure (hydrogen refuelling stations) and demand (FCEV). At the end of 2020, Germany had around 90 hydrogen refuelling stations, compared to more than 14,000 for conventional fuels such as gasoline and diesel. Regarding the light-duty vehicle sector, battery electric vehicles (BEV) are commonly accepted as the most promising technology for decarbonisation,[97] but in 2018, only 515 German registered cars were FCEV.[98] None of the large German automotive OEM companies (Daimler, BMW, Audi, VW) are currently mass-producing FCEV (FCEV production by Mercedes Benz started in 2018, but it closed down in early 2020, due to poor sales). Other manufacturers, such as VW, are only supporting BEV, instead of focusing their R&D on both technologies.

FCEVs are more likely to play a significant role in the long-distance and heavy-duty vehicle sector, as their advantage over BEVs is their range and refuelling time. It is a potentially huge market: in 2019, Germany registered around 3.5 million trucks or semi-trailer trucks and about 80,000 buses.[99] The German Energy Agency (DENA) projects a penetration of FCEVs in the heavy-duty vehicle sector of between 37-57 per cent in 2050, while BEVs are forecast to have only a minor share of 14-20 per cent. Hydrogen derivatives such as synthetic gasoline or diesel are expected to fuel the remainder of the heavy duty vehicle sector. The development of FCEVs could be an opportunity for the export-oriented German automotive industry. The world's largest heavy-duty commercial vehicle producer, Daimler, which accounts for 11 per cent of the global market, is currently preparing its FCEV for mass production.[100] The second-largest German producer, Traton (VW/MAN), started cooperating over the production of fuel cell trucks with Hino, a subsidiary of the Japanese fuel cell pioneer Toyota.[100] However, to achieve high penetration of FCEVs in the heavy-duty vehicle sector, a mature European refuelling infrastructure is necessary.

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[93] Agora Energiewende: Klimaneutrale Industrie [2019] https://www.agora-energiewende.de/fileadmin2/Projekte/2018/Dekarbonisierung_Industrie/164_A-EW_Klimaneutrale-Industrie_Studie_WEB.pdfp. 23

[94] Agora Energiewende : Klimaneutrale Industrie[2019] https://www.agora-energiewende.de/fileadmin2/Projekte/2018/Dekarbonisierung_Industrie/164_A-EW_Klimaneutrale-Industrie_Studie_WEB.pdfp.36

[95] Deutsche Energie-Agentur GmbH (dena) : Ellery Studio [08/2018] https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/181123_dena_PtX-Factsheets.pdfp. 25

[96] Agora Energiewende & Agora Verkehrswende: Dr. Matthias Deutsch :Die zukünftigen Kosten strombasierter synthetischer Brennstoffe: [19/03/2018] https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynCost-Studie_WEB.pdfp. 14

[97] OIES (2020): Hydrogen and decarbonisation of gas: false dawn or silver bullet?[03/2020] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/Insight-66-Hydrogen-and-Decarbonisation-of-Gas.pdfp 5

[98] Kraftfahr-Bundesamt https://www.pkw-label.de/alternative-antriebe/brennstoffzellenfahrzeuge-fcev

[99] Bundesministerium für Verkehr und Digitale Infrastruktur: Fahrzeugbestand [03/2020] https://www.bmvi.de/SharedDocs/DE/Artikel/G/fahrzeugbestand.html

[100] Branchendienst für Elektomobilität : Sebastian Schaal - Traton-Chef Renschler: Brennstoffzelle „sicher eine Option" [03/04/2020 – 10:58] https://www.electrive.net/2020/04/03/traton-chef-renschler-brennstoffzelle-sicher-eine-option/

Other transport sectors such as rail transport, shipping or aviation offer further hydrogen demand potential. In the German rail system, hydrogen potential is limited. Around half of the 40,000 km of track, particularly the busier rail lines, are already electrified[101] with Germany working towards a high penetration of electrification, particularly in regions with a high population density. However, hydrogen fuel cell trains could replace diesel trains in rural areas. Shipping and aviation present a different picture, as these forms of transport are hard to decarbonise.[102] According to DENA most of the 2,000 diesel-fuelled inland cargo vessels will be fuelled by hydrogen-based synthetic LNG or diesel in 2050. Aviation will follow a different trend. It is expected that the lion's share of Germany's 12,000 planes will be fuelled by the combustion of green hydrogen-based synthetic kerosene,[103] with the use of liquid hydrogen fuel cells (LH_2-FC) only playing a minor role.

Natural gas heating systems are the prevailing technology in the German heating sector. In 2017, about 20.6 million households or 49 per cent[104] were equipped with a gas heating system accounting for more than 30 per cent of German natural gas demand (around 30 bcm). Oil or diesel-based heating systems accounted for 24 per cent, mainly in rural areas where the supply of natural gas supply is limited due to poor grid infrastructure. Heat pumps are not widespread yet but are likely to become the prevailing technology in buildings, especially for new single-family houses. Furthermore, hybrid heating systems that combine conventional boilers with heat pumps could be an option for older and poorly insulated houses. Additionally, the blending of hydrogen in gas distribution grids could reduce carbon emissions in the heating sector. In the long term, transferring the existing grid infrastructure to 100 per cent hydrogen or transporting hydrogen-based synthetic methane could be a further option. According to DENA these options could still provide up to 141 TWh of hydrogen demand in 2050.[105]

4.3. Hydrogen Supply

Hydrogen in Germany is currently produced and directly converted to end products via well-integrated and optimized (petro)chemical processes. In 2019, the majority was produced from fossil fuels, particularly crude oil (45 per cent), as a by-product of refining processes, and natural gas (33 per cent). The dominant processes for natural-gas-based transformation are SMR and partial oxidation (POX), with around seven per cent of hydrogen being produced as a by-product within the Chloralkali process. Hydrogen based on water electrolysis only played a minor role, accounting for less than one per cent of German production.[106]

Since hydrogen is often generated onsite, being produced and consumed within the same chemical park, there are hardly any mature or liquid markets for the energy carrier. However, some vertically integrated industrial gas producers such as Air Liquide or Linde do produce, transport, and market hydrogen to larger industrial clients or the retail market. Some pipeline networks exist, which connect different hydrogen sources and sinks. In Germany, Air Liquide operates a hydrogen infrastructure network in the Rhine-Ruhr Area in North-Rhine Westphalia, connecting chemical parks and refineries from Dortmund through Marl and Düsseldorf to Leverkusen. Linde also operates a hydrogen pipeline network of more than 130 km, connecting industrial consumers in Eastern Germany.

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[101] Deutscher Bundestag: Wissenschaftlich Dienste - Elektrifizierungsgrad der Schieneninfrastruktur [20/02/2018] https://www.bundestag.de/resource/blob/549342/f2306e768bb6a0963f54a70143a2d81b/wd-5-027-18-pdf-data.pdf

[102] OIES (2020): Hydrogen and decarbonisation of gas: false dawn or silver bullet?[03/2020] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/Insight-66-Hydrogen-and-Decarbonisation-of-Gas.pdfp10

[103] dena/EWI: dena-Leitstudie Integrierte Energiewende [07/2018] https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdfp. 183

[104] AG Energiebilanzen e.V.: Dr. Hans-Joachim Ziesing- Energy Consumption in Germany in 2007 [02/2018] https://ag-energiebilanzen.de/index.php?article_id=29&fileName=ageb_jahresbericht2017_20180420_englisch.pdf.

[105] Deutsche Energie-Agentur: dena-Leitstudie Integrierte Energiewende [07/2018] https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9261_denaLeitstudie_Integrierte_Energiewende_lang.pdfp.96

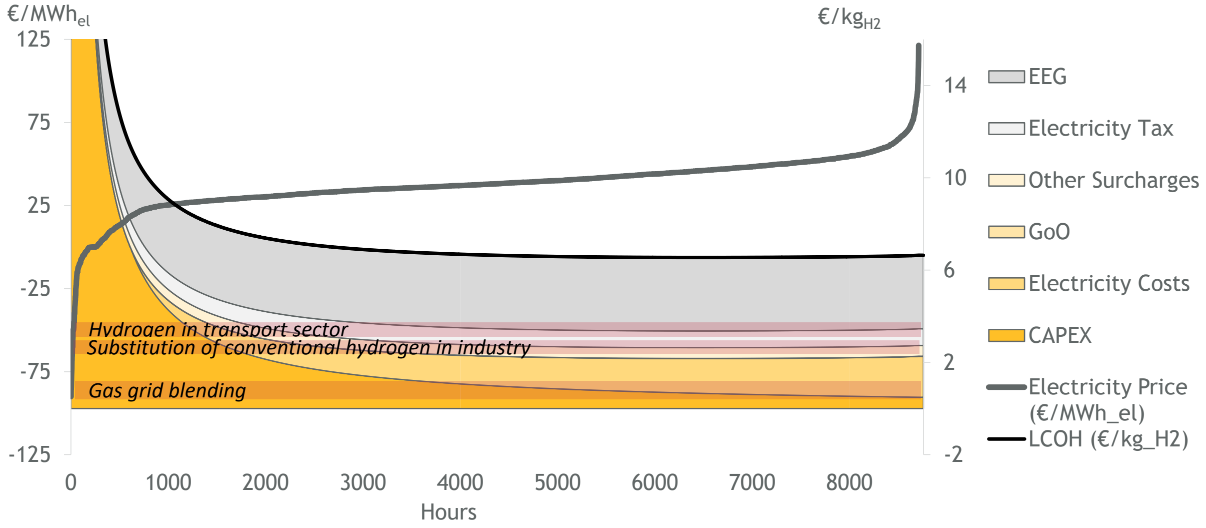
[106] Deutsche Energie-Agentur GmbH (dena) & Energiesysteme und Energiedienstleistungen: Carolin Schenuit/Reemt Heuke/Jan Paschke: Potenzialatlas Power to Gas: Klimaschutz umsetzen, erneuerbare Energien integrieren, regionale Wertschöpfung ermöglichen [06/2016] https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9144_Studie_Potenzialatlas_Power_to_Gas.pdf

4.3.1 Electrolysis of water

In 2019, cumulative water electrolysis capacity accounted for 38 MW, although the future project pipeline accounts for more than 700 MW.[107] However, several studies forecast an even bigger need for investment in electrolysis capacity in order to reach Germany's climate targets. To be in line with these national climate targets, a DENA report in 2018[108] assumed demand for electrolysis capacity of 16 GW in 2030.

