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STUDY

Renewable Hydrogen in Germany, Poland, and Portugal

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Executive Summary

This study investigates the potential for and implications of renewable hydrogen deployment in Germany, Portugal, and Poland. All three countries have produced hydrogen strategies varying in detail but united in their desire to construct a national narrative around the expansion and decarbonisation of the hydrogen sector. We explore these three national strategies, summarising their core elements and comparing them to the strategy and actual regulatory and policy developments at the European Union level.

This is complemented by an extensive overview on the potential for hydrogen to decarbonise different sectors which forms the basis for an analysis of the positions adopted by the respective strategies. The focus of this analysis is on the period until 2030. The countries are evaluated for their ability to decarbonise existing national hydrogen demand, to reduce natural gas demand and to abate carbon dioxide emissions. The required renewable electricity generation for matching this production is calculated. In evaluating the strategies, the following strategic choices emerge:

- **Where renewable hydrogen is first consumed.** The strategies are broadly united in prioritising first demand cases for hydrogen in the industrial sectors of chemicals, oil refining and steel production. The Polish and Portuguese strategies are notable for their significant focus on the deployment of hydrogen in the road transport sector (ie buses, trains, and trucks), while the Portuguese strategy is further notable for setting targets for the blending of hydrogen into natural gas grids.
- **How and where hydrogen is traded.** This concerns both the trade route which will be used, pipeline or by ship and the type of commodity which will be traded. Especially by ship, it is far more likely that hydrogen derived products (ammonia, methanol, direct reduced iron, and synthetic kerosene) will be traded than hydrogen. This will have important industrial location repercussions. Notably, calculations based upon the Portuguese strategy imply significant exports of renewable hydrogen (or derived products) while the German strategy has an explicit focus on imports.
- **The degree to which hydrogen is used for seasonally balancing electricity grids with higher shares of renewable electricity.** This option is identified in all the strategies as being an interesting use case theoretically, but so far concrete policy actions are not taken. Particularly Portugal which has the highest ambition for renewable deployment is notable for its lack of focus on the possibility of using hydrogen as a seasonally balancing tool.
- **The domestic production of hydrogen.** Concerning production, apart from Poland, the strategies are clear in only anticipating renewable (electrically derived) hydrogen to be produced domestically while the EU and German strategies are open to the temporary import of natural gas-derived hydrogen. The energy crisis of the last year and record high natural gas prices questions this temporary role for gas-based hydrogen.

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Content

1 Introduction

This study investigates the potential for and implications of renewable hydrogen deployment in Germany, Portugal, and Poland. All three countries have produced hydrogen strategies varying in detail but united in their desire to construct a national narrative around the expansion and decarbonisation of the hydrogen sector. We explore these three national strategies, summarising their core elements and comparing them to the strategy and actual policy developments at the European Union level.

The study first offers an overview of existing hydrogen supply and demand, as well as future economic areas where hydrogen might play a role in transitioning toward a zero-carbon energy system. In section 3, we provide an overview of EU regulatory and public policy announcements since the publication of the EU's hydrogen strategy in July 2020. In section 4, the hydrogen strategies of Germany, Poland, and Portugal are discussed. Section 5 provides quantitative and qualitative analysis of the strategies with a focus on the period to 2030. This includes analysis of potential volumes of current hydrogen demand that may be decarbonised as well as associated reductions in natural gas demand and carbon dioxide emissions. A final section concludes and offers policy recommendations.

2 Current and Future Hydrogen Supply and Demand

2.1 Supply

The production of hydrogen is currently one of the most greenhouse-gas emission intensive industries in the European Union. The standard method for producing hydrogen in the EU is currently steam methane reforming (SMR) of natural gas, accounting for over 90% of total production. This process splits natural gas (CH_4) into hydrogen (H_2) and carbon (C), with the latter typically being released into the atmosphere as carbon dioxide emissions. The corresponding installations qualify for trade protection via free allowances under the EU emissions trading system (ETS).[1] Decarbonising the existing production of hydrogen is essential for the EU to meet its own climate targets and provide solutions for third countries.

A variety of cleaner production methods for hydrogen have been identified. The most prominently discussed is the production of hydrogen via the electrolysis of water. This involves passing an electrical current through water to break water molecules into their constituent hydrogen and oxygen atoms. When using a source of zero-carbon electricity, hydrogen produced in this manner can be considered carbon neutral at point of production.[2] When using renewable electricity, the produced hydrogen is considered 'renewable' (this is often referred to as 'green'

[1] The Yara POX installation in Brunsbüttel obtained more than 1 million allowances worth about 100 million Euros in 2022. And Air Liquide hydrogen installations obtained some 350,000 allowances in 2022 – while power plants obtain (almost) no free allowances, via : https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.C_.2021.302.01.0001.01.ENG&toc=OJ%3AC%3A2021%3A302%3AFULL

[2] Lifecycle emissions from the production of a renewable generating electricity facility and electrolyser will be small but exist.

hydrogen).[3] Production of hydrogen via electrolysis is an established industrial process and has been used to produce hydrogen in the chemical industry, notably as a by-product of chlorine production. The EU also has a strong and growing domestic manufacturing base for the production of electrolysers. By August 2022, 162 MW electrolyser capacity had been deployed (Hydrogen Europe, 2022).

A secondary route concerns attaching carbon capture and storage (CCS) facilities to the SMR industrial application (often referred to as 'blue' hydrogen).[4] Theoretically, carbon emissions of up to 90% can be captured from the process leading to low-carbon hydrogen production. For the route to be truly low-carbon, the captured emissions should be stored geologically. Industrial applications today include the capturing of carbon dioxide from the process which is then used to enhance oil recovery (IEA, 2022). The deployment of carbon capture to SMRs is still in its infancy. Of 504 fossil-based hydrogen production sites in operation at the end of 2020 in the EU, only three were using carbon capture and storage (Hydrogen Europe, 2022).

2.2 Existing Demand

To 2030, the supply of renewable hydrogen in the EU will be constrained by the availability of renewable electricity. Sensible deployment of limited volumes of renewable hydrogen should focus first on decarbonising existing carbon-emitting consumption of hydrogen, or highly promising new uses cases, such as the production of primary steel. Table 1 (next page) provides an overview of each demand sector discussed.

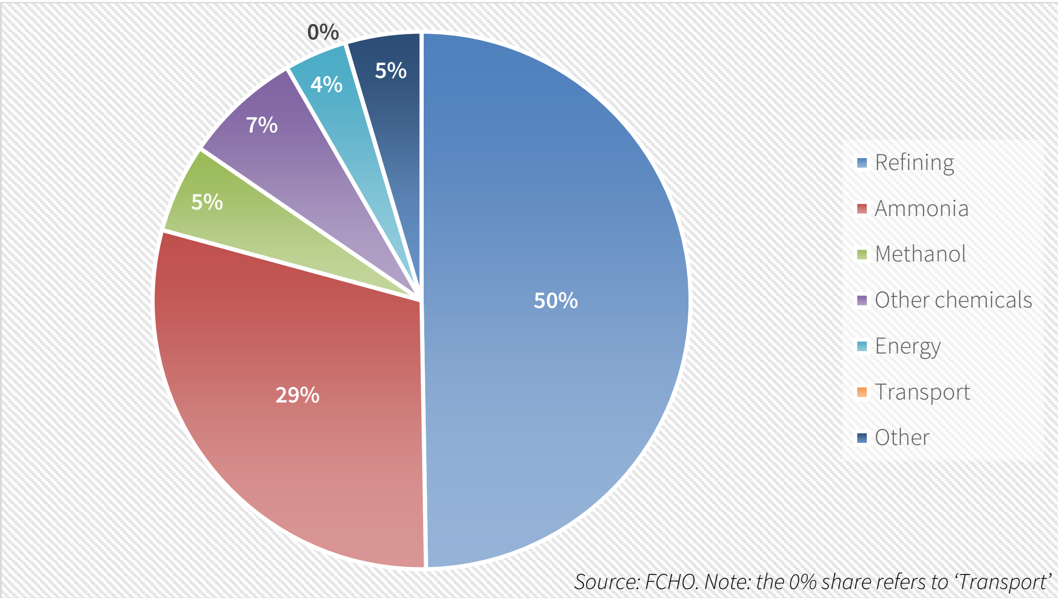


Figure 1: EU Hydrogen Demand (2020)

[3] In this study we will stick to the terminology 'renewable hydrogen' according to the definition provided here. Commonly the use of 'green hydrogen' refers to this definition.
[4] An alternative route from natural gas would involve Autothermal Reforming with associated CCS. A schematic overview of possible future low-carbon hydrogen production routes can be found in McWilliams and Zachmann (2021), while in depth explanations are available from Nikolaidis and Poullikkas (2017).

Table 1: Author's conclusions on current state of play for potential renewable hydrogen demand use-cases

Sector	Author's Summary
Existing Demand	
Ammonia	Existing feedstock demand can be directly replaced by renewable hydrogen, relevant before 2030.
Methanol	Existing feedstock demand can be directly replaced by renewable hydrogen, relevant before 2030.
Oil Refining	A certain amount of hydrogen demand could be replaced. Future demand uncertain given decline of industry, relevant before 2030.
Possible Future Demand	
Primary Steel	Currently appears the most promising option for decarbonising primary steel production in the EU, relevant before 2030.
High-temperature industrial heat	Unlikely to compete with electricity for low- and medium- temperature heat, but still uncertain for higher temperatures, relevant before 2030.
Navigation	Likely demand to emerge via consumption of methanol and ammonia produced from hydrogen, larger demands likely after 2030.
Aviation	Highly uncertain, larger demands likely after 2030.
Heating buildings	No strong business case for hydrogen beyond niche applications, any demand would materialise after 2030.
Seasonal power storage	Uncertain demand, a promising option for exploration. Significant role only likely after 2030.

