Extending the European Hydrogen Backbone

A EUROPEAN HYDROGEN INFRASTRUCTURE VISION COVERING 21 COUNTRIES

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Executive summary

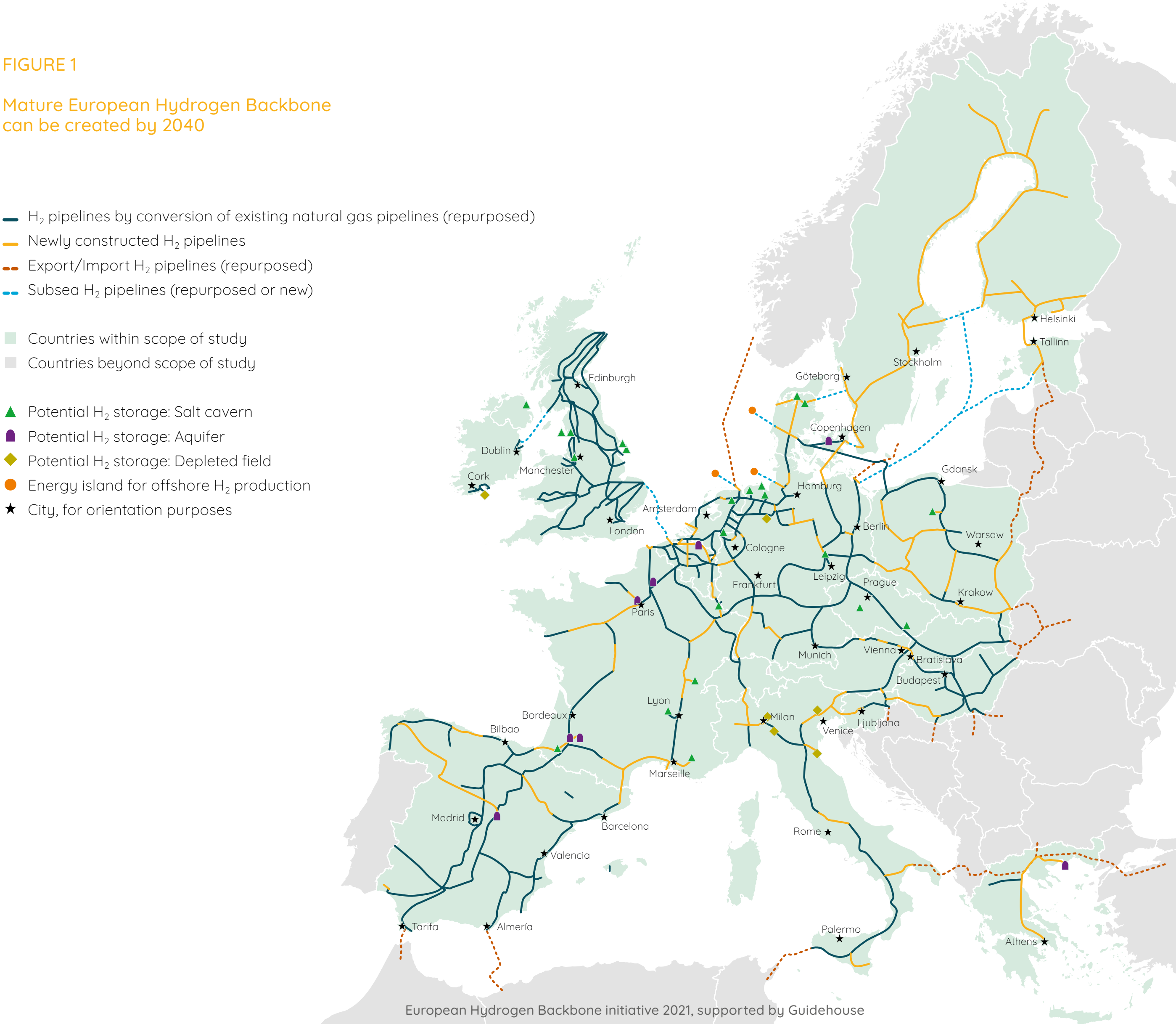
This report presents an updated and extended EHB vision, now involving 23 gas infrastructure companies from 21 countries.