Today, low-carbon hydrogen generated by the electrolysis of water is not competitive in Germany. Figure 10 shows the levelised cost of hydrogen (LCOH) within Germany in 2019 for water electrolysis with electricity consumed from the grid on the secondary axis. The electricity price, which represents an operator's electricity costs, is shown on the primary axis, while the horizontal axis shows the full load hours of an electrolyser. While CAPEX declines with increasing full load hours, electricity costs rise. For 2019 electricity prices, there was an optimum of between 5000 and 6000 full load hours. Furthermore, the figure shows the additional charges and taxes that would have to been paid by an operator who purchases electricity from the grid. In particular the renewable surcharge (EEG) amounts to around 50 per cent of the LCOH. However, following an amendment to the current law, water electrolysis using only renewable electricity no longer has to pay the EEG surcharge.

Figure 10: LCOH and cost benchmarks on the demand side in Germany in 2019



Source: EWI/DVGW forthcoming

Beside procurement from the grid, electricity can be sourced by dedicated RES, e.g. larger wind parks (onshore/offshore). Currently, in well-suited locations, the LCOH varies between EUR 4.5-6.5/kg H_2. If costs for RES and electrolysis fall further in line with expected learning rates, the LCOH could reach levels of EUR 2.2-4.4/kg hydrogen in 2030 and EUR 1.5-3.4/kg hydrogen in 2050.[110]

There are likely to be limits on available RES for hydrogen production, on account of competition from direct use of electricity. Figure 11 shows a scenario in which Germany could reduce its CO_2 emissions in its final energy consumption by 95 per cent in 2050 by using its domestic RES potential. Domestic RES capacities could also decarbonise almost all the country's electricity consumption. However, around 53 per cent of final energy demand needs to be imported (electricity, hydrogen, synthetic fuels).

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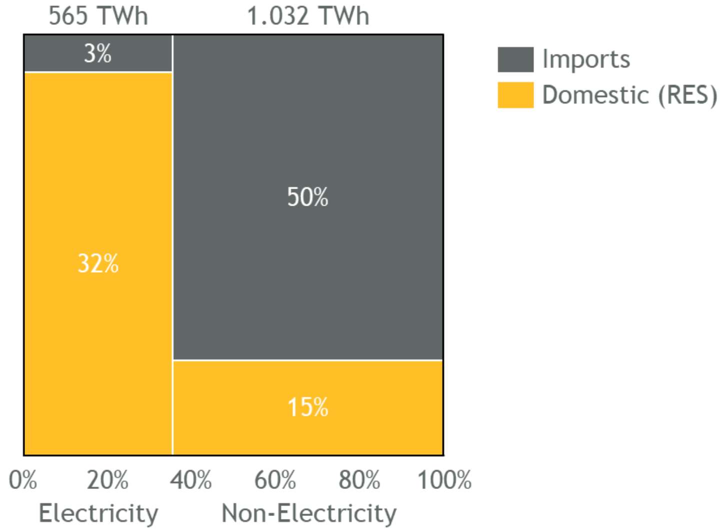
[107] IEA: Hydrogen Projects Database [06/2020] https://www.iea.org/reports/hydrogen-projects-database

[108] Dena/EWI (2018): dena-Leitstudie Integrierte Energiewende [07/2018] https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf

The potential for domestically produced hydrogen based on water electrolysis is limited to 156 TWh, due to limitations in the RES potential.[109]

Figure 11: Final energy consumption in Germany in 2050; technology mix scenario with 95 per cent carbon emission reduction[110]



4.3.2 Natural gas-based hydrogen with carbon capture

A further option for low-carbon hydrogen production is the combination of natural gas reforming with CCUS.[111] On the upside, reforming processes like SMR or POX are mature and produce hydrogen at low cost. Furthermore, Germany has a well-established natural gas supply infrastructure that allows the import of natural gas and domestic reforming of large volumes of hydrogen. There is also sizeable CO_2 storage capacity totalling more than 15 Gt, primarily in aquifers offshore in the North Sea and depleted gas fields, but the transportation of CO_2 to these facilities would need to be taken into account. Onshore CO_2 storage is currently prohibited in Germany and has faced high public opposition in the past.[112] Alternatively, the reforming process could take place outside Germany, in countries which export the natural gas. The resulting CO_2 could then be stored underground. Hydrogen transport could take place via converted natural gas pipelines, although depending on the transportation distances, hydrogen transport via pipeline is expensive, costing up to EUR10/MWh per 1000 km (IEA, 2019).

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[109] Schulte & Schlund (2020) - Hintergrund Nationale Wasserstoffstrategie [05/2020] https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2020/05/EWI_Policy_Brief_Wasserstoffstrategie_20200519.pdf p. 3

[110] Schulte & Schlund (2020) - Hintergrund Nationale Wasserstoffstrategie [05/2020] https://www.ewi.unikoeln.de/cms/wpcontent/uploads/2020/05/EWI_Policy_Brief_Wasserstoffstrategie_20200519.pdf, p. 4

[111] Although these processes are not carbon-free, large volumes of up to 90 per cent can be captured and stored. (IEAGHG(2017) -Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS).

[112] IEA 2020 – ETP: Special Report on Carbon Capture Utilisation and Storage, p. 138

5. Italy

5.1. Policy Framework

In December 2019 Italy published the Integrated National Energy and Climate Plan (NECP) setting out plans to 2030, in line with the objective to achieve full decarbonisation of the energy sector by 2050.[113] Hydrogen is mentioned repeatedly in this document, although it did not contain detailed plans or specific numerical objectives for hydrogen development. The NECP has 2030 objectives for a 30 per cent share of renewables in gross final consumption and a 40 per cent reduction in greenhouse gas emissions compared to 1990 levels.[114] At the time it was published, the 40 per cent reduction was in line with the EU-wide target. It is likely that with the EU increasing the target reduction to 55 per cent in September 2020,[115] the Italian target will be raised correspondingly.

Italy published "preliminary guidelines for a national hydrogen strategy" in November 2020. This is a consultation document rather than a firm policy document, but suggests a target of 5GW of electrolyser capacity by 2030. The approach to hydrogen development is expected to be developed further during 2021 as part of plans for achieving net-zero by 2050, and a revised Energy and Climate Plan is scheduled for 2022.

Perhaps as a consequence of the ongoing development of a hydrogen and net-zero strategy, there is little clarity on the policy framework which would apply to hydrogen developments in Italy. The hydrogen strategy guidelines appear to focus on transport and industry as the leading sectors for penetration of hydrogen, with some mention also made of power generation and potential blending into the natural gas grid. In October 2018, the government issued a Ministerial Decree on technical rules for the design, construction, and operation of hydrogen distribution facilities for automotive vehicles, but this appears to be the only specific legislation relating to hydrogen production and operation in Italy.[116]

The focus on the use of hydrogen in transport (both from this piece of legislation and from the specific development projects noted below) is perhaps surprising, since the role for hydrogen in road transport is likely to be limited by competition from BEV.[117] In general, the role for hydrogen in road transport is expected to be in the long-distance, heavy-duty sector. Italy has already invested in the most well-developed network of natural gas refuelling infrastructure in Europe, but whether this is a positive or negative for the future use of hydrogen in transport is not yet clear. It is possible that Italy may choose to continue to use methane for road transport, but with increasing quantities of biomethane used to decarbonise the sector. Further policy guidance may provide additional clarity.

The regulatory situation for hydrogen in Italy is further complicated by a large number of central, regional, and local government entities which currently have a role in approving any potential hydrogen project. There are not yet any incentive schemes to promote production of renewable hydrogen. Indeed, the most recent Renewable Energy Decree (FER1) from July 2019 provided incentives for wind, solar PV, hydroelectric, and biogas production, but made no mention of hydrogen.[118]

In summary it appears that while Italy (or at least the key industry players led by SNAM and Eni) has ambitious plans for hydrogen in the country, there is currently little sign of supportive government policy required to drive the necessary investments.

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[113] https://ec.europa.eu/energy/sites/ener/files/documents/it_final_necp_main_en.pdf

[114] SNAM: H2 Italy 2050 (Sept 2020): https://www.snam.it/export/sites/snam-rp/repository/file/Media/news_eventi/2020/H2_Italy_2020_ENG.pdf

[115] https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1599

[116] https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/italy

[117] See OIES Feb 2020: https://www.oxfordenergy.org/publications/hydrogen-and-decarbonisation-of-gas-false-dawn-or-silver-bullet/

[118] https://www.dentons.com/en/insights/alerts/2019/july/23/-/media/86d3a76f567b4b06a2f0340a8954bea2.ashx

5.2. Hydrogen Demand

Currently Italy consumes around 16 TWh/yr of hydrogen as a feedstock for refineries and fertiliser manufacture. This represents around one per cent of final energy consumption.[119] By contrast, natural gas demand totals around 780 TWh, with the breakdown by sector shown in Table 6.

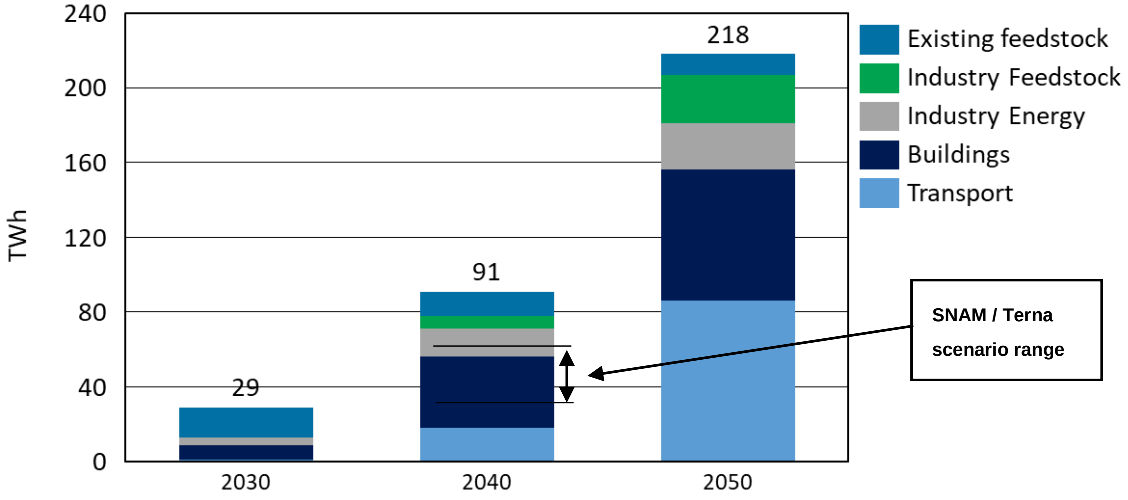
Table 6: Final energy consumption for natural gas in Italy in 2018

Sector	Gas Consumption (TWh)
Households	211
Industry	111
Services	93
Mobility	25
Power Generation	302
Energy Industry – Other	20
Total	**762**

Source: Eurostat (2020)

Some concrete steps are already starting to be taken for a wider role of hydrogen use in Italy. In June 2020, Alstom and SNAM signed an agreement to develop hydrogen-powered trains, building on the experience of the hydrogen train already in operation in northern Germany.[120] In June 2019, Toyota and Eni announced a collaboration to speed up the expansion of fuelling stations and use of hydrogen cars in Italy.[121]

Figure 12: Italy potential hydrogen demand by sector[122]



In SNAM's report "The H2 challenge", published in October 2019, it provided one scenario for the possible evolution of hydrogen demand in Italy. This is illustrated by the bar chart in Figure 12 and projects that by 2050, hydrogen could meet 23 per cent of final energy demand or 218 TWh, up from just 1 per cent of final demand or 16 TWh currently. This is an ambitious target, and other scenarios provide an indication of the broad range of potential outcomes for hydrogen in Italy.