Approximately 8.7 Mt (290 TWh) hydrogen in the EU is today consumed largely as an industrial feedstock or for improving the oil refining process (Hydrogen Europe, 2022). Figure 1 shows the breakdown of hydrogen consumption in 2020. A little over half is consumed for oil refining, 30% to produce ammonia, 5% to produce methanol and the remainder for other chemicals or limited energy uses. Less than 1% of current hydrogen demand is consumed for transport. The first significant challenge for the EU is to decarbonise existing production.

In oil refining, hydrogen is used for hydrotreating (removing sulphur impurities) and hydrocracking heavier mineral oil products to produce lighter and more valuable oil products that can be sold on the market. While some hydrogen supply comes from internal processes as a by-product, this is supplemented by SMR. This additional hydrogen demand can be replaced by zero-carbon hydrogen. Indeed, existing projects, such as REFHYNE[5] and the Porvoo Refinery[6] in Finland, are underway to explore and scale this possibility.

Future hydrogen demand in the oil refining sector will be determined by future demand for refined oil products which is largely dependent on demand in the transport sector. Driven by the electrification of transport, conventional oil refining is expected to significantly scale down in the EU over the coming years leading to lower hydrogen demand. In 2022, the IEA reported that electric vehicles took 18% of global car sales market share, and estimates that by 2030 electrification will remove 5 million barrels of oil demand per day.[7] Uncertainty remains over possible future roles for

[5] See the Refyne project, available at: https://www.refhyne.eu/refhyne-2/
[6] Reported on 23rd December 2022, https://energynews.biz/neste-gets-e27-7m-for-porvoo-refinerys-green-hydrogen-projects/
[7] IEA Press Release on 26th April 2023 summarising findings from the IEA Global EV Outlook 2023, available at: https://www.iea.org/news/demand-for-electric-cars-is-booming-with-sales-expected-to-leap-35-this-year-after-a-record-breaking-2022

refineries in a decarbonised world, with possible production of synthetic hydrocarbons or upgrading of biofuels, both of which could increase hydrogen demand.

The second largest consumption of hydrogen comes from the production of ammonia. More than two-thirds of ammonia produced today is used for mineral nitrogen fertilisers. The remainder is used to produce alternative fertilisers, with smaller use cases in the production of textiles, explosives, and for synthetic polymers (Egerer *et al,* 2023a). Conventional ammonia demand therefore depends on fertiliser demand. In turn, this is driven by food demand, with growing populations exerting pressures for ever more efficient land use. At the same time, future EU regulations and public opinions on the use of chemical or ammonia-based fertilisers may reduce fertiliser demand (McWilliams and Zachmann, 2021).

Ammonia is an easier fuel to transport than hydrogen, with a global trade already established. It is likely that the first years of international hydrogen trade will be by the transport of ammonia. While ammonia production currently relies on hydrogen production via SMR, clean ammonia can be produced using renewable hydrogen. This implies that the production costs of clean ammonia will be heavily influenced by the cost of renewable electricity used to produce hydrogen. The fact that ammonia is readily transportable means there is a chance that ammonia production will relocate to geographies with abundant renewable and land availability, which may or may not lie inside the EU. Overreliance on the import of ammonia may be considered a geopolitical risk, given its importance in fertiliser value chains.

The second largest demand for hydrogen in the chemicals sector comes from the production of methanol, which is largely used as an intermediate product to produce other chemicals. Hydrogen can be replaced with a zero-carbon production source in the synthesis. Methanol is also currently blended into conventional fuels, up to a maximum concentration of 3% (Ausfelder and Wagemann, 2019). Like ammonia, hydrogen demand from SMR can be replace by renewable hydrogen directly.

New use cases may increase demand for both ammonia and methanol. A particularly promising use case is as a fuel in the maritime industry, while countries such as Japan are also considering the use of ammonia for power generation (Egerer *et al,* 2023a). Maersk has already seen first order for large-scale methanol ships to be delivered in 2024.[8] Further potential uses for methanol may be the production of basic chemicals such as olefins and aromatics (Egerer *et al,* 2023b) as well as a base fuel for the synthesis of heavier hydrocarbons, such as synthetic kerosene.

[8] Reported by Hydrogen Insight on 30th November 2022, https://www.hydrogeninsight.com/transport/hydrogen-based-shipping-well-use-methanol-now-and-ammonia-later-if-its-ready-says-maersk/2-1-1363838

2.3 Demand-Side: Possible Future Uses

Hydrogen may also contribute to the decarbonisation of sectors where it is currently not consumed. Hydrogen can be consumed as a fuel or feedstock for decarbonising certain hard-to-abate applications, particularly where electricity is not competitive - either due to the need for chemical properties, very high temperatures, or high fuel density requirements. This study explores a range of sectors with existing or potential use cases for hydrogen, as summarised in table 1.

2.3.1 Production of Primary Steel

Hydrogen consumption in the steel sector is currently marginal. Two routes are used to produce steel in the EU. Primary steel is produced via the Blast Oxygen Furnace, where coking coal is used to reduce iron ore with large associated carbon emissions. This production method accounts for approximately 60% of the EU's steel production. The remaining 40% is produced using the electric arc furnace, primarily based upon recycling scrap steel.[9] To produce primary steel without carbon emissions, iron ore can be reduced to direct reduced iron using hydrogen before being passed through an electric arc furnace to produce steel. While other options for decarbonisation in the steel sector, such as electrowinning or carbon capture and storage, are being explored, hydrogen currently appears the most promising option (Somers, 2022). This is confirmed by the fact that all major European steelmakers are currently building or testing hydrogen-based reduction. The HYBRIT plant in Sweden delivered the world's first steel produced using green hydrogen as a reducing agent in 2021.[10]

Future demand in the EU will depend on the volume of scrap steel recycled, domestic demand for steel, and the extent to which the EU imports green steel. The EU may import direct reduced iron rather than iron ore which can then be transformed into steel domestically. Given that hydrogen consumption occurs at the stage of iron ore transformation to direct reduced iron, this would reduce potential domestic demand for green hydrogen significantly.

2.3.2 High-temperature industrial heat

Beyond steel, an imperative for industry is to decarbonise the generation of heat. For low- and medium-temperature applications (below 400-500°C) electric options are established in industry and likely to be deployed in the coming years, incentivised by climate policy. For these temperatures, heat applications are not sector-specific, and technologies such as heat pumps and electric boilers will benefit from commercialisation across many industries. Maddedu *et al* (2020) have demonstrated that 78% of industrial heat in the EU can be met by electric technologies that are already commercialised. There is not likely to be a role for hydrogen in low to medium heat provision.

Hydrogen is more suited for higher temperatures above 500°C, which account for around 40% of industrial heat demand in the EU (table 2). This may include cement production for which the manufacture of cement clinker in rotary kilns requires temperatures above 1,400°C or the melting of glass with temperature requirements up to 1,700°C that are currently met by natural gas. (Egerer, 2023b). This demand is still uncertain and may yet be met by electric options. Maddedu *et al* (2020) found that up to 99% of industrial heat can be met by electric options already under development.

[9] See Eurofer, https://www.eurofer.eu/about-steel/learn-about-steel/what-is-steel-and-how-is-steel-made/
[10] See Reuters, https://www.reuters.com/business/sustainable-business/swedens-hybrit-delivers-worlds-first-fossil-free-steel-2021-08-18/

Electric technologies are already proven for high temperature heat with the electric arc furnace reaching up to 3,500°C in the manufacture of secondary steel. The inefficiency of producing renewable hydrogen from electricity before generating heat means hydrogen will be an option where electric solutions are unable to satisfy specific requirements on an application-by-application basis.

Table 2: Natural gas final energy consumption in the industry sector by application temperature in TWh (% of total), 2017

	< 100°C	100°C - 500°C	> 500°C	Total
EU	341 (39%)	215 (24%)	322 (37%)	878
Germany	81 (33%)	67 (28%)	95 (39%)	243
Poland	13 (30%)	12 (28%)	18 (42%)	43
Portugal	6 (39%)	3 (23%)	5 (38%)	14

Source: Agora Energiewende and AFRY Management Consulting (2021)

2.3.3 Road Transport

For passenger road transport, (i.e., personal-sized vehicles) future demand for hydrogen is unlikely to be competitive with pure battery electric vehicles. No European automobile manufacturer is treating fuel cell vehicles comparably to battery electric, with then CEO of Volkswagen Herbet Diess commenting, "You won't see any hydrogen use in cars".[11] By June 2022, just under 50,000 fuel cell cars have been sold globally compared to over 25 million battery electric cars (IEA, 2022).[12] A few years ago, when electric cars had a limited range and slow charging, a role for fuel cell cars was possible for addressing these concerns. However, the pace of battery development has removed this potential use case with battery electric vehicles now offering 400 km range and the newest generation able to charge the equivalent of 200 km in about 15 minutes (Plötz, 2022).

Hydrogen has greater potential for heavy-duty road vehicles because the fuel can store more energy in a smaller space and at a lower weight than a lithium-ion battery. However, there are already 30,000 battery electric trucks deployed globally (mostly in China) while fuel cell trucks have only been operated in trials (Plötz, 2022). Daimler and Volvo, the two largest truck manufacturers in Europe with strong hydrogen interests, only see the sale of their fuel cell models in the second half of this decade. Meanwhile, the capacity of batteries and hence range that an electric vehicle can drive on a single charge continues to expand at a rapid pace, as well as charging infrastructure. Concerning charging, European regulation mandates that drivers pause every four hours, meaning battery electric trucks should permit driving 400 km periods followed by a 45-minute driver rest and battery charge (Plötz, 2022). The first generation of battery electric trucks have proposed ranges of 250km in medium freight trucks and 300-350km range in heavy freight trucks (Plötz, 2022). Large scale roll-out of medium-to-heavy freight battery trucks will require a high-power fast charging system across Europe. With currently available information, the competitiveness case for battery electric vehicles generally seems stronger than fuel cell vehicles. However, unlike passenger vehicles, this is a nascent industry and further developments may yet change this picture.