Last year, eleven gas infrastructure companies published a vision of a European Hydrogen Backbone (EHB), a dedicated hydrogen pipeline transport network spanning ten European countries. That report sparked a debate on the role that a hydrogen network can play in the future European energy system. The role of hydrogen in enabling climate neutrality is widely acknowledged, as is the need for hydrogen pipeline transport. This report presents an updated and extended EHB vision, now involving 23 gas infrastructure companies from 21 countries. It presents updated hydrogen infrastructure maps for 2030, 2035 and 2040 with a dedicated hydrogen pipeline transport network largely based on repurposed existing gas infrastructure.

By 2030, the EHB could consist of an initial 11,600 km pipeline network, connecting emerging hydrogen valleys. The hydrogen infrastructure can then grow to become a pan-European network, with a length of 39,700 km by 2040. Further network development can be expected after 2040. In addition, the maps show possible additional routes that could emerge, including potential offshore interconnectors and pipelines in regions outside the area where the EHB members are active. The proposed expanded pan-European hydrogen backbone can further support the integration of renewable and clean energy sources in regions that were not yet included in the initial European Hydrogen Backbone plan as published in 2020. These include Finland, Estonia, large parts of central and eastern Europe, Greece, Ireland, and the United Kingdom.

FIGURE 1

Mature European Hydrogen Backbone can be created by 2040



The European Hydrogen Backbone creates an opportunity to accelerate decarbonisation of the energy and industrial sectors whilst ensuring energy system resilience, increased energy independence and security of supply across Europe. Such a vision can be achieved in a cost-effective manner, but it requires close collaboration between EU Member States and neighbouring countries and a stable, supportive, and adaptive regulatory framework.

In addition to maps showing the possible future topology of hydrogen infrastructure, the report also provides an updated breakdown of repurposed versus new pipelines and estimates of total investment costs up to 2040. The 39,700 km European Hydrogen Backbone for 2040 as proposed in this report requires an estimated total investment of €43-81 billion, based on using 69% of repurposed natural gas pipelines and 31% new pipeline stretches. This cost is relatively limited in the overall context of the European energy transition.

EHB is an attractive and cost-effective option for long-distance transportation of hydrogen

The investment per kilometre of pipeline is lower compared to the network investment costs as estimated in the initial European Hydrogen Backbone plan. While the initial plan only included cost estimates for pipelines with a diameter of 48 inch, this update takes into account that a large part of today's natural gas infrastructure and of tomorrow's hydrogen infrastructure consists of smaller 24- or 36-inch pipelines. Smaller pipelines are cheaper to repurpose leading to lower investment costs overall. However, the operating costs to transport hydrogen over 1,000 km are higher for smaller diameter pipelines compared to bigger diameter pipelines, which raises the levelised transportation costs for the entire EHB to €0.11-0.21 per kg of hydrogen. This is slightly higher than last year's estimate of €0.09 to €0.17, but confirms that the EHB is an attractive and cost-effective option for long-distance transportation of hydrogen, taking into account an estimated future production cost of €1.00-2.00 per kg of hydrogen.

The proposed infrastructure pathway up to 2040 shows the vision of 23 European gas TSOs, based on national analyses of availability of existing natural gas infrastructure, future natural gas market developments, and future hydrogen market developments. Nonetheless, it is important to note that the eventual infrastructure solution will be highly dependent on future supply and demand dynamics of the integrated energy system, including natural gas, hydrogen, electricity, and heat. The real development of hydrogen supply and demand and the increasing integration of the energy system may lead to alternative or additional routes compared to the ones described in this paper, and the timeline of some of the 2030, 2035 and 2040 proposed routes may be shifted forward or backward in time.

The EHB initiative is looking forward to discussing its vision with stakeholders including policy makers, companies and initiatives along the hydrogen value chain.

1. Introduction

The European Hydrogen Backbone (EHB) initiative is a group of European gas Transmission System Operators (TSOs) that has drafted a proposal for a dedicated hydrogen pipeline infrastructure, to a large extent based on repurposed natural gas pipelines. The initiative published a vision paper in July 2020, with maps covering nine EU Member States plus Switzerland, home to the eleven TSOs participating at that time. Since then, the EHB initiative has grown to 23 European gas TSOs with gas networks covering 19 EU Member States plus the United Kingdom and Switzerland. This report contains a geographically extended vision for a dedicated hydrogen infrastructure stretching across these 21 European countries.