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[119] SNAM: The Hydrogen Challenge (Oct 2019): https://www.snam.it/it/hydrogen_challenge/repository_hy/file/The-H2-challenge-Position-Paper.pdf

[120] https://www.snam.it/en/Media/Press-releases/Agreement_Alstom_and_Snam_hydrogen_trains_in_Italy.html

[121] https://www.eni.com/en-IT/media/press-release/2019/06/toyota-and-eni-together-on-the-road-to-hydrogen.html

[122] Data from SNAM: The Hydrogen Challenge (Oct 2019),

A shorter-term view is set out in a report published in April 2020 by the EU Fuel Cell and Hydrogen Joint Undertaking (FCH JU) with renewable hydrogen forecasts by sector to 2030.[123] Each sector has a wide range of uncertainty with demand ranging from 1-6.5 TWh in industry, 0.75-7.5 TWh in buildings, 2-5 TWh in transport and 0-0.4 TWh in power. The total hydrogen demand in 2030, when added to the 16 TWh of existing demand, ranges from a low of 20 TWh to a high of 36 TWh, a wide range, but one which is broadly consistent with the SNAM view. As discussed in the overview section (Section 2 above), these forecasts are based on broad-brush assumptions of the percentage penetration of hydrogen into each sector so they clearly have a wide range of uncertainty and are probably optimistic. The transport sector projection is particularly ambitious as Italy currently has no hydrogen refuelling stations although ENI is developing two, one at San Donato Milanese and one in the Venice area.[124]

By contrast, the latest (2019) edition of the regular future energy scenarios published jointly by SNAM and Terna[125] has much lower projections for hydrogen demand in 2030 and 2040, despite both scenarios envisaging meeting the target CO_2 reductions (from 1990 levels) of 40 per cent by 2030 and 60 per cent by 2040. In 2040, total hydrogen demand, including existing, ranges from 29 TWh to 47 TWh as indicated in Figure 12. By contrast, the SNAM/Terna scenarios both envisage that by 2040, biomethane demand will have reached 125 TWh (12 Bcm), thus playing a much larger role than hydrogen in the decarbonisation of gas.

5.3. Hydrogen Supply

Following the NECP inclusion of hydrogen as part of the energy transition pathway, the Ministry of Economic Development set up a Working Group on Hydrogen. This working group sees that "hydrogen from renewable energy can play an important role in achieving the objectives of the NECP".

The main focus for hydrogen production in Italy is on "green" hydrogen, using the relatively abundant and lower cost solar power available in southern Italy.[126] There are also several pilot projects for the production of renewable hydrogen in limited quantities,[127] but there do not yet appear to be significant (i.e. >100MW) production projects under development.[128]

There are differing views on the potential application of CCS. According to FCH JU, "Italy has limited readiness for wide-scale deployment of CCS". It assesses Italy's readiness for CO_2 storage as "low",[129] and the scenarios presented assume that all low-carbon hydrogen production is from electrolysis using renewable electricity. On the other hand, ENI is developing plans for "the world's largest CO_2 storage site" capable of storing between 300 and 500 million tonnes in depleted fields under the Adriatic Sea off the coast of Ravenna.[130] The idea of a CCS hub offshore Ravenna had been proposed as early as 2008,[131] but progress in realizing the project has been slow. There does not appear to be a specific timeline to progress the CCS project, although the SNAM/Terna scenarios suggests that around 7 bcm (73 TWh) of natural gas demand in 2040 would be associated with CCS, out of a total forecast gas demand of around 55 bcm (570 TWh).[132]

On account of its geographical location and its existing gas pipeline network and interconnections to other countries, Italy is also assessing imports of hydrogen from North Africa.[133] This view was echoed

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[123] FCH JU: Opportunities for Hydrogen Energy Technologies considering the NECPs: Italy https://www.fch.europa.eu/sites/default/files/file_attach/Brochure%20FCH%20Italy%20%28ID%209473094%29.pdf

[124] https://www.eni.com/en-IT/operations/hydrogen-clean-energy-strategy-eni.html

[125] https://download.terna.it/terna/DDS%202019%2010%2015_8d7522176896aeb.pdf

[126] SNAM: The Hydrogen Challenge (Oct 2019).

[127] https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/italy

[128] See for example: http://ieahydrogen.org/pdfs/Member-Update-Table-2020-v7.aspx

[129] FCH JU (ibid) p. 10

[130] https://www.eni.com/en-IT/low-carbon/catching-co2-off-coast-ravenna.html

[131] https://www.ogj.com/general-interest/article/17269137/eni-enel-to-develop-italys-first-ccs-project

[132] SNAM / Terna (op. cit), p 14-15

[133] SNAM H2 Italy (op. cit) p24.

in the European Hydrogen Backbone report[134] published in July 2020, which envisaged that by 2030 a hydrogen pipeline (converted from existing natural gas) would run from Sicily to the Rome region, and by 2035 would extend the full length of Italy to Milan, with a link to North Africa being added around 2040.

6. Netherlands

6.1. Policy Framework

The Netherlands government set out its national hydrogen strategy and policy agenda in March 2020.[135] This builds on the Netherlands Climate agreement of June 2019, which aims to reduce CO_2 emissions (from the 1990 baseline) by 49 per cent by 2030 and 95 per cent by 2050. In September 2020, the EU raised its climate ambition to target a 55 per cent reduction by 2030,[136] and it is likely that the Netherlands target will be increased accordingly. To achieve even the 49 per cent target will, however, require an acceleration of emissions reductions, since in 2019 total emissions in the Netherlands were 184 million tonnes CO_2, only a 17 per cent reduction from 1990 levels.[137]

The Climate Agreement states an intention to focus on green hydrogen as much as possible, primarily using electrolysis, but also based on sustainable biogenic feedstocks. It also acknowledges a role for hydrogen produced from natural gas with carbon capture, but "without impeding the growth of green hydrogen".

The Netherlands has an advantage over some other countries in that it already has much duplication of its existing natural gas network: one network was designed to carry “L-Gas", low calorific gas primarily from the Groningen field, and one for “H-gas", higher calorific gas from other sources.[138] It is expected that this duplication will facilitate conversion of one network to carry hydrogen. The government envisages that the gas network operator, Gasunie, will be incentivized to establish a hydrogen infrastructure, but the detailed mechanisms to achieve this have not yet been established.

Some consideration is also being given to enabling the blending of higher quantities of hydrogen into the existing (predominantly methane-carrying) gas grid. There is, however, not yet any specific legislation relating to hydrogen, so at present the existing laws on the regulation of gas also apply to hydrogen. The current Gas Quality Decree only permits up to 0.5 per cent hydrogen in regional networks and 0.2 per cent in the national network.[139]

The Northern Netherlands Investment Plan, published in November 2020,[140] sets out some key policy actions which it sees as necessary in the next 1-2 years to enable the ambitious plans to be achieved, including:

- A supportive regulatory framework, including an exemption from REDII requirements which would require green hydrogen production to be associated with additional (rather than existing) renewable energy capacity;
- Government funds to support the scale-up of hydrogen production;
- Support for the development of critical infrastructure (pipelines and storage);
- Mandates to support the use of green rather than grey hydrogen in end-use application.

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[134] https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/

[135] https://www.government.nl/binaries/government/documents/publications/2020/04/06/government-strategy-on-hydrogen/Hydrogen-Strategy-TheNetherlands.pdf

[136] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1599

[137] Netherlands Climate and Energy Outlook 2020: https://www.pbl.nl/sites/default/files/downloads/pbl-2020-netherlands-climate-and-energy-outlook-2020-summary-4299.pdf

[138] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/07/The-great-Dutch-gas-transition-54.pdf

[139] https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/netherlands

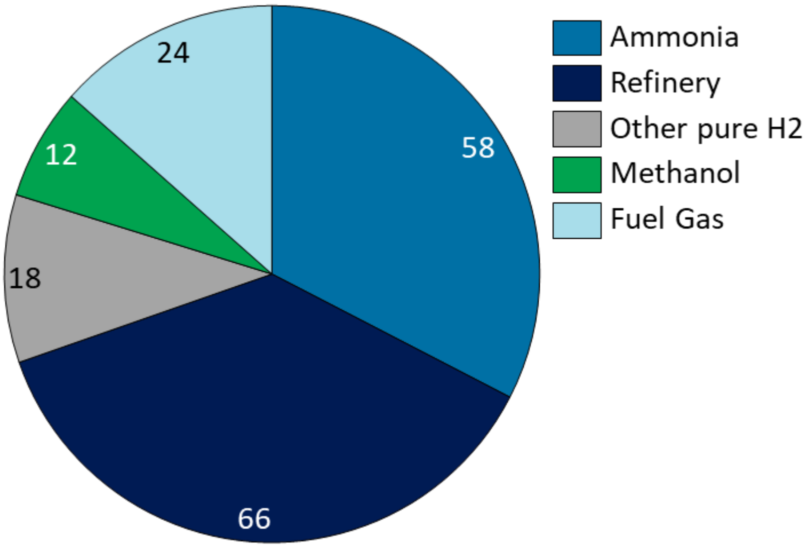
[140] https://www.mijntoekomstiswaterstof.nl/app/uploads/2020/10/investment-plan-hydrogen-northern-netherlands-2020.pdf p. 30

There are clearly a significant number of policy changes required to meet the ambitious plans for hydrogen development. However, in the Netherlands Climate and Energy Outlook 2020, it is clear that the Netherlands is lagging behind other European countries in achieving overall CO_2 reduction targets. Indeed, it notes that GHG emissions in the power sector in 2019 were higher than in 1990 (compared with 50 per cent reduction in UK and 45 per cent reduction in Germany). Thus it suggests that climate policy in the Netherlands will focus initially on the promotion of renewable power generation, so it is less clear the extent to which hydrogen will be a priority for policymakers.