[11] See FT, https://www.ft.com/content/a1325d48-6c76-4b6f-81e8-2be504c21791

[12] Global electric car stock available from the IEA, https://www.iea.org/data-and-statistics/charts/global-electric-car-stock-2010-2022

2.3.4 Navigation and Aviation

The shipping industry currently consumes heavy fuel oil, but global and EU level initiatives are spurring decarbonisation which will require fuel substitution. For short distances, hydrogen fuel cells may play a role while longer distance shipping is more likely to see consumption of hydrogen-derived fuels such as ammonia. The coordination challenge that ships need to refuel in multiple locations around the world favours an outcome of one dominant fuel. The possibility of green ammonia being transported globally as it stands for domestic demand (fertilisers) might push for an ammonia-solution. In the nearer term, market signals point to a swifter uptake of methanol, due to cost and safety considerations of ammonia. The fuelling of ships via methanol or ammonia derived from green hydrogen is considered a sensible use case which is likely to grow in the second half of this decade.

For aviation, short distance flights might similarly be serviced by pure hydrogen running in a fuel cell, electricity in a battery, or a combination of both. However, none of these options are yet commercially developed and which option will be competitive in the future is uncertain. Longer distance flights will require fuels with higher energy densities, where again electrically derived fuels, that have hydrogen as an input, might develop (McWilliams and Zachmann, 2021). Synthetic kerosene can be produced from the combination of hydrogen with captured carbon dioxide. This raises the important issue that in many future cases it is unlikely that hydrogen will be produced and consumed as the same commodity, but as a derived commodity. For both short and long-distance flights, advanced biofuels are currently another option under consideration.

2.3.5 Building Heat

While countries such as the United Kingdom are exploring the possibility of hydrogen for heating homes, independent expert studies have not supported this possibility. Rosenow (2022) identified 32 independent studies, all of which failed to provide evidence that would support the widespread use of hydrogen for heating. The primary reason for this is the energy inefficiency associated with generating heat from hydrogen. One unit of electricity will result in around 0.7 units of heat after being passed through an electrolyser and hydrogen boiler, while one unit of electricity will provide three to four units of heat when a heat pump is used. Some studies do identify uses in district heating or hybrid systems (e.g., as peaking reserve) suggesting a geographically limited role may evolve. Countries with large gas distribution networks, and high shares of district heating that are not decarbonised may find such niche use cases. There may be a small role for hybrid heating with hydrogen to reduce electricity demand during periods of peak demand.

The possibility of blending hydrogen into the gas grid has been discussed as a temporary bridge toward a pure hydrogen network. Blending shares of up to 20% hydrogen in a natural gas grid is technically possible with associated challenges. However, this does not aid the transition to a pure hydrogen grid. Above quantities of 20%, the pipeline system must be retrofitted for carrying hydrogen. The capital costs of performing this retrofit do not depend on whether the pipeline previously carried 20% hydrogen.

Blending is not a solution for a fully decarbonised system and should therefore not receive any public funding on this notion. The case for blending hydrogen into the natural gas grid should therefore rest on the immediate useful energy and greenhouse gas abatement. To 2030, with limited volumes of green hydrogen available and huge potential offtake in the chemical and steel industries, blending into a natural gas grid does not appear a sensible option to receive public support. The lower energy density of hydrogen in volumetric terms compared to natural gas, mean that a blending share of 20% (typically considered an upper bound) into the gas grid will only displace 6-7% the energy content of natural gas, and hence abate 6-7% of the associated greenhouse gas emissions. Per energy unit of hydrogen consumed, Bard *et al* (2022) have shown that blending hydrogen into the natural gas grid performs poorly against other considered uses of hydrogen based on its ability to reduce greenhouse gas emissions.

2.3.6 Power Sector

Future electricity systems are set to absorb high volumes of renewable generation. One associated challenge is the fact that renewable (solar) output is higher in summer months with longer daylight hours, while peak demand on a power system occurs during colder and darker winter months. The ability to generate hydrogen from periods of abundant renewable supply, store this hydrogen in salt caverns, and then produce electricity from hydrogen at periods of higher net demand may become a valuable role in future electricity grids. The potential role will depend upon capital costs of production, transport and storage of both hydrogen and alternative options. The extent to which power demand becomes more flexible to accommodate variable supply is also highly relevant.

The German draft electricity network development plan of 2023[13] foresees in all scenarios 38 GW (2037) / 34 GW (2045) of gas-fired power plants to back up the renewables system. Given German climate targets they can not only run on natural gas until 2037 (so may involve some hydrogen co-firing, or even some specific hydrogen power plants); and must all run on climate-neutral gases by 2045. In the near-term there are plans to construct 17-21 GW of "hydrogen-ready" gas fired power plants.[14]

3 European Union Regulatory Developments

3.1 Clean Hydrogen Supply

In 2020, the EU launched its Hydrogen Strategy, declaring "the priority for the EU is to develop renewable hydrogen", while in the short- and medium-term, other forms of "low-carbon hydrogen are needed to rapidly reduce emissions from existing hydrogen production" (European Commission, 2020).

The strategy is divided between phases, with the first phase from 2020 to 2024 setting a strategic objective of installing at least 6 GW electrolysers in the EU and producing 1 million tonnes of renewable hydrogen. This compares to an installed electrolyser capacity in the EU of 0.16 GW as of August 2022 (Hydrogen Europe, 2022). A second phase sees the strategic objective of installing 40 GW electrolysers and producing 10 million tonnes of renewable hydrogen in the EU. Table 3 highlights the relationship between electrolyser capacity (GW) and hydrogen output (TWh) which is dependent on the number of hours in a year which an electrolyser runs. This is expected to be

[13] The plan is available at: https://www.netzentwicklungsplan.de/sites/default/files/2023-03/NEP_2037_2045_V2023_1_Entwurf_Teil1_7.pdf
[14] Reported by Hydrogen Insight on 7th March 2023, https://www.hydrogeninsight.com/power/germany-to-build-17-21gw-of-new-hydrogen-ready-gas-fired-power-plants-says-chancellor/2-1-1415040

limited by renewable electricity availability. A safe conclusion is that significantly more than 40 GW electrolyser capacity will be necessary for producing 10 million tonnes renewable hydrogen in the EU.

Table 3: Relationship between electrolyser capacity, load hours, and hydrogen output

Electrolyser Capacity (GW)	Load Hours (load factor)	Renewable Input (TWh)	Hydrogen Output (TWh)	Hydrogen Output (million tonnes)
1	2,628 (30%)	2.6	1.8	0.06
1	3,504 (40%)	3.5	2.5	0.07
1	4,380 (50%)	4.4	3.1	0.09
6	2,628 (30%)	15.7	11.0	0.33
40	2,628 (30%)	105.1	73.6	2.21

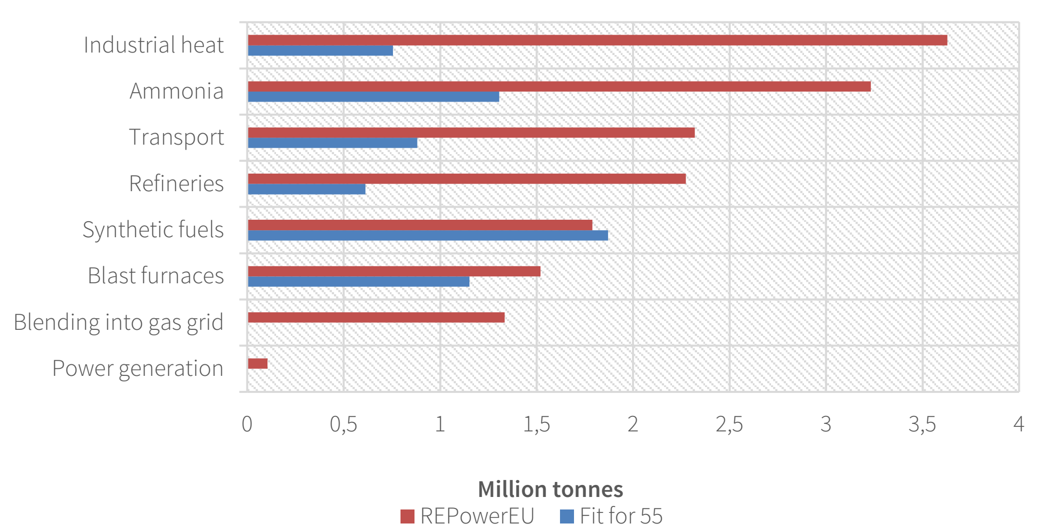
Source: Author's calculations. Note: the calculations assume an electrolyser efficiency of 70%. Load hours refer to the equivalent hours in a year for which an application is operating. This can be limited by maintenance, or repairs, but in the case of electrolysers for producing renewable hydrogen, the limiting factor will be the hours in which renewable generation is available.

3.2 Clean Hydrogen Demand

Concerning hydrogen demand, the strategy identifies two main lead markets: industrial applications and mobility. For industrial applications, the focus is on replacing the use of carbon-intensive hydrogen in oil refineries, the production of ammonia and methanol and to replace fossil fuels in steel making. In transport, hydrogen is imagined for areas where electrification is more difficult. The strategy mentions "local city buses, taxis, or specific parts of the rail networks", while encouraging the exploration of hydrogen for heavy-duty road vehicles. For inland waterways and short-sea shipping, the strategy considers that hydrogen can become a useful fuel. In the longer term, hydrogen is considered as an option to decarbonise the aviation and maritime sector through the manufacture of synthetic kerosene and other synthetic 'drop-in' fuels. Currently, such synthetic fuels are very expensive to produce, and so are considered only possible options for the longer term.