This updated European Hydrogen Backbone represents a vision of the growing initiative, with extended hydrogen infrastructure maps for 2030, 2035, and 2040. The report also provides an updated breakdown of repurposed versus new pipelines and estimates of total investment costs. As in the last report, this paper includes the locations of possible hydrogen storage locations. The amount of storage that would be required in the future depends on a number of factors and is not further analysed in this paper. Neither does this paper analyse the cost of hydrogen storage. The suggested pathway for the creation of dedicated hydrogen backbone infrastructure is informed by studies[1] commissioned by the Gas for Climate consortium in 2019 and 2020 which showed a large future role for hydrogen in a decarbonised European energy system and a gradually declining role for natural gas, partially replaced by biomethane.

Natural gas remains important to ensure security of supply during the 2020s and 2030s, yet increasingly, gas infrastructure could be freed-up for the transportation of hydrogen as over time, hydrogen will become a competitive commodity and energy carrier with a key role in the future energy system. Based on these insights, the EHB initiative has created a possible and reasonable scenario on how hydrogen infrastructure in Europe may be created that would be technically viable and achievable. The EHB vision is based on the abovementioned Gas for Climate studies, national hydrogen strategies and planning processes as well as an evaluation of announced projects on hydrogen supply and demand across Europe, partly through a series of hydrogen supply chain stakeholder interviews.

The European Hydrogen Backbone vision starts from the current status quo yet assumes a high ambition level for future climate change policies. This report presents a vision rather than a final proposal based on detailed network planning. The timelines for the scale up of hydrogen can vary from country to country, reflecting national energy policy discussions and the status of hydrogen investment projects. Hence, while for some countries more detailed information on planned hydrogen infrastructure is already available, this information is not yet available in other countries. On certain routes, natural gas and hydrogen may compete for existing pipeline infrastructure. Across Europe, the speed with which dedicated hydrogen transport infrastructure can be created depends on market conditions for natural gas and hydrogen as well as political support to stimulate hydrogen production and demand and regulatory frameworks for hydrogen transport.

Modelling of hydrogen and natural gas flows would provide further insights on whether and by when specific gas pipeline stretches would become available for hydrogen transport and investments in hydrogen infrastructure would be desirable. This is out of scope of the present report.

1 https://gasforclimate2050.eu/publications/

2. Gradual creation of a dedicated hydrogen infrastructure

2.1. Connecting industrial clusters to an emerging infrastructure in 2030

The EHB vision published in 2020[2] showed that by 2030, separated hydrogen networks can develop, consisting mainly of repurposed existing natural gas pipelines. These initial stretches include the proposed Dutch and German national backbones, with additional sections in Belgium and France. Hydrogen networks were also expected to emerge in Denmark, Italy, Spain, Sweden, France, and Germany. The updated European Hydrogen Backbone map in Figure 2 shows that additional repurposed stretches are expected to emerge by 2030 in Hungary and the United Kingdom, with new stretches emerging in Finland. In this updated vision, some of the countries already depicted in the previous report show an accelerated deployment of their hydrogen networks. For 2030, this holds for Sweden, France and Italy. Some stretches of the network are now envisioned to emerge already by 2030, representing updated insights.

In **Hungary**, the emergence of dedicated hydrogen pipelines by 2030 is attributable to rapidly changing natural gas flows, growing hydrogen demand in the region, and proximity to abundant renewable energy sources. The changing natural gas flows are due to the new LNG terminal in Croatia, new pipeline connections in the region and a changing of the gas market. At the same time, hydrogen demand in the region is expected to ramp up. A dedicated hydrogen infrastructure connecting the region's customers to potential green hydrogen supply regions (Ukraine and southern Hungary) will be beneficial for the energy system at large.

In **the UK**, hydrogen could contribute significantly to meeting climate targets. By 2030, four of the country's five major industrial clusters could be connected through the phased repurposing of existing gas pipelines to form an initial hydrogen backbone. Due to the sensitivities around industrial cluster developments, National Grid Gas does not hold any views on the phased sequencing of which industrial clusters in the UK are likely to connect first as it relates to this study, which is the reason for the dotted lines.