6.2. Hydrogen Demand

Total hydrogen consumption in the Netherlands in 2019 is estimated at around 180 PJ (50 TWh), including the hydrogen content of mixed gas streams, or 117 PJ (33TWh) if only pure hydrogen is included. Of the 117 PJ, 104 PJ is produced from natural gas.[141] The share of current hydrogen use by application is shown in Figure 13, from which it can be seen that the major consumers of hydrogen are ammonia production and refineries, in line with trends globally and in other European countries. Current natural gas demand in the Netherlands by sector is shown in Table 7.

Figure 13: NL Hydrogen use by application in petajoule (PJ) in 2019 Source



Source: Author's analysis of TNO data

Table 7: Final energy consumption for natural gas in the Netherlands in 2018

Sector	Gas Consumption (TWh)
Households	88
Industry	65
Services	39
Mobility	2
Power Generation	122
Energy Industry – Other	20
Total	**336**

Source: Eurostat 2020

A 2019 report by the Netherlands Organisation of Applied Scientific Research (TNO) collated several scenarios for future hydrogen demand in the Netherlands, drawing on several recent studies.[142] The

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[141] TNO (2020) The Dutch Hydrogen Balance: http://publications.tno.nl/publication/34636791/BMHkKB/TNO-2020-P10915.pdf

[142] TNO (2019) The Future Role of Hydrogen in the Netherlands. http://publications.tno.nl/publication/34635022/HBSOpX/TNO-2019-P11210.pdf

study found a very wide range of estimates for hydrogen use in 2050. A 2014 study had 2050 hydrogen demand below 200 PJ (55 TWh), with nearly all demand in the transport sector, but that study can probably be discounted as the understanding of hydrogen's potential role in the energy transition has evolved considerably since 2014. Even in studies from 2018 onwards, however, total hydrogen use in 2050 ranged from 420 PJ (115 TWh) to 1700 PJ (470 TWh).

In the buildings sector, results for hydrogen consumption in 2050 varied widely, from negligible amounts in scenarios which assumed widespread use of electric heat pumps, heat networks and/or renewable methane, up to a high of 200 PJ (55 TWh), on the assumption that a large share of current natural gas use is converted to hydrogen.

In the power sector, there was a similarly wide range of estimated hydrogen consumption in 2050, typically in the range 100-350 PJ/yr (28-97 TWh). The range depends on assumptions regarding the level of decarbonisation of the power sector by 2050. High use of hydrogen relates to full decarbonisation, as forecast for example by Gasunie suggesting that by 2050 all power plants used to supplement renewable energy during periods of little sunshine or no wind will be running exclusively on hydrogen.[143]

In the transport sector, many studies project a rapid shift to BEVs for cars and other light duty vehicles. If all current diesel vehicles were replaced by hydrogen-driven FCEVs, hydrogen use in road transport would be around 125 PJ/yr (35 TWh).[144] At present there are just eight hydrogen refuelling stations in the Netherlands, with plans for a total of twenty by end-2021 and fifty by 2025.[145] A major potential demand for hydrogen comes from the manufacturing of synthetic hydrocarbon fuels for aviation and marine bunkers. This is estimated to lead to a hydrogen demand of 700 PJ/yr (195 TWh) or more by 2050.

For industry, hydrogen is likely to have a role for providing high temperature heat, and demand in this sector is estimated at around 100 PJ/yr (28 TWh) to replace current natural gas use in that application. Industrial hydrogen demand would increase substantially to over 480 PJ/yr (135 TWh) if used to replace fossil fuels as a feedstock in base chemical production.

6.3. Hydrogen Supply

As can be seen from Figure 14, current (fossil fuel-based) hydrogen production is concentrated in a small number of industrial clusters, with over 60 per cent of total production in the Maasdelta (Rotterdam) and South Flanders (Vlissingen) areas.

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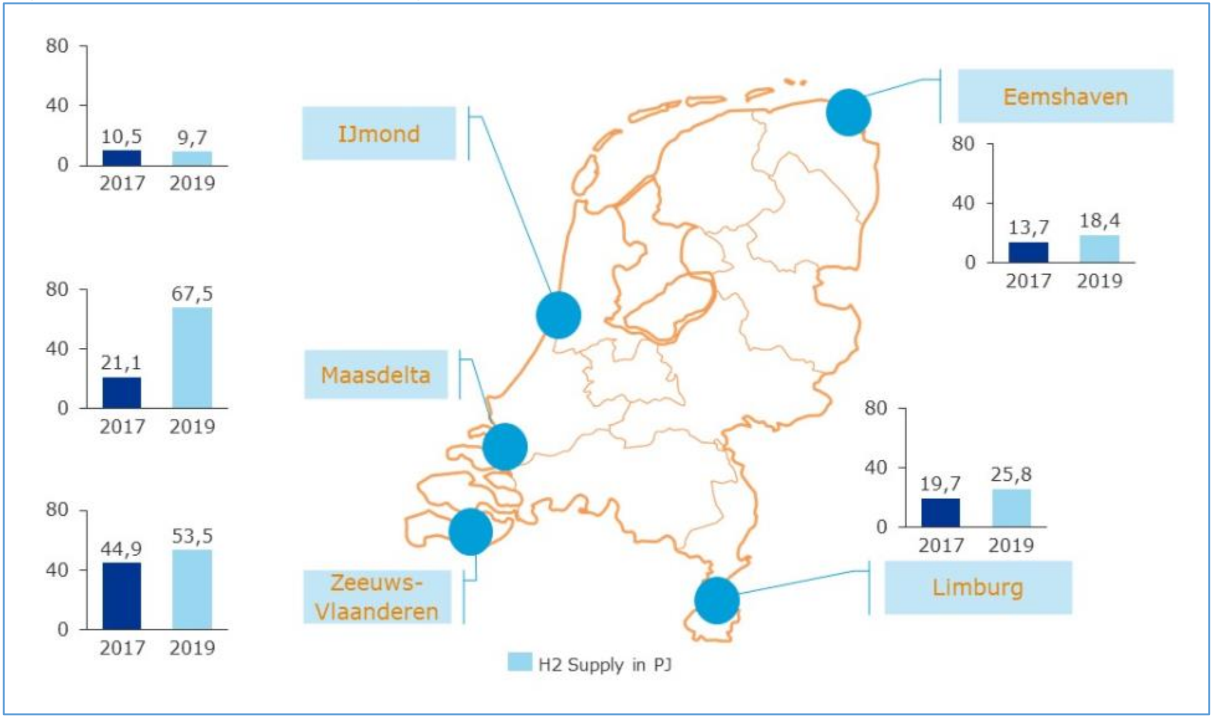
[143] https://www.gasunie.nl/en/energy-transition/energy-system-of-the-future/$1840/$1839

[144] TKI Nieuw Gas, 2018:

[145] https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/netherlands

Figure 14: Estimated 2019 hydrogen supply by industrial cluster



Source: DNV-GL

In the short term, the Climate Agreement of June 2019 envisages an objective of 800 MW of electrolysis and 15kt hydrogen production from biogenic fuels by 2025.[146] It goes on to target 3-4 GW of electrolyser capacity by 2030, while also envisaging that the cost of electrolysers will fall from around EUR 1 million/MW today to around EUR 0.35 million/MW by the same date. Electrolyser capacity of 4 GW operating at 4000 hours per year would generate around 15 TWh of green hydrogen, or less than half of current pure hydrogen demand.

The Northern Netherlands region has even more ambitious targets set out in a detailed investment plan to establish a "hydrogen valley".[147] This envisages regional production of 5-10 PJ/yr (1.5-3 TWh) by 2025, rising to 100 PJ/yr (28 TWh, from capacity of 6 GW) by 2030, with an expectation that 75 per cent will be green hydrogen and 25 per cent will be blue hydrogen.

The Netherlands is also envisaged as a key location for the first steps towards the development of a European hydrogen transmission network (the "Hydrogen backbone").[148] This role is facilitated by the presence of parallel gas networks (originating from the low- and high-calorific value systems) some of which it is predicted will be converted to hydrogen transportation.

Several large-scale hydrogen production projects are under development in the Netherlands:

- **Porthos**: a large-scale CCS project, aiming at gathering CO_2 produced in the Rotterdam area and transporting it to a depleted gas field 20 km offshore. The project, which has an estimated investment cost of EUR 400-500 million, is aiming to take a final investment decision in 2021 and to be operational and able to store 2-2.5 million tonnes CO_2 per year from 2023 onwards.[149]

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[146] Climate Agreement, June 2019, p180: https://www.government.nl/binaries/government/documents/reports/2019/06/28/climate-agreement/Climate+Agreement.pdf

[147] https://www.mijntoekomstiswaterstof.nl/app/uploads/2020/10/investment-plan-hydrogen-northern-netherlands-2020.pdf

[148] European Hydrogen Backbone July 2020, p. 5: https://gasforclimate2050.eu/?smd_process_download=1&download_id=471

[149] https://www.porthosco2.nl/wp-content/uploads/2020/04/January-2020-handout-Porthos-ENG.pdf

- **H-vision**: While the Porthos project is focused on capturing and storing CO_2 from existing industry in the Rotterdam area (including existing hydrogen production) rather than aiming to produce additional blue hydrogen, the H-Vision project[150] is exploring the economic and technical feasibility of building a large, centrally located hydrogen plant in the Maasdelta area. The CO_2 would be transported and sequestered by the Porthos project and a new hydrogen network would be constructed in the Rotterdam port area.
- **NortH2:** a large-scale green hydrogen project, aiming to generate 3-4 GW of offshore wind energy for hydrogen production by 2030 and possible expansion to 10 GW by 2040.[151]

In the longer term, the available capacity for renewable electricity production may become a constraint for the Netherlands. According to a 2017 study of offshore wind potential in Europe, the Netherlands was projected to have an economically attractive potential (in 2030) of between 300 and 500 TWH/yr.[152]

7. Spain

7.1. Policy framework

To support its net-zero 2050 ambition targeting climate neutrality, the Spanish government published its Renewable Hydrogen Roadmap in July 2020.[153] An update of the roadmap will be provided every three years. For its implementation, the government calculates that EUR 8.9 bn will be necessary, which should be provided mainly by the private sector, although it will be determined if public support will be required. In November 2020, the Spanish prime minister announced that EUR 1.5 bn of the support which Spain receives from the EU's economy rescue fund will be used to develop Spanish green hydrogen production[154].