Following Russia's invasion of Ukraine, the European Commission published its REPowerEU plan which was seen as a response to the global energy market disruption – and Europe's need to displace some 1,500 TWh of Russian natural gas (European Commission, 2022a). The political imperative of reducing dependence on Russian fossil fuels and particularly natural gas, led to an anticipation for an increased reliance on hydrogen by 2030 in the strategy. The plan provided the output from energy-economy modelling work performed for the European Commission on exactly how the EU could reduce natural gas demand by 50bcm (approximately 500 TWh) by 2027.

A working document accompanying the plan detailed the proposed role for hydrogen in this ambitious scenario (European Commission, 2022b). The existing strategic objective for 10 Mt domestic production by 2030 was to be accompanied by 10 Mt of renewable hydrogen imports, 4 Mt of which would be hydrogen derivatives such as ammonia. Given the unfavourable economics of moving pure hydrogen by ship, an implicit assumption is that the 6 Mt renewable hydrogen will be imported by pipeline, while 4 Mt derivates will be imported by ship. Figure 2 shows the increase in assumed hydrogen demand by application from assumptions in modelling carried out by the European Commission for Fit for 55 (which formed the input for the 2020 Hydrogen Strategy) and that performed for REPowerEU.



Source: Bruegel on European Commission (2022b)

Figure 2: Anticipated hydrogen demand under Fit for 55 package and REPowerEU (million tonnes)

The plan was produced at a time of high political stress, during a global energy crisis and with significant public pressure to find solutions to the EU's natural gas crisis. This background is important for understanding the updated hydrogen assumptions, which we consider likely to be overestimates of realistic EU renewable hydrogen demand in 2030.

Beyond political targets, the Renewable Energy Directive sets explicit targets at member state level for the share of renewable energy in final energy demand. Negotiations between the European institutions are now essentially concluded on the updating of the Renewable Energy Directive to its third version (RED III). This version will include a new target, which is the percentage of hydrogen consumed by industry which must be "renewable". Technically this is expressed as a target for Renewable Fuels of Non-Biological Origin (RFNBOs), which refers to non-biologically produced hydrogen, or fuels derived from hydrogen.

Under the Fit for 55 package, the European Commission proposed a target for 50% RNFBOs share of hydrogen consumed in industry and 2.6% in transport. The ambitious REPowerEU targets discussed above were based on increasing these shares to 75% and 5%, respectively. On 30th March 2023, a trilogue agreement was reached between the European Commission, the European Parliament, and the European Council to set the targets at 42% for industry and 1% for transport.[15] Therefore, while the REPowerEU communication seemed to politically raise ambition for renewable hydrogen consumption by 2030, the negotiated outcome is that binding hydrogen targets are lower than those previously proposed by the European Commission. The targets do not set an upper limit and it is possible that economics of continuing high natural gas prices and carbon prices will drive renewable hydrogen adoption, irrespective of policy.

A further debate has been exactly how hydrogen produced from electricity would qualify as "renewable" under this legislation. The debate centres around exactly how an electrolyser connected to a power grid can attribute its electricity consumption. A delegated act by the European Commission sets out the criteria for electrically derived hydrogen to qualify as RNFBOs.[16] The core principle of the act is additionality, which is the concept that the deployment of renewable

[15] As reported by Euractiv, https://www.euractiv.com/section/energy-environment/opinion/how-the-eus-revised-renewables-directive-facilitates-hydrogen-market-ramp-up/
[16] See the European Commission Q&A for further discussion, https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_595

hydrogen projects should contribute additional renewable electricity generation, in appropriate times and places, that was not otherwise planned. For hydrogen to be counted as renewable, it must be connected - directly or via a power purchase agreement - to a "new" renewable electricity plant, which will not itself count toward renewable energy targets. This is defined as the plant coming into operation not more than 36 months before the hydrogen plant, and not receiving other operating or investment support.

The act contains exemptions. Most notably, to facilitate a swift ramp-up of the hydrogen economy, hydrogen projects that come into operation before the end of 2027 will be exempt from the additionality rule until 2038. The temporal correlation requirements for a power purchase agreement (PPA) connecting a power plant to electrolyser are also relatively weak until 2029, with only monthly correlation required. In other words, the sum of solar or wind output from a project in the month of July can be attributed to hydrogen production. Post 2029, hourly correlation is envisaged to be required. Electricity grids with shares of renewables above 90%, or carbon emission below 18gCO_2/MJ (which would apply to electricity grids that have a high share of nuclear generation, such as France or Sweden) are permanently exempted from the additionality requirement.

A second delegated act sets the methodology for assessing lifecycle emissions from RFNBOs and recycled carbon fuels. A complex framework is developed based on lifecycle emissions, which should see a reduction of 70% compared to a fossil fuel benchmark of 11.3 tCO_2/tH_2. This implies low-carbon hydrogen would be produced at 3.38 tCO_2/t Hydrogen.

Complementing the RNFBO target of 1% in the transport sector, the REFuelEU Aviation proposal sets an explicit target for clean fuels to be consumed in European aviation. This is expressed as a minimum quota of sustainable aviation fuel that is to be supplied to operators at EU airports as a share of total (fossil) fuel supply. While sustainable aviation fuel includes biofuels, a sub-target is set for consumption of synthetic aviation fuels – which are hydrogen derivatives. A final agreement on the exact numbers is yet to be reached, while the European Commission and Council propose a 0.7% target by 2030, the European Parliament is pushing for a 2% target. In the maritime sector, the inclusion of ships above 5,000 gross tonnage into the emissions trading system will accelerate decarbonisation, and has been adopted by the European Council. The FuelEU Maritime provisional agreement sets a target for 6% greenhouse gas savings relative to a 2020 baseline by 2030.[17]

3.3 Financial Support

At the European level, the hydrogen bank is the main policy tool for channelling funds to support the deployment of clean hydrogen production. The hydrogen bank aims to boost domestic production of clean hydrogen and to explore options for renewable hydrogen imports. The Bank is envisaged to invest 3 billion euros coming from the Innovation Fund. For domestic production, a first auction has been announced of around 800 million euros which will offer a fixed subsidy per kilogram of hydrogen produced for ten years. Pre-qualification criteria for auction include having a hydrogen purchase agreement (a legally binding contract between a supplier and customer detailing conditions for the purchase of hydrogen) and producing renewable hydrogen according to the delegated act discussed in section 3b (European Commission, 2023). The European Commission is still considering via a task force at DG ENER the different options for potential support for the import of clean hydrogen imports.

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[17] See Briefing for the European Parliament, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698808/EPRS_BRI(2021)698808_EN.pdf

The inclusion of clean hydrogen producers into the ETS is also a relevant step. While currently grey (gas-based) hydrogen producers receive free allowances, the reform will include clean producers also meaning they will receive free allowances based on a yet-to-be-agreed benchmark. Implicitly, this will provide a further subsidy to the production of clean hydrogen in the EU. The level that the benchmark is agreed upon will be key for determining the implicit subsidies received for renewable hydrogen producers.

At the same time, hydrogen has also been included in the EU's carbon border adjustment mechanism which means that these free allowances will be phased out progressively between 2026 and 2033. By 2034, the CBAM legislation foresees that no more free allowances are issued to covered products. The initial scope of hydrogen under CBAM will cover only direct emissions, consideration of the inclusion of indirect emissions (i.e., those generated by the electricity used for running an electrolyser) will remain an important topic.

National public funding for the hydrogen industry typically must pass through state aid review from DG COMP at the European Commission. In the past couple of years, state aid has been granted for two Important Projects of Common European Interest. The two projects total public funding of €10.6 billion and span the hydrogen value chain. (European Commission, 2023). More requests for public funding via this route are likely.

3.4 Infrastructure

The draft *Hydrogen and Decarbonised Gas Market* package was published by the Commission in December 2021.[18] It contains the proposal for a Gas Directive which will set common rules for the internal EU markets in renewable gases and hydrogen (European Commission, 2021). The directive aims to set the legal basis for the decarbonisation of gas markets and to establish an internal hydrogen market. Important areas of discussion include the rules on 'unbundling' – which is the concept that hydrogen network operators be independent from the producers or consumers of hydrogen (Tanase and Herrera Anchustegui, 2022). This would be different from the few current hydrogen pipelines in operation in North-West Europe where monopolies are permitted. The directive is still under negotiations and yet to be formally adopted. It is an important piece of legislation for providing regulatory certainty to companies interested in building out a hydrogen pipeline network inside the EU.

The Alternative Fuels Infrastructure Regulation sets mandatory targets for deploying hydrogen refuelling stations, focusing on hydrogen for road transport. Trialogue negotiations are discussing the level at which minimum targets between stations should be set, which will imply the number of hydrogen refuelling stations that will be deployed across the EU.

[18] See https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/hydrogen-and-decarbonised-gas-market-package_en

4 National Strategies

4.1 Germany

Germany currently consumes 55 TWh hydrogen for industrial uses, almost all coming from fossil fuel production. Demand is split between the ammonia sector (19 TWh), the oil refining sector (23 TWh), and the production of methanol (9 TWh). The Federal Government published its Hydrogen Strategy in 2020,[19] although an update is expected this year.[20] The draft strategy outlines the government's position on certain key hydrogen topics and sets a range of targets. Several of Germany's state governments have also defined hydrogen strategies or roadmaps.