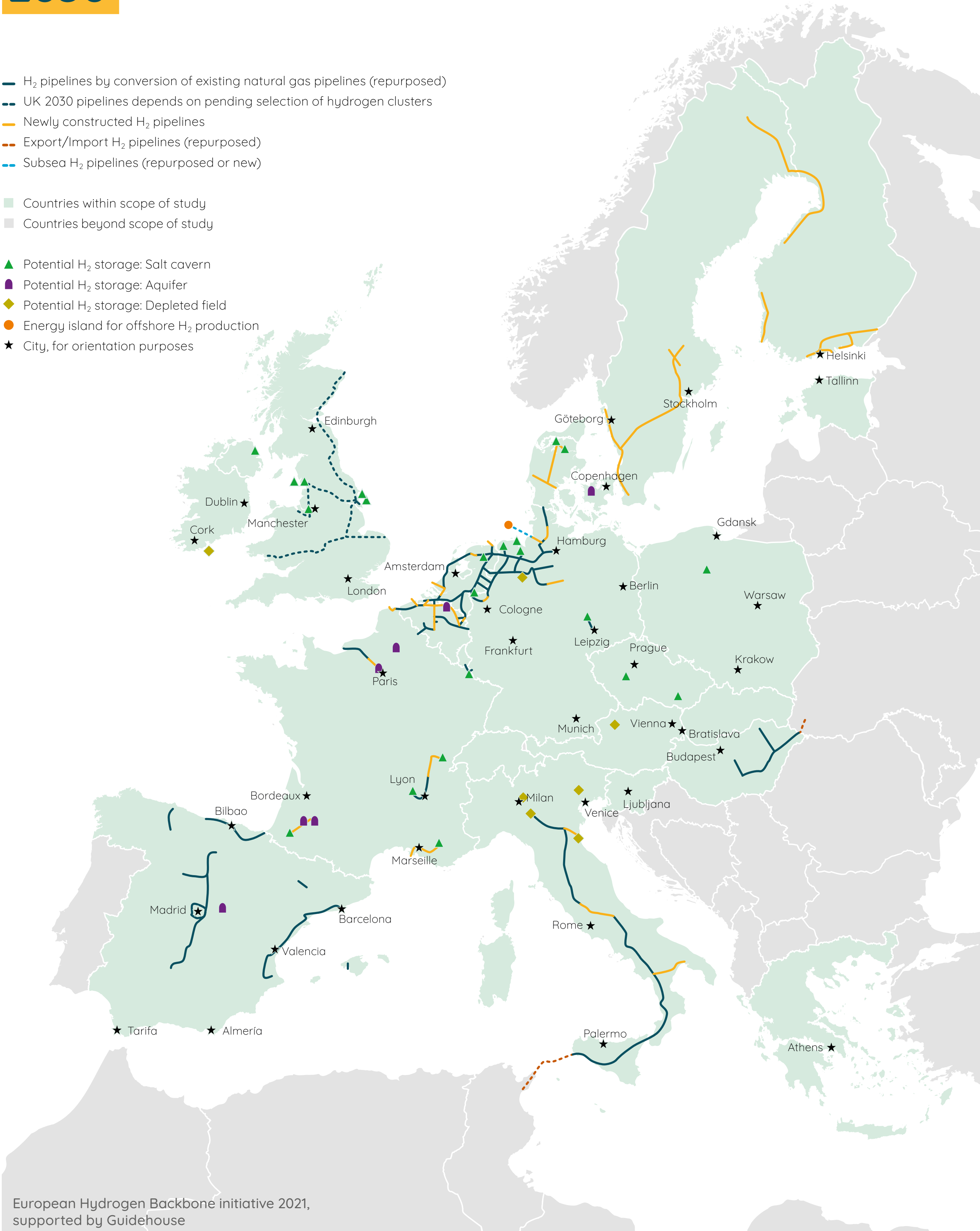
In **Finland**, the hydrogen network could develop near the first hydrogen valleys in the south, southwest and northwest. Here, significant use of hydrogen in industry is envisioned in low-carbon fuel production, chemicals, steel, and mining, while also the hydrogen network develops along the west coast, which has a large share of the onshore wind potential. Additionally, the hydrogen production potential is enhanced by land and water availability while the recovery of waste heat from electrolysers could be a potential solution to decarbonise district heating, which is widely used in Finland.