The roadmap to decarbonizing the Spanish economy with hydrogen focuses on renewable or green hydrogen only. Other forms of low-carbon hydrogen are not considered sustainable. As Spain has great potential for PV and onshore wind compared to other European countries, it has the ambition to become an exporter of renewable hydrogen to the rest of Europe. To ramp-up the hydrogen market, the government has set out ambitious targets for renewable hydrogen production. It plans the rollout of at least 4 GW of electrolysis capacity by 2030, 10 per cent of the EU's electrolysis capacity target. In the first phase, Spain aims for 300-600 MW by 2024.

The roadmap sees the highest decarbonisation potential for green hydrogen in the industrial and the transport sectors. The idea is to produce renewable hydrogen in the vicinity of industrial sites, and the government is targeting a green hydrogen share of 25 per cent in the industrial sector by 2030. For the transport sector, there are specific targets for a fleet of hydrogen vehicles including government-owned buses, transport vehicles, trains, and additionally ports and airports. Furthermore, the roadmap defines 57 measures, addressing the regulatory framework and sector-specific instruments, as well as R&D support.

Measures defined in the Spanish hydrogen roadmap

At the moment, production costs of large-scale renewable hydrogen generation are high. Support for first-movers or pilot projects is planned via direct investment support for specific projects (CAPEX support). Additionally, the roadmap aims to reduce regulatory barriers for renewable hydrogen

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[150] https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-fuels-and-feedstock/hydrogen-for-a-sustainable-energy-supply/h-vision-blue-hydrogen-to-accelerate-carbon-low-industry/

[151] https://www.gasunie.nl/en/news/europes-largest-green-hydrogen-project-starts-in-groningen

[152] https://windeurope.org/wp-content/uploads/files/about-wind/reports/Unleashing-Europes-offshore-wind-potential.pdf Figure 18.

[153] Ministerio para la Transición Ecológica y el Reto Demográfico (2020), Hoja de Ruta del Hidrógeno: una apuesta por el hidrógeno renovable, https://www.miteco.gob.es/images/es/hojarutadelhidrogeno_tcm30-513830.pdf

[154] Reuters (2020), Spain to channel $1.8 bn in EU rescue funds to 'green' hydrogen, https://www.reuters.com/article/spain-energy-hydrogen-idUSL8N2I55HU

production plants. It could reduce variable costs (OPEX), for example by passing the cost of financing renewable subsidies from the electricity tariff to oil and gas tariffs thereby reducing procurement costs for electricity. Furthermore, it involves non-monetary regulatory simplifications that address environmental barriers or approval processes, for example for on-site renewable hydrogen production. The government is planning to simplify trade in renewable hydrogen by introducing a system for guarantees of origin, aiming to protect the market from non-renewable hydrogen imports from outside the EU.

On the demand side, the Spanish hydrogen roadmap sees the highest potential in the industrial sector, aiming to boost applications for renewable hydrogen. Other options, such as electrification, for hard-to-decarbonise processes are also being considered. There is particular emphasis on industries that already consume hydrogen as a raw material and which would therefore provide an opportunity to boost renewable hydrogen in the short term by replacing conventional, CO_2-intensive hydrogen. For the medium term, the government will provide financial instruments to support transformation in industrial processes and infrastructure. One problem will be the intermittency of RES supply and renewable hydrogen production, which will make additional grid infrastructure and storage necessary. The government will identify so-called hydrogen valleys, locations which are close to large industrial consumers, where integrated pilot projects will be financially supported.

The Spanish hydrogen roadmap defines several measures for the mobility sector. First and foremost, it mentions a revision of the Renewable Energy Directive (Directive (EU) 2018/2001; REDII), which sets incentives for the use of renewable hydrogen in the mobility sector. Regarding FCEVs, the strategy sets specific targets and milestones. By 2030, it plans a fleet of at least 150-200 renewable hydrogen fuel cell buses and 5,000-7,500 light- and heavy-duty hydrogen fuel cell vehicles for freight transport. For vehicle refuelling, the government intends to establish a grid of at least 100-150 publicly accessible hydrogen refuelling stations by 2030. However, compared to other countries, these targets seem to lack ambition (Germany already has 100 hydrogen refuelling stations in operation). Additionally, the roadmap spells out the use of hydrogen-powered trains on at least two commercial medium- and long-distance lines, on tracks which are currently not electrified.

In the long run (2040-2050), Spain will use renewable hydrogen as seasonal storage for RES. The country has sizeable underground storage potential. To reach the vision of a 100 per cent RES-based energy system by 2050, the government also sees some demand potential in the heating sector, both industrial and residential. However, as noted above, the penetration of the latter seems rather limited.

7.2. Hydrogen Demand

There is not much data available on current hydrogen consumption in Spain. According to the Spanish National Hydrogen Roadmap,[155] annual consumption amounts to around 0.5 million tonnes (approximately 13 TWh). A significant share of the hydrogen is produced from fossil fuels, and more than 90 per cent was consumed in the industrial sector. Of this, 70 per cent was used as a feedstock in refineries, and 25 per cent in the chemical industry. Consumption in other sectors, such as transport, is insignificant. In comparison, Spanish natural gas demand in 2018 is shown in Table 8.

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[155] Ministerio para la Transición Ecológica y el Reto Demográfico (2020), Hoja de Ruta del Hidrógeno: una apuesta por el hidrógeno renovable, p.11, https://www.miteco.gob.es/images/es/hojarutadelhidrogeno_tcm30-513830.pdf

Table 8: Final energy consumption for natural gas in Spain in 2018

Sector	Gas Consumption (TWh)
Households	35
Industry	106
Services	36
Mobility	5
Power Generation	116
Energy Industry – Other	40
Total	**338**

Source: Eurostat 2020

There are not many market analyses which provide estimates for hydrogen demand potential in Spain to the best of our knowledge. Trinomics and LBST's study in 2020[156] highlights the uncertainty regarding Spanish hydrogen demand potential and depicts two scenarios: a high- and a low-demand scenario. In the low-demand scenario, hydrogen is mainly employed in the industrial feedstock and transport sectors, while the high-demand scenario envisages a large demand share for heating applications and power generation. Total hydrogen demand potential in 2030 varies from 4 TWh/yr in the low-demand scenario to almost 17 TWh/yr in the high-demand scenario, all of which underlines that the potential differs strongly between sectors.

The Spanish industrial sector's share of the country's gross value added is below the EU27 average. In 2019, it accounted for 16 per cent compared to 20 per cent at an EU27 level. Spanish industry made up about 7 per cent of the gross industrial value-added of the EU27 in 2019.[157] Also, its hydrogen consuming industries are less significant than in other large European economies, such as the Netherlands, Germany or France. Furthermore, Spanish ammonia production accounts for only 3 per cent of the EU27 ammonia production.[158] A similar conclusion can be drawn for the entire chemical industry: Spain holds only a 6 percent share of the EU27 value added for the chemical industry, compared to, say, Germany with a 33 percent share.[159]

The steel industry is one of the most promising industrial sectors for potential hydrogen demand. New process technologies, such as direct iron reduction with low-carbon hydrogen, can reduce emissions from carbon-intensive steel production to a minimum. However, the technology is at an early stage, so financial support would be necessary to assist a technological change in an industry facing global competition. Within the EU27, Spain is the fourth-largest steel producer, accounting for around 9 per cent or 13.5 million tonnes of the EU's crude steel production.[160]

A further low-carbon hydrogen demand potential in the Spanish industrial sector could be the provision of process heat. Industrial process heat accounts for around 40 per cent of the Spanish heating and cooling demand for final energy (2015).[161] While fossil fuel-based low- and medium-temperature heating processes could be decarbonised by electrification, the use of low-carbon hydrogen could play an essential role in high-temperature process heat. An example is the cement industry, which produces large amounts of CO_2. While half of the emissions are process emissions that can only be reduced by

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[156] Trinomics and LBST (2020), Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans, p.10, https://www.fch.europa.eu/sites/default/files/file_attach/Brochure%20FCH%20Spain%20%28ID%209474179%29.pdf

[157] Eurostat (2020), Gross value added and income by A*10 industry breakdowns, https://ec.europa.eu/eurostat/databrowser/product/view/NAMA_10_A10?lang=en

[158] Eurostat (2020), PRODCOM – 20151077 (Ammonia in aqueous solution) & 20151075 (Anhydrous Ammonia), https://ec.europa.eu/eurostat/de/web/prodcom/data/database

[159] Odyssee database (2020), Value added chemical industry, https://odyssee.enerdata.net/database/

[160] European Steel Association (Eurofer) (2020), European Steel in Figures, p.14, https://www.eurofer.eu/assets/Uploads/European-Steel-in-Figures-2020.pdf

[161] S. Pardekooper et al. (2018), Heat Roadmap Spain: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps, p.19, https://vbn.aau.dk/ws/portalfiles/portal/287932746/Country_Roadmap_Spain_20181005.pdf

using CCS or new technologies, around 40 per cent of the emissions result from thermal heating[162] and the use of low-carbon hydrogen could reduce these emissions. Spain is a large producer of cement, producing roughly 19.1 million tonnes in 2019, which is comparable with German production (23.0 million tonnes) and 58 per cent more than France in the same year.[163]

Moreover, the Spanish transport sector provides some demand potential for hydrogen. In passenger cars or the light-duty commercial vehicle sector, BEVs are viewed as the most promising option for decarbonisation, particularly in large city centres such as Madrid. However, Spain is the second largest state by land area within the EU and is characterized by a comparatively low population density, so demand for long-distance travel is higher than in other EU member states. Since BEVs are limited in driving range, FCEV could play a more critical role than in other European countries. Nonetheless, in 2018, there were roughly 763,000 new registrations for passenger cars with gasoline engines, around 11,000 new registrations for passenger cars with electric motors, and only 12 new registrations for passenger cars with hydrogen fuel cells.[164] The total number of hydrogen filling stations in Spain in 2020 was 3, or 0.02 per 100 km highway.[165]

A more promising sector for hydrogen demand growth is heavy-duty transport (trucks and buses), which is harder to electrify. In Spain, the energy demand for heavy-duty transport as a proportion of total transport energy demand is 37 per cent, higher than the EU average of 32 per cent.[167] In September 2020 Barcelona became the first Spanish city to announce the introduction of hydrogen buses, which are expected to be delivered in 2021.[166] Hydrogen penetration in the Spanish railway sector is more challenging because it is mostly already electrified. Only 20 per cent of energy use in the railroad sector is diesel. Here, hydrogen could be an option but will face intense competition from further electrification.[167]

Hydrogen demand potential in the Spanish heating sector is limited since the demand for residential heat is low. In 2019 the total number of heating degree days (HDD) in Spain was 1,671, which is less than half the average HDD for the EU27. On the other hand, Spain recorded 248 cooling degree days (CDD) in the same year, more than double the CDD of the EU27.[168] Accordingly, Spain is responsible for only 4 per cent of final energy consumption in the residential space heating sector for the EU27 as a whole, but 17 per cent of the final energy consumption in residential space cooling.