Concerning the production of hydrogen, the government considers only hydrogen produced from renewable energy to be sustainable in the long term, while conceding that a global and European market may involve the trade of low-carbon hydrogen (this includes hydrogen from nuclear and gas-based hydrogen with carbon capture) in the short run which will be "temporarily used". Indeed, despite this renewable focus, German RWE and Norwegian Equinor have presented plans for powering a range of hydrogen ready power plants in Germany via pipeline imports from Norway which are expected to be natural gas-based hydrogen with carbon capture.[21] No serious volumes of low carbon (non-renewable) hydrogen are expected to be produced domestically. The plan instead targets 5 GW of electrolyser capacity in Germany by 2030, although an updated version of the strategy is expected to target 10 GW.[22]

The plan foresees hydrogen demand of 90-110 TWh in Germany by 2030. The immediate priorities are using hydrogen as a sustainable base material in the industrial sector, for the decarbonisation of oil refining, clean production of ammonia and methanol, as well as hydrogen-based reduction of iron or for steel production. Public funds of 7 billion euros are allocated for speeding up the rollout of hydrogen technology in Germany.

Germany's hydrogen strategy is notable for a strong focus on imports and the recognition that German demand will far exceed national supply (the plan for 5 GW electrolyser is estimated to produce 14 TWh renewable hydrogen compared with demand of 90-110 TWh). The plan envisages that most of Germany's hydrogen demand will have to be imported. This manifests itself clearly in the establishment of the H2Global platform[23] which channels public funds for the imports of clean hydrogen and the fact that Germany has signed a Memorandum of Understanding with at least 7 countries to explore the possibility of future hydrogen trade (IRENA, 2022). The plan makes 2 billion euros available for fostering international hydrogen partnerships. Benefits for German companies are also imagined via the export of hydrogen technologies abroad.

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[19] The Federal German Government (2020)

[20] Editorial note: The updated version of the national hydrogen strategy of Germany was published during the editorial process of this study and is available at https://www.bmwk.de/Redaktion/DE/Wasserstoff/Downloads/Fortschreibung.html
The final updated version of the German strategy is consistent with the information taken from the draft version, which were used in this study.

[21] See CNN, https://edition.cnn.com/2023/01/05/energy/germany-norway-hydrogen-pipeline/index.html

[22] The draft update is discussed in Clean Energy Wire in March 2023 by Julian Wettengel, https://www.cleanenergywire.org/news/draft-update-germanys-hydrogen-strategy-sees-higher-2030-demand-media. This target was also included in the coalition treaty of the current government.

[23] https://www.h2-global.de/

4.2 Poland

Poland officially adopted its hydrogen strategy on 1st November 2021, the "Polish Hydrogen Strategy Until 2030 with an Outlook Until 2040".[24] Poland is currently the third largest producer of hydrogen in the EU, with an annual production of around 1.3 million tonnes almost all from fossil fuel sources. The Polish government is set to finalise an update to the country's most important strategic energy document: "The Energy Policy of Poland until 2040". A press release suggests that a target of 73% of electricity demand to be met by renewables and nuclear will be established for 2040, with 50 GW installed renewable capacity by 2030 and 88 GW in 2040.[25] The substantial increase in these targets is an important step towards Poland establishing a renewable hydrogen industry.

The Polish hydrogen strategy outlines six key objectives. The first is the implementation of hydrogen technologies in the power and heating sector. Here, the document discusses the concept of sector coupling and the need to support effective cooperation of the gas and electric power systems. The Polish strategy is broadly in line with the EU strategy which also sees a key role for hydrogen in supporting energy systems integration via its role of absorbing excess renewable electricity. In power and heating the strategy discusses the need for further R&D but does not set hard targets.

A second objective is the use of hydrogen as an alternative fuel for transport. The idea is that hydrogen fuel cells can replace diesel or gasoline powered engines, particularly with a focus on buses. The strategy sets a target of 100-250 hydrogen buses expected to be in operation by 2025 and at least 25 hydrogen filling stations. By 2030, 800-1,000 hydrogen buses are expected to be in operation. The largest Polish fuel and energy company PKN Orlen appears to support for this goal, having announced plans for 57 bus refilling stations by 2030 (Bednarczyk, 2022). The Hydrogen Eagle investment programme supports more than 100 hydrogen stations across Poland, Czechia and Slovakia including 0.5 GW new clean hydrogen production coming from electrolysis and municipal waste.[26]

The third objective is supporting the decarbonisation of industry. Here, the strategy again is in line both with the EU strategy and expert consensus which sees industry as the no-regret option for deploying zero emission hydrogen. This is especially the case for Poland with significant industrial hydrogen demand in the chemicals sector. A focus on sub-sectors that require high-temperature heat is noted and there is public support promised for the implementation of pilot projects in hard-to-abate sectors such as steel, refining and chemicals.

At least five hydrogen valleys are planned in Poland: Pomeranian, Sub-Carpathian, Silesian-Lesser Poland, Lower Silesian and Mazovian (Bednarczyk *et al,* 2022). This shows a clear focus on the need for developing integrated industrial solutions for clean hydrogen, which may incorporate transport refuelling options. The strategy discusses the possibility that beyond 2030, a network of refuelling stations will continue to evolve into hydrogen-based fuels (such as ammonia and methanol). Such fuels are likely to be more easily transported and suitable for production in industrial hubs or valleys. On the other hand, pure hydrogen production perhaps for consumption in buses is likely to be based on decentralised production at point of consumption.

The Polish strategy in its fourth objective cites a technologically neutral approach aiming to support low-carbon hydrogen. Under the most recent understanding of the RED III delegated acts,

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[24] Polish Ministry of Climate and Environment (2021)
[25] On the 4th March 2023, available at: https://www.gov.pl/web/klimat/minister-a-moskwa-odpowiedzia-na-najwazniejsze-wyzwania-transformacji-energetycznej-w-polsce-jest-spojna-strategia-dzialania
[26] See Hydrogen Europe, https://hydrogeneurope.eu/orlen-group-invests-in-hydrogen/

this implies a level of 3.38 kg CO2/kg H2, or 70% below the fossil fuel benchmark. Beyond renewable hydrogen, hydrogen produced in the future from nuclear electricity, from municipal waste, or the inclusion of carbon capture and storage on existing sites would qualify depending on assumptions.

The fifth objective relates to infrastructure and concerns the need for efficient and safe hydrogen distribution and storage. The final objective is for a stable regulatory environment which again rests both on the Polish government's position but also the adoption of regulations at the EU level (such as the definition of renewable or low-carbon hydrogen).

4.3 Portugal

Portugal launched its hydrogen strategy in 2020[27] with a clear focus on green hydrogen, which is unsurprising given the absence of domestic natural gas reserves, lack of integration into the wider European natural gas grid, and reliance on liquefied natural gas imports. Production deployment targets are for 2-2.5 GW electrolyser capacity to be installed by 2030. Thus, focus on renewable hydrogen production is backed by strong action on deploying renewable capacities - the new government has accelerated the target for renewable electricity in the power mix to 80% by 2026.

Portugal’s current hydrogen demand is weighted much more toward oil refining that the chemical industry, than is typical for other European countries. The strategy envisages specific demand targets both for the blending of hydrogen into the country's natural gas grid (10-15%) and in the energy consumption of road transport (2-5%). To that end, a target of 50-100 hydrogen refuelling stations is set. A 2-5% green hydrogen target is set for industry, while an overall demand target is set of hydrogen meeting 1.5-2% of the country's final energy demand by 2030. Based on Portugal's final energy demand currently, that equates to 2.5-3.5 TWh, although trends of electrification and energy efficiency are likely to decrease final energy demand.

Meanwhile, the Portuguese Directorate General of Energy and Geology estimates that the achievement of these targets would result in a €380 to €740 million reduction in natural gas imports, as well as a €180 million reduction in ammonia imports (Cabrita, 2021). The report sees the advantages of hydrogen in: i) complementing electrification, ii) increasing security of supply, iii) reducing external energy dependences, iv) reducing GHG emissions, and v) promoting economic growth.[28]

The Portuguese strategy, and subsequent project announcements, are notable for their focus on the port of Sines, with plans for up to 1 GW electrolyser capacity to be deployed there. The two largest projects announced concentrate on exports. A consortium led by Copenhagen Infrastructure Partners plans to construct a 500 MW electrolyser producing 500,000 tonnes green ammonia and 50,000 tonnes hydrogen,[29] while a consortium led by Neogreen hydrogen plans to build a 500 MW electrolyser for the "production of green hydrogen and derived fuels".[30]

Further inland, the Nazare Green Hydrogen Valley project[31] combines Portugal's three main glass producers and two biggest cement producers in a planned initial 40 MW electrolyser project, potentially expanding to up to 600 MW. The consortium is exploring the potential of hydrogen for high-grade industrial heat, themselves making clear that electrification should be the first considered decarbonisation option for industry - but that where this is not possible, hydrogen may have a role.

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[27] Portuguese National Hydrogen Strategy (2020)
[28] See for example, Brandao and Vasconcelos (2020).
[29] https://madoquapower2x.com/the-project/, https://www.rechargenews.com/energy-transition/iberia-fast-becoming-europes-green-hydrogen-hub-after-fourth-large-scale-project-unveiled-this-year/2-1-1203685
[30] See Reuters, https://www.reuters.com/business/energy/canadian-portuguese-joint-venture-plans-104-bln-hydrogen-plant-sines-2022-11-14/.
[31] See https://www.nghv.pt/en

5 Assessment of National Hydrogen Strategies

5.1 Renewable Electricity Demand and Electrolyser Deployment

Considering national production targets, we calculate the required renewable electricity demand in each country. We consider whether the target for deployed electrolysers in capacity would be sufficient to produce the targeted clean hydrogen demand.

5.1.1 Germany

The German national hydrogen strategy sees between 90 and 110 TWh hydrogen demand domestically by 2030, up from 55 TWh today. Of this, 14 TWh is expected to be green hydrogen. An update to Germany's national hydrogen strategy is anticipated to significantly strengthen these targets. Total demand is envisaged at 95 to 130 TWh, with green hydrogen providing 40 to 75 TWh. A target for domestic electrolyser capacity is set at 5 GW in the existing hydrogen strategy but anticipated to be strengthened to 10 GW.