In **Italy**, the use and production of hydrogen is expected to increase, also given the Italian Hydrogen Strategy guidelines published in 2020. Domestic production will ramp up, and growing demand also creates the possibility of green hydrogen imports from North Africa as early as 2030, of course subject to market conditions. This possible import could be enabled by repurposing given there are five parallel pipelines between Tunisia and Italy.

2 https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/

Figure 2

Emerging European Hydrogen Backbone in 2030



European Hydrogen Backbone initiative 2021, supported by Guidehouse

2.2. Growing network by 2035 covers more countries and enables imports

Between 2030 and 2035, the European Hydrogen Backbone will continue to grow, covering more regions and developing new interconnections across Member States as shown in Figure 3 below. The increase in dedicated hydrogen pipeline transport reflects the urgency to mitigate climate change and the opportunity for cost-effective decarbonisation. A rapidly increasing number of hydrogen projects are expected to receive public support. Industries will require access to a liquid, mature and cross-border European hydrogen market, enabled by a growing hydrogen backbone. Pipeline transport will be valuable to connect regions with abundant solar PV and wind potential with energy demand centres, including areas which are out of reach for power transmission infrastructure. Whereas initially the hydrogen backbone predominantly mainly serves industrial hydrogen demand, studies including the Gas for Climate Gas Decarbonisation Pathways 2020-2050 study show that during the 2030s hydrogen will become a significant energy vector in other sectors, including heavy transport, and electricity production and storage, thereby complementing the electricity grid to integrate large volumes of renewables in the energy system.

In **central and eastern Europe** - in addition to what was presented in the 2020 EHB paper - by 2035 an import route from Ukraine to the EU could emerge, passing through the networks in Slovakia and the Czech Republic into Germany. This transit route consists of large diameter pipelines that can be repurposed. Ukraine has high land availability and good on- and offshore wind and solar PV resources. Combinations of offshore and onshore wind plus solar PV can reach high capacity factors, thus ensuring a high utilisation of electrolysers and pipelines, with limited storage.

Through **Spain and France**, a corridor towards Germany could emerge by 2035. This route could connect hydrogen demand clusters in the north of Europe with sources in the Iberian Peninsula, or even North Africa. This enables these intermittent renewable energy sources across Europe to complement one another, while also providing connection to storage options. This further enables the transport of large quantities of hydrogen to facilitate a liquid, cross-border hydrogen market.