Current heating demand for Spanish households is mainly met by primary solid biofuels, which account for around 37 per cent of demand. With a share of 20 per cent, natural gas-based heating plays only a minor role. Hence, the potential for blending natural gas distribution grids with low-carbon hydrogen to decarbonise the heating sector is limited. Space heating with electricity at 7 per cent has a higher share than the EU27 average (5 per cent), but as electricity generation is expensive, the percentage is not as large as in France (13 per cent) or in Scandinavian countries (for example, Sweden with 29 per cent). RES play an insignificant role in the Spanish heating sector; heat pumps only have a share of 2 per cent, and solar thermal is below 1 per cent.[169]

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[162] L. Rodgers (2018), Climate change: The massive CO2 emitter you may not know about, BBC, https://www.bbc.com/news/science-environment-46455844

[163] Eurostat (2020), PRODCOM – 23511100 (Cement Clinker), https://ec.europa.eu/eurostat/de/web/prodcom/data/database

[164] Eurostat (2020), New registrations of passenger cars by type of motor energy, https://ec.europa.eu/eurostat/databrowser/view/ROAD_EQR_CARPDA__custom_294925/default/table

[165] European Alternative Fuels Observation (2020), H2 Filling Stations Spain, https://www.eafo.eu/alternative-fuels/hydrogen/filling-stations-stats#

[166] https://eurocities.eu/latest/city-news-barcelona-to-introduce-spains-first-hydrogen-fuel-cell-busses/

[167] Trinomics and LBST (2020), Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans, p.7, https://www.fch.europa.eu/sites/default/files/file_attach/Brochure%20FCH%20Spain%20%28ID%209474179%29.pdf

[168] Eurostat (2020), Cooling and heating degree days by country - annual data, https://ec.europa.eu/eurostat/databrowser/view/nrg_chdd_a/default/table

[169] Eurostat (2020), Disaggregated final energy consumption in households – quantities, https://ec.europa.eu/eurostat/databrowser/view/NRG_D_HHQ__custom_357403/default/table

7.3. Hydrogen Supply

Currently 0.5 million tonnes of annual hydrogen production is generated near industrial sites. As in other European countries, the predominant production process is natural gas-based steam methane reforming, which emits CO_2. Since production takes place close to consumption, there is no hydrogen pipeline system in Spain.

7.3.1 Electrolysis of water

There are currently four electrolysis-based projects in operation in Spain, with a total capacity of less than 0.2 MW. However, nine more projects are in the pipeline with a total capacity of 410 MW. The planned projects involve different kinds of electrolysis (PEM, alkaline) and various applications for the resulting hydrogen, such as the injection of hydrogen into natural gas or pure hydrogen grids, and use in the mobility, industrial or power generation sectors.[170]

Spain has immense technical potential for RES and is in an excellent position to produce RES-based hydrogen. In 2019, 37 per cent of power generation in Spain was derived by RES. The largest share was provided by onshore wind (20 per cent), followed by hydropower (10 per cent), and solar power generation (3 per cent).[171] According to a 2019 report by the European Union's Joint Research Centre, Spain has the largest onshore wind potential for high-capacity factors (between 20-25 per cent) within the EU27. It accounts for 383 GW, followed by France (263 GW) and Romania (140 GW). While Spanish offshore wind potential is low, its technical potential for thermal solar generation and photovoltaic (PV) is huge. In a recent study, the World Bank Group analysed Spain’s PV potential[172] and stated that for PV, the average levelized cost of electricity (LCOE) was EUR 0.07/kWh, the second-lowest LCOE in the EU27, with only the average LCOE for PV in Italy being lower. Furthermore, the study showed that Spain's seasonality index is the lowest of the EU27, indicating the smallest difference in seasonal PV output on average.

Hence, Spain has a good potential for RES and RES-based hydrogen production, especially in the long term (2040-2050) and if cost reductions for RES and electrolysis progress further. Under these assumptions, electrolysis could benefit from a comparatively high number of full load hours, particularly from onshore wind and PV. Since the RES potential exceeds electricity demand by far, Spain could potentially become an exporter of RES-based hydrogen. This still holds even if domestic electricity consumption doubles or triples in the long term, due to further energy system integration and a penetration of electricity into other sectors.[173]

7.3.2 Low-carbon natural gas based hydrogen

According to the IEA[174] Spain has significant experience with research and development for CCS. In 2006, the country initiated several CCS projects on a pilot-scale for pre-combustion, post-combustion, and oxyfiring, primarily in combination with (coal-fired) power plants to decarbonise electricity generation, with one project also focusing on the refining industry. However, due to the lack of a positive political and market environment, Spanish CCS projects have never progressed beyond pilot status.

In general, Spain is in a good position for the generation of carbon capture-based hydrogen. The country already has some experience with CCS technologies from the above-mentioned pilot projects in its power sector. Furthermore, the country has sizeable CO_2 storage capacities onshore, for around 3,500

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[170] IEA (2020), Hydrogen Projects Database, https://www.iea.org/reports/hydrogen-projects-database

[171] IEA (2020), Data and statistics, https://www.iea.org/data-and-statistics?country=SPAIN&fuel=Energy%20supply&indicator=ElecGenByFuel

[172] ESMAP (2020), Global Photovoltaic Power Potential by Country, World Bank, https://globalsolaratlas.info/global-pv-potential-study?c=36.137875,-6.855469,5

[173] Trinomics and LBST (2020), Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans, p.6, https://www.fch.europa.eu/sites/default/files/file_attach/Brochure%20FCH%20Spain%20%28ID%209474179%29.pdf

[174] IEA (2015), Energy Policies of IEA Countries: Spain 2015 Review, p. 153, https://webstore.iea.org/energy-policies-of-iea-countries-spain-2015-review

million tonnes CO_2, and the same offshore.[175] Moreover, while domestic natural gas production is limited, Spain possesses a large natural gas import infrastructure. Seven LNG import terminals have a capacity of almost 70 bcm per year, by far the largest in Europe. Furthermore, two natural gas import pipelines from Algeria provide an additional import capacity of around 23 bcm per year. Additionally, Spain has pipeline connections to its neighbouring countries France and Portugal.[176] As shown in Table 8, Spanish natural gas demand in 2018 amounted to 30 bcm per year.[177]

8. United Kingdom

8.1. Policy Framework

Unlike the EU and several European countries (e.g. Portugal, Spain, France, Germany, Norway, and the Netherlands), the UK does not yet have a national hydrogen strategy. In its latest Progress Report to Parliament, the UK Committee on Climate Change recommended that the Department of Business, Energy & Industrial Strategy develop a hydrogen strategy by 1H 2021, aiming for large scale hydrogen trials to begin in the early 2020s.[178] The UK government's "Ten Point Plan for a Green Industrial Revolution" was published in November 2020[179] stating the intention of publishing a hydrogen strategy in 2021. This also set a target of 40 GW of offshore wind generation capacity and 5 GW of low carbon hydrogen production by 2030, appearing to indicate an intention to play a leading role in European hydrogen development. In December 2020, the Scottish Government produced a "Hydrogen Assessment"[180] setting out three possible scenarios for hydrogen production in Scotland including the potential for exports. This assessment is expected to lead to a Hydrogen Action plan and Hydrogen Policy Statement for Scotland.

In November 2018, the Committee on Climate Change made a clear recommendation to government that hydrogen for heat in industrial processes, heating buildings on cold winter days, and for heavy transport was "likely to be an important part of the next stage of the UK's energy transition".[181] The report advocated near-term deployment at scale of 'hybrid' heat pumps, whereby much space heating would be provided by electricity, with gas and potentially hydrogen in the future, being used on the coldest days. In July 2020, the UK government announced a "Green Homes Grant" scheme to incentivise up to 600,000 UK households to install home insulation or heat pumps.

In some European countries there is an almost exclusive focus by policymakers on the production of hydrogen via electrolysis, while in the UK there is much more active consideration of the potential for hydrogen production by methane reforming with CCUS. In the March 2020 budget, the UK government committed £800 million of funding for a CCS Infrastructure Fund, to establish CCS in at least two sites in the UK, one by the mid-2020s and one by 2030.[182] This was expanded further in the November 2020 Ten Point Plan, with an aim to capture 10 million tonnes of CO_2 by 2030, with a government investment

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[175] Navigant Consulting (2019), Gas for Climate. The optimal role for gas in a net-zero emissions energy system, p.156, https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

[176] Entsog (2019), The European Natural Gas Network 2019, https://www.entsog.eu/sites/default/files/2020-01/ENTSOG_CAP_2019_A0_1189x841_FULL_401.pdf

[177] At a calorific value of 11.11 kWh/m^3.

[178] CCC Report to Parliament June 2020, p.31: https://www.theccc.org.uk/wp-content/uploads/2020/06/Reducing-UK-emissions-Progress-Report-to-Parliament-Committee-on-Cli.._-002-1.pdf

[179] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

[180] https://www.gov.scot/binaries/content/documents/govscot/publications/research-and-analysis/2020/12/scottish-hydrogen-assessment-report/documents/scottish-hydrogen-assessment/scottish-hydrogen-assessment/govscot%3Adocument/scottish-hydrogen-assessment.pdf

[181] Hydrogen in a low-carbon economy, CCC, Nov 2018 https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

[182] House of Commons briefing paper CBP8841, March 2020 http://researchbriefings.files.parliament.uk/documents/CBP-8841/CBP-8841.pdf

of £1 bn to support CCUS in four industrial clusters[183]. Hydrogen production was, however, only one of the proposed uses of CCS, so it is not clear that this funding will necessarily support production of blue hydrogen. An August 2020 government document outlining potential business models for CCUS also made clear that this funding was intended for decarbonisation of industry and power generation as well as low-carbon hydrogen production.[184]

There is not yet a preferred business model and regulatory structure to support hydrogen deployment in the UK. Indeed, the August 2020 report states that further work will consider a range of potential business models such as Carbon Contract for Differences, a regulated asset base, obligations, direct grants and tax credits. In that report, the government also stated its intention to provide its assessment of potential business models to deploy low-carbon hydrogen by end-2020, with a view to finalising such business models by 2022, in line with expected investment decisions for specific projects.