If Germany were to produce all this green hydrogen domestically it would require 20 TWh renewable output to meet the existing strategy targets and between 57 and 107 TWh to meet the targets reported in the draft update. In 2022, wind output in Germany was 126 TWh and solar output 61.5 TWh, together accounting for 34% of total generation.[32] The government has set a target for 80% of electricity to be renewable by 2030, and 100% by 2035.[33]

In table 1, we compare demand targets for green hydrogen in Germany with targets for deployed electrolyser capacity as taken from the strategy. The output of these electrolysers will depend on their usage or load hours. Load hours relate to the number of hours in a year that an installation operates. For producing 'green' hydrogen, these hours are limited by the output of a renewable installation. An electrolyser coupled to a solar PV plant will operate at 15% load factor, while an electrolyser coupled to a wind farm will operate at 25 – 45% load factor due to the available load hours of the respective renewable plant. Electrolysers connected to the grid will necessarily sign power purchase agreement contracts with renewable generators and operate according to monthly output. They will still be restricted by load hours corresponding to renewable generation. In our calculations we consider two scenarios with 30% load factor and 50% load factor, which we see as a realistic range for electrolysers connected directly or virtual to renewable electricity sources in 2030.

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[32] Calculated via Ember, https://ember-climate.org/data-catalogue/yearly-electricity-data/.

[33] Is it worthwhile, to also indicate that DE has other numbers in its most recent network development plan (NEP) and its long-term-scenarios (LFS).

Table 4 highlights that domestic green hydrogen production will not be sufficient to meet anticipated demand. Between 35% and 65% of German green hydrogen demand will need to be imported. This calculation is confirmed by the German strategy which shows a clear government focus on the need for future imports of hydrogen.

Table 4: Overview of German green hydrogen targets

	Load factor	Renewable Hydrogen Demand (TWh)	Electrolyser capacity (GW)	Renewable hydrogen production (TWh)	Renewable electricity demand (TWh)	Implied renewable hydrogen imports (TWh)
Published Plan	30%	14	5	9	13	5
	50%	14	5	15	22	0
Draft Update	30%	40 to 75	10	18	26	14 to 49
	50%	40 to 75	10	31	44	0 to 31

Source: German National Hydrogen Strategy, and Euractiv reporting on the draft. An electrolyser efficiency of 70% is assumed.

5.1.2 Poland

The Polish national hydrogen strategy does not have an explicit estimation or target for overall demand. It defines a production capacity target of 2 GW to be deployed domestically. This is defined as 'low carbon' and not explicitly electrolysers (e.g., it could be SMR coupled with CCS, or biomass gasification). For this study, we assume that the deployed 2 GW are electrolysers. In which case, for qualification as 'renewable' hydrogen from the Polish grid we assume a load factor of 30%.

The resulting hydrogen output ranges between 3.7 TWh and 6.1 TWh per annum, resulting in a renewable electricity demand between 5.3 TWh and 8.8 TWh, depending on load factor (table 5). In 2022, wind output in Poland was 18.8 TWh and solar output 8.1 TWh, together accounting for 17% of total generation.[34] Poland is currently in the process of revising its national energy plan, and exact targets for renewable deployment are not yet clear.

Table 5: Overview of Poland green hydrogen targets

	Renewable Hydrogen Demand (TWh)	Electrolyser capacity (GW)	Renewable hydrogen production (TWh)	Renewable electricity demand (TWh)
30% Load	n/a	2	3.7	5.3
50% Load	n/a	2	6.1	8.8

Source: Poland Hydrogen Strategy, author's calculations. An electrolyser efficiency of 70% is assumed.

[34] Calculated via Ember.

5.1.3 Portugal

The Portuguese national hydrogen strategy sets an explicit target for between 1.5 and 2% hydrogen in final energy consumption by 2030. Compared to final energy consumption today in Portugal of 182 TWh,[35] this range is between 2.5 and 3.5 TWh (with a downward bias as final energy consumption is expected to be lower in 2030 compared to today). This compares to 3.5 TWh hydrogen consumption in Portugal in 2020 (FCHO).

For matching these demand targets with domestic renewable hydrogen output, demands for renewable electricity generation will be between 3.6 and 5 TWh (assuming an electrolyser efficiency of 70%). In 2022, wind output in Portugal was 13.0 TWh and solar output 2.6 TWh, together accounting for 38% of total generation.[36]

The Portuguese strategy also sets a target for deploying between 2 and 2.5 GW electrolyser capacity. The Portuguese government has set an ambitious target for 80% of electricity generation to be renewable by 2026.[37] High solar irradiation, the potential for offshore wind, and hydro capacities grant Portugal a good opportunity for achieving this target. Consequently by 2030, a large proportion of Portugal's grid may be renewable, this will provide greater opportunity for electrolysers to operate at higher load hours.

Under both scenarios, domestic generation in Portugal exceeds planned domestic demand (table 6). There is significant potential for Portugal to export renewable hydrogen or derivatives.

Table 6: Overview of Portuguese green hydrogen targets

	Renewable Hydrogen Demand (TWh)	Electrolyser capacity (GW)	Renewable hydrogen production (TWh)	Renewable electricity demand (TWh)	Implied renewable hydrogen exports (TWh)
30% Load	3	2.25	4.1	5.9	2.9
50% Load	3	2.25	6.9	9.9	6.9

Source: Portuguese National Hydrogen Strategy, Bruegel calculations. An electrolyser efficiency of 70% is assumed. Renewable hydrogen demand of 3 TWh is the midpoint of the 1.5 to 2% of final energy consumption range. 2.25 GW electrolyser capacity is the midpoint of the 2 – 2.5 GW target in the Portuguese strategy.

[35] Eurostat Database NRG_BAL_S
[36] Calculated via Ember.
[37] See Reuters, https://www.reuters.com/business/sustainable-business/portugal-speed-up-switch-renewable-power-wake-ukraine-war-2022-04-01/

5.2 Alternative production routes: CCS hydrogen

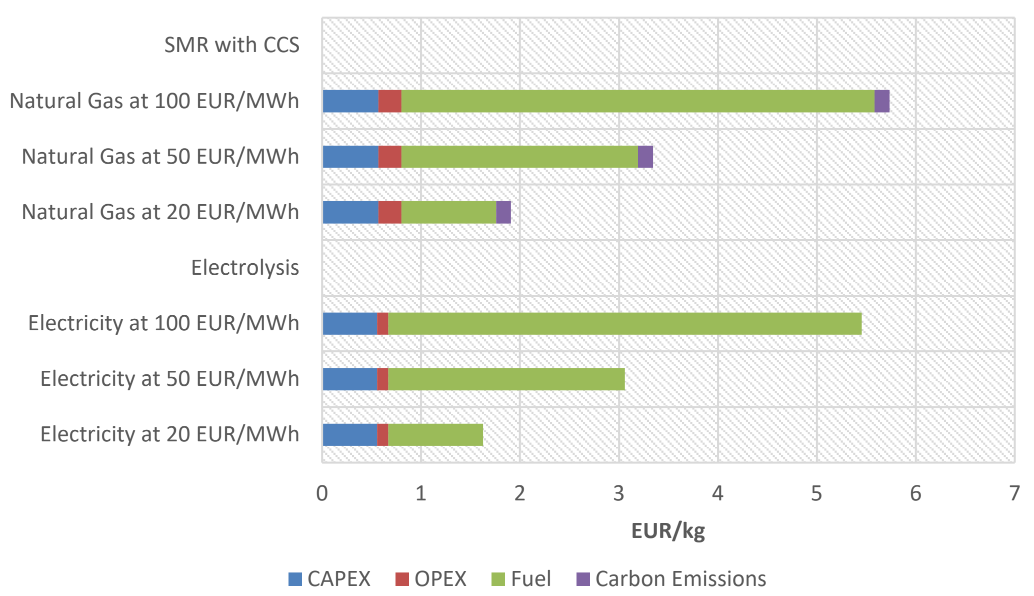
The EU, German and Portuguese strategies do not see an explicit role for the production of CCS hydrogen (SMR coupled with CCS) domestically. The Polish strategy leaves the door open with its technological neutrality approach but also does not offer explicit support to CCS hydrogen.

Significant CCS hydrogen production is not expected to occur inside the EU. Storage of the captured carbon requires geological storage sites, of which not all European countries have great capacities. Additionally, public opinion on the concept of storing serious volumes of carbon dioxide under the ground is not overwhelmingly positive. A more likely approach is that a gas producing country, such as Norway, might retrofit infrastructure to send CCS hydrogen to Germany, while storing captured carbon geologically. The EU has not set goals for CCS hydrogen or brought forward serious policy for incentivising deployment.

Small roles might be available for SMR with carbon capture and utilisation, in which case a European industrial cluster could immediately use captured carbon removing storage requirements. Examples could include the production of methanol or synthetic hydrocarbons which will require carbon input. However, this route is not likely to be a net zero application as depending on the use case for the produced commodity, the carbon dioxide will still end up in the atmosphere. For example, by burning a synthetic hydrocarbon to power a plane. This study also does not have the scope to cover the potential production of hydrogen via methane pyrolysis, where the only by-product is carbon black, which may yet play an important role.

The energy crisis and record high natural gas prices significantly impacted competition between electrically and natural gas derived hydrogen. With such uncertainty, and a policy push for reducing natural gas consumption, businesses will have strongly biased investments toward the electricity route. Natural gas is likely to continue to have a high price in the EU for the next one-two years until a wave of liquefication projects should relax the global LNG balance. Conversely, it is also possible that structural demand reduction for natural gas in the EU will end up producing lower natural gas prices in the second half of this decade.

Figure 3 shows the significant impact of electricity and natural gas prices in the final price of hydrogen, for the electrolyser and SMR with CCS routes, respectively. The energy required for capturing carbon emissions further increases natural gas demand beyond that for SMR. The figure is illustrative of the huge impact that the recent spikes in gas prices will have had for determining project feasibility of gas-derived hydrogen in the EU.



Source: Authors calculations based on assumptions from IEA (2019) and Ueckerdt et al (2022)

Figure 3: Production cost of hydrogen in the EU (EUR/kg)

5.3 Potential for decarbonising existing hydrogen demand

Figure 4 shows current decomposition of hydrogen demand in each country, which is dominated by the oil refining and chemical sectors. Electrolysers are a mature technology that can be immediately deployed. Hence, there is no technical reason why all the current hydrogen consumed in the chemicals sector (which is currently produced by SMR) could not be replaced with renewable hydrogen before 2030. The economic challenge is that this would require rapid capital turnover and for industry to close plants before the natural end of their lifespan.

To make a reasonable assumption about the real potential for replacement in the chemicals sector, we therefore consider the politically agreed targets discussed in section 4 under the RED III legislation. This target for industry was for 42% of hydrogen consumed by industry in 2030 to be renewable hydrogen, which is our assumption for 2030.

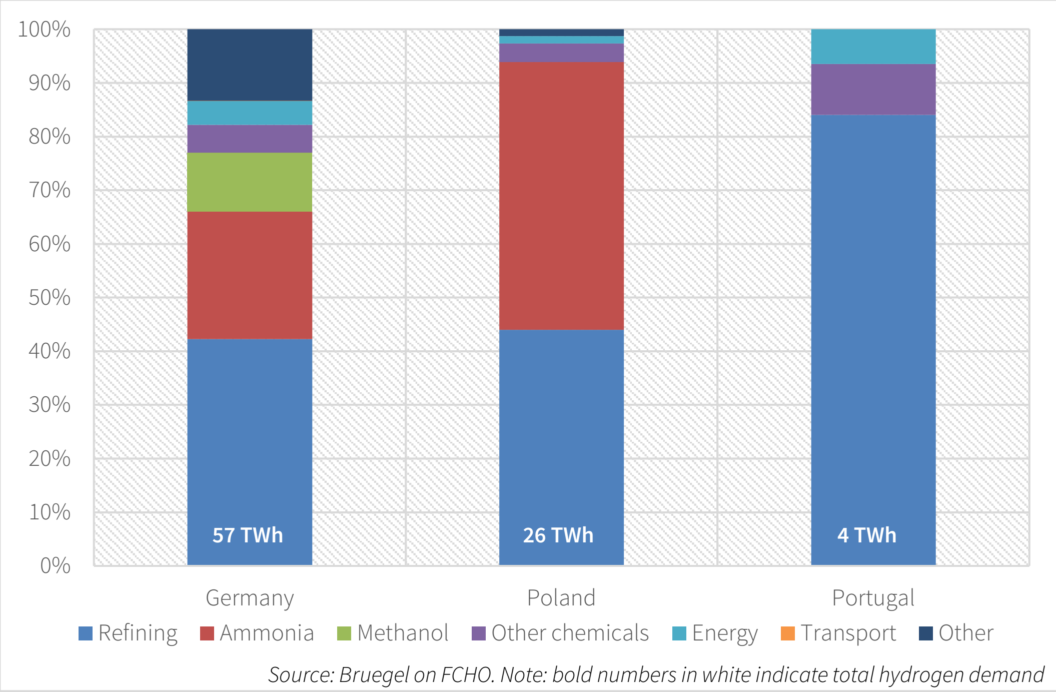


Figure 4: Current hydrogen demand in the EU by sector, 2020 (proportional)

Hydrogen consumption in the oil refining sector is not covered under the RED III industrial target. Moreover, a significant share of hydrogen demand is met with by-product hydrogen. This is hydrogen that is produced as a waste product of other processes on the refinery. This hydrogen will not be replaced by renewable hydrogen. Estimates suggest that additional (non-by-product) hydrogen demand accounts for approximately 45% of an oil refineries hydrogen demand on average. We treat 45% as the realistic share of oil refinery demand that could be replaced by 2030. It is likely that the reduction of oil refining in the EU will also contribute to lower emissions from refining.

Using these assumptions and current demand data from the FCHO, table 7 provides estimates for hydrogen which countries could decarbonise by 2030. The final column shows the share of today's total hydrogen demand that would be decarbonised.

Table 7: Potential for hydrogen decarbonisation in the oil refining and chemicals sector, by country (TWh)

	Oil Refining Demand	Potential for decarbonisation by 2030	Chemicals Demand	Potential for decarbonisation by 2030	Share of total Demand Decarbonised
Germany	24.6	11.1	23.2	9.8	36%
Poland	11.3	5.1	13.8	5.8	42%
Portugal	3.0	1.3	0.3	0.1	42%

Source: FCHO, and author's calculations. Note: demand assumptions include that 42% hydrogen in industry is renewable by 2030 in accordance with the RED III targets, and that 55% of oil refinery hydrogen needs are met by by-product hydrogen which does not have potential to be replaced by renewable hydrogen.

5.4 Potential for reducing Carbon Emissions and Natural Gas Demand

Steam methane reforming is the dominant method for supplying the chemicals industry with hydrogen and for supplying additional hydrogen to the oil refining sector. We calculate the share of carbon emissions and natural gas demand abated when renewable hydrogen displaces the production of SMR hydrogen. SMR hydrogen results in direct emissions of 8.9 tonnes CO_2 per tonne hydrogen produced.[38] These assumptions allow the calculation of carbon dioxide emissions (in tonnes) abated presented in table 8, and natural gas demand reduced in table 5 (in TWh and % of national 2022 natural gas demand).

Table 8: Carbon dioxide emissions abated by switch to renewable hydrogen (tonnes)

	Oil Refining	Chemicals
Germany	2,980,000	2,630,000
Poland	1,380,000	1,560,000
Portugal	363,000	38,000

Source: Author's calculations.

The efficiency of the SMR process at converting natural gas into hydrogen is 69% giving a natural gas demand of 1.45 tonnes natural gas per tonne hydrogen produced. This provides the estimate for the reduction in natural gas demand by 2030 as totals (TWh) and as a percentage of national 2022 demand, shown in table 9.

Table 9: Natural Gas Demand abated by switch to renewable hydrogen, TWh (as a % of 2022 demand)

	Oil Refining	Chemicals
Germany	16.0 (1.9%)	14.1 (1.7%)
Poland	7.4 (4.2%)	8.4 (4.8%)
Portugal	2.0 (3.3%)	0.2 (0.3%)

Source: Author's calculations.

Finally, Portugal is the only country of those considered with an explicit target for blending hydrogen into the natural gas grid (10-15%). This holds limited potential for reducing both natural gas demand and carbon emissions. The authors interpret the Portuguese strategy to refer to a blending target for the distribution grid (e.g., household consumption) and not the transmission grid (e.g., large power stations and industrial consumers). This is because blending high volumes of hydrogen into the transmission grid is associated with higher technical challenges (Bard, 2022). The authors also interpret the numbers to refer to the percentage of hydrogen on a volumetric basis.

Hydrogen carries only about one-third as much energy per unit of volume compared to methane, therefore a 15% blend of hydrogen will reduce the energy content of natural gas by 15%. In 2022, demand on the Portuguese distribution grid was 22 TWh, while total natural gas demand was 59 TWh. Blending 15% hydrogen by volume into the distribution grid would reduce natural gas demand by 1.1 TWh, and carbon emissions by 200,000 tonnes.[39] Hypothetically, if blending were possible into the whole grid, natural gas demand would be reduced by 3 TWh, with associated carbon emissions reductions of 540,000 tonnes.

[38] These calculations do not include indirect emissions associated with methane leakage in transporting natural gas to the site of SMR. Depending on the case, these additional emissions may be highly significant and should be considered on a case-by-case basis when evaluating emissions reduction potential.

[39] Using the assumption that the direct combustion of natural gas results in emissions of 181g CO_2/kWh, from Bard *et al* (2022).

5.5 Critical evaluation of the National Strategies

This section evaluates consistency of the national strategies with each other and the European strategy in a range of areas, as summarised in table 10.

Table 10: Key features and comparisons of discussed hydrogen strategies and enacted policies

	Germany	Poland	Portugal	EU
Production	Renewable (electrolyser) hydrogen	Low-carbon hydrogen (technologically neutral)	Renewable (electrolyser) hydrogen	Renewable (electrolyser) hydrogen
Trade	Strong focus on imports	No clear focus	Exports are implied	Strong focus on extra-EU imports
Trade route	Clear progress on shipping; pipeline is only project announcements		Stronger focus on shipping	Strong focus in strategy on pipeline imports; shipping imports likely to be realised first
Geography	Imports likely to facilitate hydrogen valleys at ports or pipeline routes	Five Hydrogen Valleys	Hydrogen Valleys, especially the Port of Sines	Supports hydrogen valleys
Demand cases				
Industry	Strong focus	Strong focus, but no indicators and underdeveloped policy vision	Strong focus – notable lack of existing significant hydrogen demand in chemicals sector	Largest focus on industry
Power sector	Substantial focus: hydrogen-ready turbines	Strategy sees relevance, but no clear action	No focus	Sees one of the main applications of hydrogen being the integration of renewable electricity
Road transport	No strong focus	Explicit targets for hydrogen buses and refuelling stations.	Explicit targets set for both road transport consumption and refuelling stations	Focus on use of hydrogen as an e-fuel; AFID sets targets for refuelling stations
Households	Significant role not explicitly planned	Strategy intends to explore, but no serious commitments	Explicit target of blending 10-15% hydrogen into the natural gas grid	Not considered relevant under Hydrogen Strategy, but REPowerEU considered 3% blending of hydrogen into the gas grid

Source: author's conclusions.