8.2. Hydrogen Demand

In 2019, around 0.7 million tonnes hydrogen (23 TWh energy equivalent) was produced and consumed in the UK.[185] As in other European countries, most UK hydrogen production uses methane reforming without CCUS, with an estimated carbon footprint of 10-12 kg CO_2 per kg of hydrogen. Currently hydrogen is mostly used as a feedstock for industrial processes, e.g. in oil refining and the production of ammonia for fertilisers.

By contrast total UK natural gas consumption by sector in 2019[186] is shown in Table 9.

Table 9: Final energy consumption for natural gas in the UK in 2018

Sector	Gas Consumption (TWh)
Households	308
Industry	105
Services	82
Mobility	0
Power Generation	303
Energy Industry – Other	57
Total	**855**

Source: Eurostat 2020

Comprehensive projections of future UK energy supply and demand are provided by the National Grid Future Energy Scenarios (NG FES), the 2020 edition of which was published in July 2020.[187] This presents four alternative scenarios, of which three (Consumer Transformation (CT), System Transformation (ST) and Leading the Way (LtW)) are consistent with the UK government's target of Net Zero emissions by 2050. (A fourth scenario "Steady Progression" envisages a slow path to decarbonisation and is not considered further here). An outline of the key features of each of the Net Zero scenarios is given in Table 10.

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[183] UK Government, 10 Point Plan booklet (op. cit) p. 22

[184] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/909706/CCUS-government-response-business-models.pdf

[185] National Grid, Future Energy Scenarios 2020, p 73. https://www.nationalgrideso.com/document/173821/download and ERP UK (2016) ERP-hydrogen-report-oct-2016.pdf (erpuk.org)

[186] https://www.gov.uk/government/statistical-data-sets/historical-gas-data-gas-production-and-consumption-and-fuel-input

[187] https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents

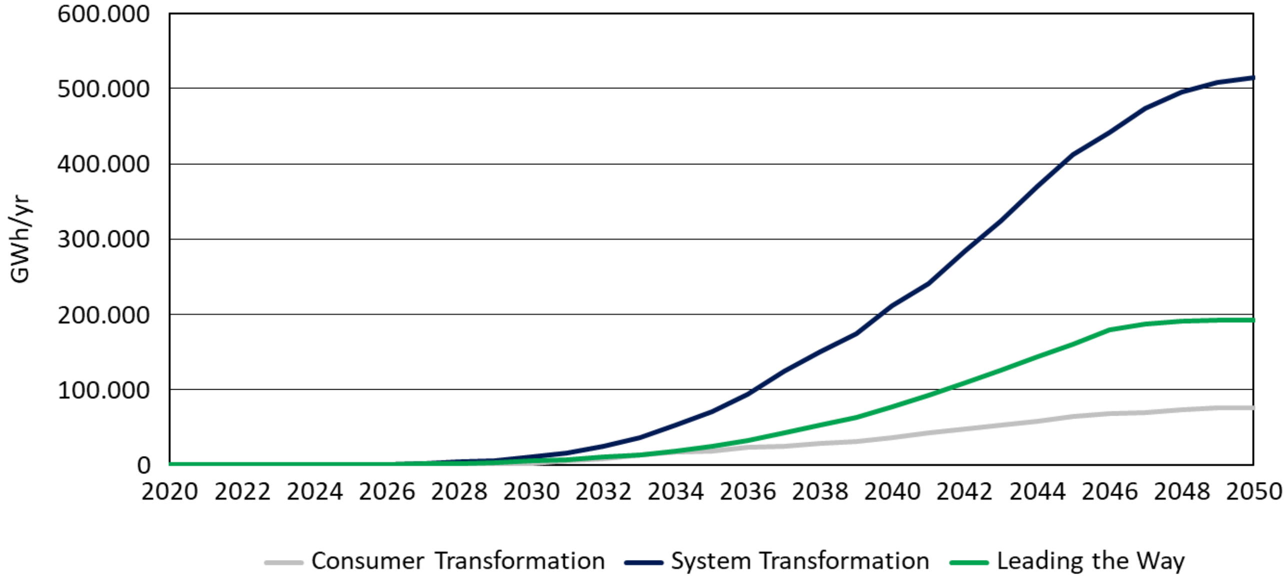
Table 10: Key features of UK National Grid Future Energy Scenarios 2020

Scenario	System Transformation	Consumer Transformation	Leading the Way
Overall assumptions	• Consumers less inclined to change behaviour • Lower energy efficiency • Supply-side driven	• Consumers willing to change behaviour • High energy efficiency • Demand-side flexibility • Electrification of heating	• Significant lifestyle change • Fastest credible decarbonisation
Hydrogen-specific assumptions	• Widespread hydrogen for heating • Most hydrogen from SMR / CCS	• Little hydrogen (mainly electrification) for heating • Most hydrogen from renewables / electrolysis	• Both electrification and hydrogen for heating • Large share of offshore wind to electrolysis
	• Hydrogen for dispatchable power generation • Hydrogen for long range / rapid refuelling road transport • Hydrogen to ammonia for shipping		

Source: Authors' analysis of Future Energy Scenarios[185]

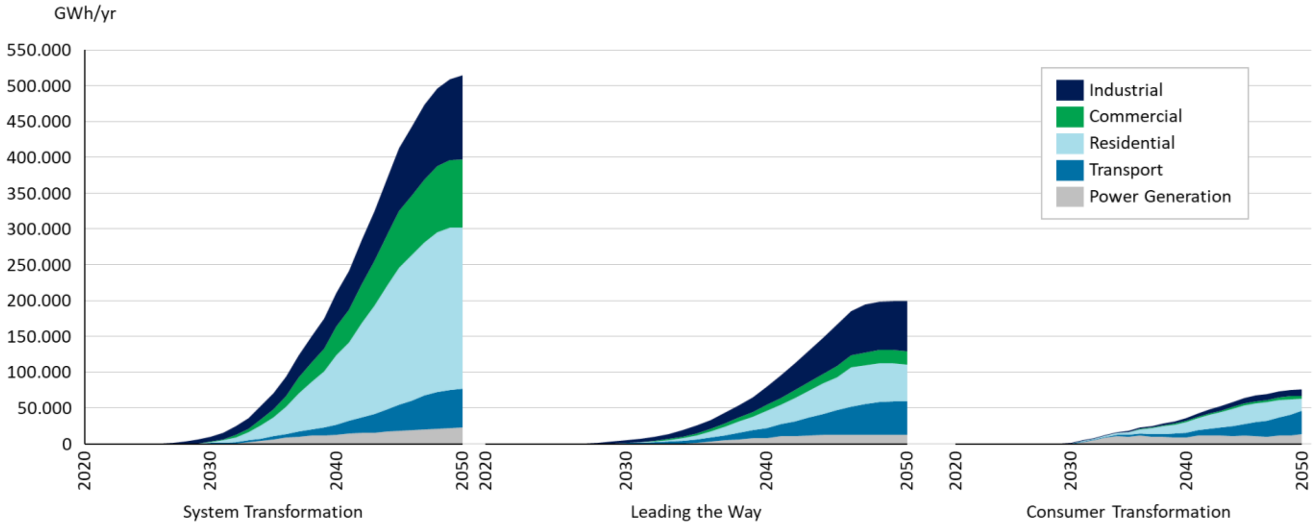
It can be seen from Figure 15 that the total hydrogen demand varies enormously between the different scenarios, from 76 TWh in 2050 under Consumer Transformation to over 500 TWh under System Transformation. It is important to re-iterate that all of these scenarios are designed to meet the Net Zero objective by 2050. This high range of uncertainty underlines the importance of government policy to set a clear direction and to enable the private sector to establish credible business cases for the required investments. Figure 16 shows the demand by sector in each of the scenarios, from which it can be seen that while power generation and transport play similar, relatively small roles in each scenario, the large differences arise from variations in predicted demand for industrial and residential use.

Figure 15: UK total hydrogen demand by scenario



Source: UK National Grid

Figure 16: Hydrogen demand by sector and scenario



8.3. Hydrogen Supply

In the scenario with highest hydrogen demand, ST, the NG FES estimates that 591 TWh of hydrogen supply will be required by 2050, of which 527 TWh would be produced by methane reforming with CCS. The highest level of hydrogen production from electrolysis in 2050 is in the LtW scenario with a production of 188 TWh. At an assumed conversion efficiency of 80 per cent for both methane reforming and electrolysis by 2050 (up from 73 per cent and 70 per cent respectively today) this would require 651 TWh of natural gas or 248 TWh of renewable electricity respectively. At an assumed 6500 running hours for a methane reformer per year, 651 TWh equates to 100 GW of reforming capacity. At an assumed 4000 running hours per year for offshore wind, 248 TWh equates to additional renewable generation capacity of around 60 GW. The LtW scenario includes, by 2050, 23 GW of “non-networked offshore wind” (i.e. offshore windfarms not connected to the electricity grid, but built to produce hydrogen which is then piped to shore).

Given that the maximum total natural gas demand of 651 TWh is somewhat less than current UK natural gas consumption, supply of natural gas would not appear to be a constraint on potential hydrogen production. More important is to consider the potential capacity for CO_2 storage (in the case of methane reforming with CCS) and for renewable electricity production (in the case of electrolysis).

527 TWh of hydrogen (2050 production from methane reforming with CCS under the ST scenario) is equivalent to around 13 million tonnes per year. Methane reforming produces around 10 tonnes CO_2 per tonne hydrogen, requiring a CO_2 storage potential of 130 million tonnes per year. This level of CO_2 storage is consistent with a 2017 report which found that the “top 20” CO_2 storage locations in the UK, with a total storage potential of 6,900 million tonnes were more than enough to meet a storage requirement of 110-130 million tonnes CO_2 per year between 2040 and 2050 and well beyond.[188] The same report estimated that CO_2 transport and storage costs within those top twenty locations varied considerably from less than £10/tonne CO_2 for large, near-shore fields to over £30/tonne CO_2 for smaller stores further offshore. Without considering costs, the total potential CO_2 storage for the UK could be over 70,000 million tonnes.

All three of the Net Zero scenarios in the NG FES envisage between 80-90 GW of offshore wind capacity connected to the electricity grid, generating between 300-320 TWh per year. In addition, LtW

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[188] ETI (2017): Taking stock of UK CO2 storage: https://www.eti.co.uk/insights/taking-stock-of-uk-co2-storage

has an additional 23 GW of offshore wind capacity which, at a similar load factor, would generate around 85 TWh dedicated to the production of hydrogen via electrolysis. A 2017 assessment of Europe's offshore wind resource concluded that the economically attractive potential for the UK was well in excess of 1000 TWh per year,[189] indicating that the supply of renewable power generation would not be constrained by available resources.

A further potential constraint on meeting the projected demand will be the ability to justify the required infrastructure investments. In 2019, the UK had 8.8 GW of offshore wind capacity and 13 GW of onshore wind. For offshore wind to grow to 80 GW over the next thirty years will require an average new installed capacity of around 2.5 GW per year. In September 2019, the UK Government awarded 5.5 GW offshore wind at a record low contract price of around £40/MWh, scheduled to be onstream by 2023 and 2025.[190] This successful auction, at a strike price lower than the expected wholesale market price of electricity, gives reasonable confidence that bringing onstream 2.5 GW of capacity per year should be achievable.

The capital cost of offshore wind is estimated at around £2.4m/MW, with annual operating costs of £76,000/MW (for an investment decision in 2019 coming onstream in 2022).[191] Thus an additional 60 GW of offshore wind will have a capital cost around £140 bn. In addition, electrolyser costs are estimated at around £1m/MW[192], giving a total capital cost for offshore wind plus electrolysers in the order of £200 bn.

The capital cost of methane reforming (either SMR or ATR) is estimated at around £0.5 m/MW, plus around £0.35 m/MW for carbon capture.[193] 100 GW of reforming capacity, including carbon capture, would thus require capital expenditure of £85 bn. The H21 North of England study estimated a capital cost of £1.3 bn for CO_2 transport and storage for a quantity of around 16 tonnes CO_2 per year. At the same rate, the capital cost of storing 130 million tonnes per year could be around £11 bn, although this estimate would be highly dependent on the specific location and geological structures involved.

In line with these costs, the required price of green hydrogen is estimated in the range £80-120/MWh, and the price of blue hydrogen in the range £40-60/MWh.[194] As costs of renewable power and electrolysers fall further, the cost of green hydrogen is expected to fall below that of blue hydrogen by the early 2030s, although this cannot be certain at this stage. With natural gas prices at £20/MWh or lower, it is clear that there is not a business case to make the substantial investments required in either blue or green hydrogen without strong policy support from government.

9. Conclusion

This paper has looked in some detail at the prospects for hydrogen demand and supply, together with the associated policy developments for France, Germany, Italy, Netherlands, Spain, and the UK. With such a wide scope, it is difficult to summarise the conclusions in a few paragraphs, but some overall themes can be identified.

For demand, looking out to 2050 and even in the shorter term to 2030, there is a very wide range of forecasts for each of the countries considered. This is largely based on widely varying assumptions of the extent to which different sectors will become significant for hydrogen consumption. In particular, space heating and transport show large variations depending on assumptions over the extent to which consumers will adopt electric solutions (heat pumps and BEVs respectively). Larger uptake of electrical solutions, which, where they are possible, typically have a higher efficiency, will lead to a smaller role

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[189] Wind Europe (2017) Unleashing Europe's offshore wind potential: https://windeurope.org/wp-content/uploads/files/about-wind/reports/Unleashing-Europes-offshore-wind-potential.pdf

[190] https://www.energyvoice.com/otherenergy/208201/offshore-wind-costs-continue-to-tumble-as-uk-gov-award-contracts/

[191] https://guidetoanoffshorewindfarm.com/wind-farm-costs

[192] Gas Goes Green, May 2020, p32: https://www.energynetworks.org/assets/files/FINAL_Project%20Altair_Hydrogen%20cost%20to%20customer.pdf

[193] Gas Goes Green, May 2020, p39

[194] Gas Goes Green, May 2020, p8

for low-carbon hydrogen. The use of hydrogen to decarbonise industry is a common theme in projections for all countries and provides a solid baseline for potential hydrogen demand, at least for initial development until 2030. Longer term, there is a possibility that heavy industry may relocate to those regions, both within and outside Europe, with large and low-cost renewable energy potential, but that should not constrain initial development of low-carbon hydrogen supply within Europe. There also appears to be considerable uncertainty regarding the level of hydrogen demand for power generation. Consistent with net-zero, there appear to be limited options for long-term energy storage to cover those periods (beyond the capability of batteries) when wind and solar power generation is limited by weather conditions. Hydrogen appears to be one of the more promising options for this role and may provide considerable upside for hydrogen demand.

On the supply side, even over the six countries considered in this study, there is a wide variety of different approaches being considered and for different reasons. Blue hydrogen is only being considered in the Netherlands and the UK, where public and government opinion regarding carbon capture and storage, at least as a transition solution, is more favourable. Green hydrogen is favoured in the southern European countries of Spain and Italy, perhaps with some justification as the higher incidence of solar irradiation leads to lower-cost solar PV electricity. Germany is also focused on green hydrogen mainly because of the societal unacceptability of carbon capture and storage. We remain unconvinced of the logic for significant investment in hydrogen from electrolysis as long as marginal incremental power generation is provided by fossil fuels. It would be more logical to focus on blue hydrogen initially, until around 2030 when there should be sufficient large-scale renewable power generation to justify significant investment in electrolysis. France is perhaps the outlier among the countries considered, on account of its high share of nuclear power generation. While it remains uncertain to what extent France will continue to rely on nuclear power in the future, at this stage, consideration is being given to hydrogen production using nuclear electricity to drive electrolysers at times of low electricity demand.

Comparing supply and demand projections, it is clear that at least until 2030 total low-carbon hydrogen supply (both blue and green) will be lower than the existing industrial use of grey hydrogen. Thus, there is scope for the production of low-carbon hydrogen to be accelerated, without any limitation on demand. That statement, however, ignores pricing considerations, since without clear policy drivers, existing users of grey hydrogen will have little incentive to switch to higher cost low-carbon hydrogen. It will also be important in the next few years for policy to clarify the extent to which new infrastructure investments should be made “hydrogen ready”. This could, for example, apply to a stipulation that all new gas boilers in buildings should be hydrogen ready, although this will not be required if electric heat pumps become the preferred solution for heat for buildings. Similarly, it may be beneficial to stipulate that new gas-fired power plants should be designed for ready conversion to hydrogen in future.

Thus, government policy remains key to driving the growth of low-carbon hydrogen production. Each of the countries considered has an evolving policy framework relating to low-carbon hydrogen, and all have either published, or are working on, ambitious hydrogen strategies. As yet, there is little clarity on the precise policy mechanisms which will be put in place to enable the required investments which will lead to significant low-carbon hydrogen production. It is expected that in the course of 2021 further clarity on such mechanisms will be provided by further EU directives and policy publications from individual country governments. OIES and EWI intend to follow such developments and provide further commentary as appropriate.

Annex

Comparison of policies

Overall policies	DE	FR	ES	UK	NL	IT
Investment support	EUR 9bn (EUR 7bn in Germany + EUR 2bn in partnering countries)	EUR 5-10bn in 2030 and EUR 15bn by 2050		£1bn for CCS by 2025 (not just H2). H2 only mentions private investment)	Research funding rather than investment project funding	EUR 10bn needed – hope to tap EU Recovery Funds
Electrolysis capacity target	5 GW in 2030 10 GW between 2035-2040	Installing 870 MW electrolysis by 2023 and 6.5 GW by 2030	4 GW until 2030	5 GW in 2030	3-4 GW by 2030	0.7 million tonnes low carbon H2 by 2030
RES based Hydrogen	90-110 TWh in 2030	RES based & nuclear based	RES based hydrogen only	SMR/CCS and RES based	SMR/CCS and RES based	
CCUS based hydrogen	As bridging technology for imports only	As bridging technology	Not mentioned	As bridging technology	As bridging technology	Not mentioned
Import / Export	Most of domestic hydrogen demand will be imported; Export of technologies	Domestic hydrogen production to reduce energy import dependence; Export of technologies	Export to other European countries	Possible exports	Possible exports	Potential hydrogen hub – imports from N. Africa, exports to N Europe
Governance	National Hydrogen Council (Industry & Science)	Afhypac (French Association for Hydrogen and Fuel Cells)	RH2	Hydrogen Advisory Council	H2 Platform	H2IT: Italian Hydrogen and Fuel Cell Association

Industrial sector	**DE**	**FR**	**ES**	**UK**	**NL**	**IT**
Targets		10% carbon-free hydrogen by 2023, 20%-40% by 2028	25% RES based hydrogen by 2030	CCS deployment	CCS deployment; H2 use for high temperature heat	
Policy support	CCfD			Clean Steel Fund		

Transport sector		**DE**	**FR**	**ES**	**UK**	**NL**	**IT**
Targets	Fuel cell vehicles, e.g. Light utility vehicles (LUV), light-duty vehicles (LDV), heavy-duty vehicles (HDV).	No clear target stated	200 FCEV HDV by 2023, 800-2000 by 2028; 5,000 FCEV LUV by 2023, 20,000-50,000 by 2028	500 FCEV by 2020, 150-200 FCEV buses by 2030 5,000-7,500 LDV/HDV by 2030 35% by 2050	Focus on BEV rather than FCEV	15,000 FCEV by 2025, 300,000 FCEV by 2030	2% of trucks to be FCEV by 2030
	Refuelling infrastructure	400 HRS by 2025, 1,000 HRS by 2030	100 HRS by 2023, 400-1,000 by 2028	20 HRS by 2020, 100-150 HRS by 2030	13 HRS (2019)	8 HRS (2020) Target 50 HRS by 2025	4 HRS in operation, 2 under construction
Policy support		RED II in national law BMVI 50 HRS Programme	APP, PIA,	RH2	Hydrogen for transport programme		Mainly EU funded

Household heating sector	**DE**	**FR**	**ES**	**UK**	**NL**	**IT**
Targets	Hydrogen use in buildings only long term	1-2 TWh of hydrogen blended with natural gas by 2028 and by 12% by 2050		Hydrogen village heating trial by 2025	Hydrogen use in buildings not expected	No explicit targets
Policy support		Lettre de mission du 12 février 2015				

Infrastructure (Grid & Storages)	**DE**	**FR**	**ES**	**UK**	**NL**	**IT**
	Admixture, transformation of existing natural gas grids, separate hydrogen infrastructure	Admixture, transformation of existing natural gas grids, separate hydrogen infrastructure	Admixture, transformation of existing natural gas grids, separate hydrogen infrastructure; Shipping of LH2	Up to 20% H2 blending	Parallel methane and hydrogen networks	Hydrogen blending, potentially up to 100%
Targets		long-term energy storage and/or sector coupling of up to 8% of total power generation				
Policy support	EnWG amendment 2021					