5.5.1 Trade and Geography

The future trade of hydrogen will be possible either in its pure form (by pipeline) or as a further processed commodity. Pipelines have high upfront capital costs, while low operational costs. An advantage is that they can consistently transport large volumes of gaseous hydrogen, while a challenge is the need to acquire permitting rights along the route. Retrofitting existing natural gas pipelines will have lower costs and less challenging regulatory requirements. For shorter distances of up to 1,500 km, the IEA (2019) estimates that transporting hydrogen by pipeline is likely to be the most competitive option for moving hydrogen from one point to another, with a cost of around $1/kgH$_2$.

For hydrogen to be shipped in its pure form it must first be liquefied at a temperature of -253 C, with a cost of around $1/kgH$_2$ (IEA, 2019). This high liquefication cost, alongside relatively high costs for shipping hydrogen are likely to make this route prohibitively expensive. Hydrogen can be shipped in as a derived commodity, such as ammonia. The costs of shipping ammonia are around 20% of those for shipping hydrogen (IEA, 2019). If the desired product is ammonia, then shipping hydrogen already converted into ammonia is likely to be competitive. If hydrogen is required, then the ammonia must be cracked back into hydrogen with a cost of around $1/kgH$_2$ (IEA, 2019). While for longer trade at 5,000 km, IRENA (2022b) find that building a new pipeline is not competitive with transporting hydrogen in liquified form, or as ammonia. However, retrofitting an existing natural gas pipeline is competitive given lower capital costs.

By 2030, the most likely candidates for shipping hydrogen in derived form are ammonia, methanol, or direct reduced iron (which can be transported by sea). The form in which hydrogen is traded will have important consequences for the extent to which certain industries retain their existing location. Existing ammonia plants could be serviced by green hydrogen imports, or green ammonia could be imported. Existing steel plants might import green hydrogen for the reduction of iron, or domestic steel production may use imported green direct reduced iron.

The European strategy sees a substantial role for pipeline transport of green hydrogen, as does the German strategy. However, project developments have been slow to materialise. The EU is still negotiating the Third Gas Directive which will set out the rules that govern cross-country trade of hydrogen, concerning the extent to which ownership of transport infrastructure must be separated from production and consumption, and third-party access. It is possible that once these rules are adopted the process will accelerate.

Meanwhile, projects for the import of seaborne hydrogen products are moving ahead more quickly. Germany has launched its H2Global platform, which is a double-sided auction that will support the production of hydrogen-derived products, namely ammonia and methanol and subsequent import to Germany. The focus of the platform on ammonia and methanol is representative of this dilemma that Germany struggles to decide which stages of the value chain are worthwhile maintaining, and which could be outsourced. The European Union, under the Hydrogen Bank, will launch its own vehicle for supporting imports and can learn lessons from the German experience in designing such a tool.

The Portuguese focus is clearly on seaborne export of hydrogen from the port of Sines, while Poland does not see a significant role for trade pre-2030. The calculations in section 5a have shown substantial potential for Portugal to export green hydrogen or green hydrogen products, while substantial import requirements will exist for Germany. Co-operation between Portugal and Germany on this value chain would be sensible, as would cooperation between countries in similar positions not considered. Portugal and the Netherlands, for example, are co-operating on exports from the Port of Sines to the Port of Rotterdam.

The European Union strategy sees an important role for hydrogen valleys. These are clusters of industrial hydrogen demand that either produce on-site hydrogen or are connected via transmission pipeline, or shipping routes, to large sources of hydrogen supply. It is normal for industrial energy demand to co-locate around sources of cheap energy, and to benefit from integrated supply routes, examples include chemical and petrochemical plants. Hydrogen valleys are likely to emerge because of the early demand for renewable hydrogen likely being to replace existing hydrogen demand in industrial applications. The national strategies are broadly consistent with this approach. Poland clearly identifies five target valleys, while Portugal has an explicit focus on developing the Port of Sines into a hydrogen hub. The German strategy emphasises the role of Germany as a gas transit country with the potential to serve cross-border industrial valleys.

5.5.2 Demand Use Cases

The national strategies are broadly consistent with the European Union approach that the most obvious no-regret hydrogen applications lie in existing industry uses of hydrogen, namely oil refining and the chemicals sector. Germany is keen on the deployment of green hydrogen for decarbonisation of the steel sector, as too is Poland. Portugal is an outlier here, largely owing to the lack of a significant ammonia production industry. However, if Portugal wants to export green hydrogen by ship this is very likely to be in the form of ammonia and hence clear strategy and policy support is likely necessary to grow a hydrogen-consuming chemicals industry from scratch. An interesting omission from the Portuguese strategy is the concept of producing direct reduced iron from hydrogen for export. Portugal faces the same challenge in having only either a small or no domestic steel industry, but cooperation with companies from third countries, such as Germany or Poland, could take advantage of renewable conditions in Portugal.

Germany appears set to provide public support for the deployment of gas-fired power plants which are to be hydrogen-ready. Germany sees an important role for hydrogen in balancing renewable electricity generation. This is in line with the narrative developed by the European Union strategy (and the fact it was published on the same day as the energy integration strategy).

Meanwhile, Portugal does not explicitly outline a clear focus for hydrogen in balancing renewable electricity. Portugal has a high share of run-of-the-river hydro, which complements the seasonality of solar PV by generating higher output in winter months. However, this production is dependent on rainfall and at risk in a changing climate, as was highlighted by weaker than usual hydro output across the EU in the summer of 2022. Portugal could more clearly evaluate the possible role for hydrogen in seasonally balancing deployment of renewables. Lack of geological storage sites means that this might necessitate pipeline connections with Spain or France to provide seasonal storage possibilities. The Polish strategy is relatively immature in this respect. This likely owes to Poland’s relatively slow position in renewable deployment, one advantage is that the Polish government can monitor and learn from neighbouring European countries experiences.

Poland has the most concrete targets for hydrogen as alternative fuel in road transport, setting targets for the number of hydrogen buses that should be deployed by 2030. While Portugal has a target for the energy share in road transport that should be met by hydrogen. The European Union strategy did outline transport, alongside industry, as a lead deployment market. The German strategy is less focused on deployment in road transport, though it does recognise potential, instead setting a clearer target for the minimum quota of synthetic kerosene to be consumed in the aviation sector, for which €1.1 billion is set aside through to 2023.

The German strategy also sees a limited role for hydrogen in household energy consumption, which is broadly in line with the 2020 European Union hydrogen strategy. Poland sees a role for exploration but no strong messages. At the EU level, the hydrogen strategy was somewhat contradicted by the inclusion of 3% hydrogen blending into natural gas grids in the modelling work for REPowerEU. Given huge industrial demand for clean hydrogen and challenges in deploying renewable electricity capacity to meet this, blending is not a sensible use case for hydrogen. Portugal itself sets an explicit target for the blending of hydrogen into gas grids. The Portuguese case is unique in that Portugal lacks a chemical industry demanding hydrogen as an obvious first use case, the export of green hydrogen might be a more sensible route for early offtake markets.

6 Conclusions and Policy Recommendations

Electrification, energy efficiency, and deployment of renewables remain the imperative for energy and climate action and should be considered a priority above hydrogen. This involves rapid build-out of new renewable generation capacity as well as working with grid operators to smartly integrate this capacity.

Concerning hydrogen, policymakers should retain a **focus on no-regret hydrogen applications**, which are overwhelmingly in the industrial sectors and concern the chemical sector, the refining of crude oil, and the production of primary steel via direct reduced iron. The production of synthetic aviation fuels will not play a substantial role until 2030 but may become an important fuel thereafter and deserves further exploration. Until 2030, consumption of hydrogen for fuelling buses and trains that are not easily electrified has its merits, but the scale involved implies this will not be a large energy consumption. Policymakers should be careful to distribute limited resources toward these priority decarbonisation areas.

The fact that most of the early renewable hydrogen demand will come from industrial sectors will result in **geographic clusters of industrial hydrogen demand developing**. European governments should co-operate with each other and industry to consider best cases for connecting industrial clusters to facilitate the trade of hydrogen. Until 2030, this may involve transmission pipelines across and into the EU connecting regions of attractive production with demand sinks and is likely to also involve a growing maritime trade of hydrogen derived products.

Consequently, Europe faces a **defining question on the future of its heavy industry**, for which hydrogen is at the centre. Existing industrial structure has largely developed from the location of fossil fuel sources, or their easy import (e.g., importing oil to a port). Future energy intensive industries will be based on renewable electricity supply, and its transport. Drastic changes in the relationship between energy costs in different regions of Europe and the world will imply a certain change the economic efficiencies of energy-intensive production occurring in different locations. The agglomeration effects and established labour forces in certain areas will be a ‘sticky factor’ encouraging industry to remain in existing place, as will potential government subsidies to incumbent industry.

A European strategy should reflect deeply on new supply-chain integration and the import and export of hydrogen, or hydrogen derivatives between countries. There will be employment, economic, energy and further societal implications. At the core of this debate lies the future form in which hydrogen is traded, whether that be hydrogen in pure form, hydrogen products for the chemical industry (ammonia or methanol), hydrogen products for the steel industry (direct reduced iron), or hydrogen products for fuelling transportation (synthetic kerosene).

Finally, strategies discuss a role for hydrogen in **smoothing electricity grid supply and demand between seasons**. This function will become more important in the second half of the decade as the share of variable renewable electricity grows, and fossil fuel options are gradually phased out. The exact role that hydrogen may play is still very uncertain. Further research is needed, and countries should collaborate to share best practices.

In conclusion, the three strategies are broadly consistent with both the European Union original hydrogen strategy framing and the wider industry and academic consensus on the role hydrogen can play in decarbonising economies to 2030. However, the modelled hydrogen consumptions in the REPowerEU communication are a significant outlier, above both the ambition contained in national strategies and a sensible trajectory as evaluated by this study.

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Notes:

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