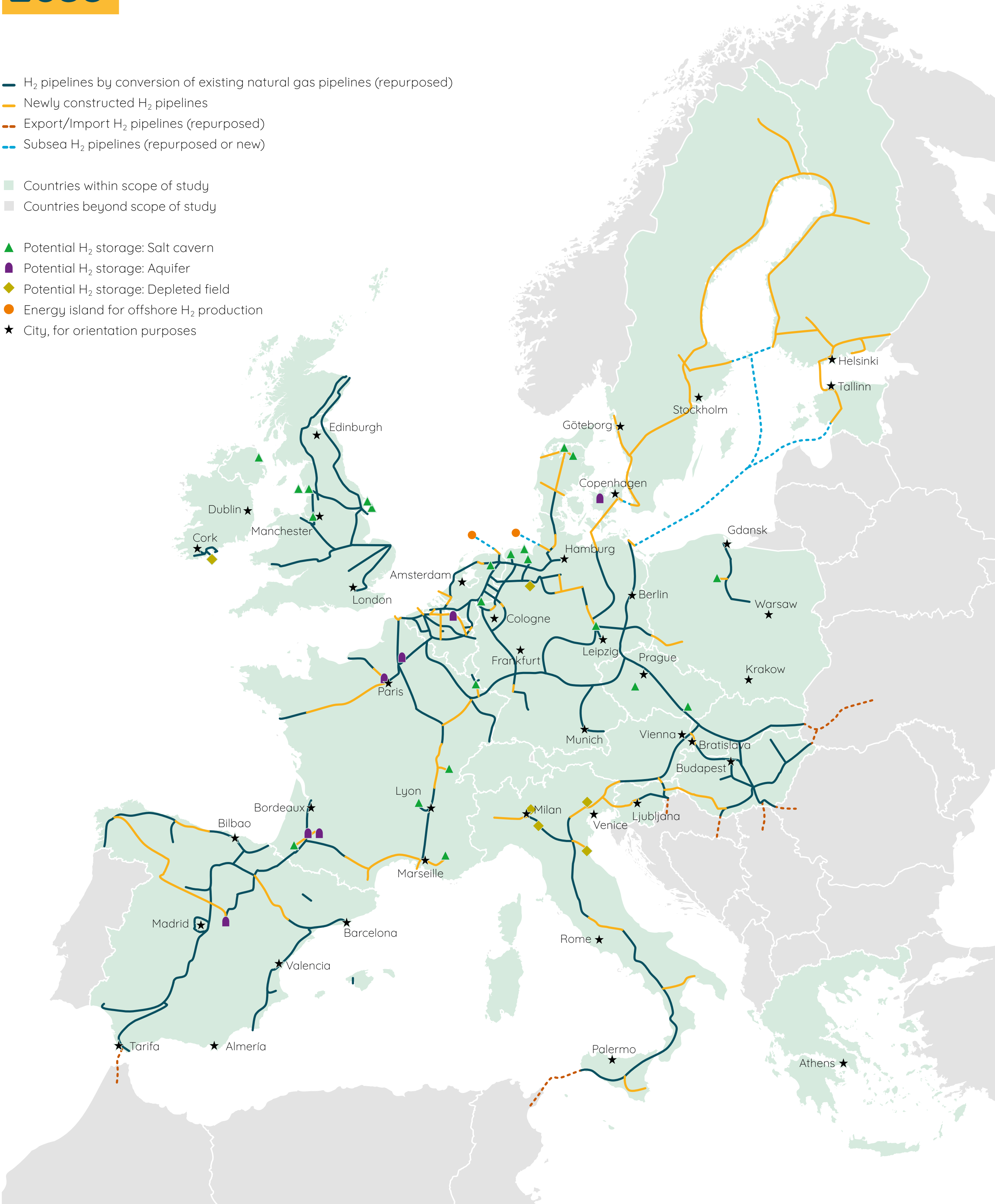
Hydrogen Europe's 2x40 GW Initiative[3] has called for 24 GW of electrolyser capacity in North Africa and 8 GW in Ukraine to be developed by 2030 for exports to Europe. Increased collaboration with those countries, as priority partners, was also specifically identified in the EU's Hydrogen Strategy.[4] The corridors connecting regions with abundant renewable energy resources would hereby not only serve for hydrogen imports, but also enhance the integrated energy system by connecting diverse renewable sources, such as offshore wind in the north and Solar PV in the south.

3 2x40 GW initiative, available at https://www.hydrogen4climateaction.eu/2x40gw-initiative

4 COM (2020) 301, published on 8 July 2020

Figure 3

Growing network covering more countries in 2035



European Hydrogen Backbone initiative 2021, supported by Guidehouse

In many parts of Europe, gas pipelines can be repurposed to hydrogen in an affordable manner. In **Sweden, Finland, and the Baltic states**, however, little gas infrastructure exists today. A significant new hydrogen infrastructure is proposed for these countries, which reflects the ambitious plans to use hydrogen in heavy industry in Sweden and Finland. In addition, development of this hydrogen network can enable more extensive utilisation of clean energy sources and provide important connections between hydrogen production and demand in the EU. The network will also support the increased need to balance the future decarbonised energy system. The possible nuclear phase out in Sweden and ambitious national targets to reach climate neutrality by 2045 in Sweden and already by 2035 in Finland require a massive scale-up of variable renewable electricity. Because energy demand is centred in the southern parts of Finland and Sweden, large amounts of energy would need to be transported from north to south. In combination with electricity transmission, hydrogen pipelines can provide this energy transport cost-effectively. Moreover, next to transporting energy from north to south, hydrogen from the Nordics could eventually also be exported into the rest of Europe, using the hydrogen infrastructure and interconnections. This development would benefit from excellent onshore wind conditions along the coast of the Gulf of Bothnia, and from the Baltic sea offshore wind potential. Land and water availability will enable significant development of onshore wind projects in these countries.

In **the Baltic Sea**, in the 2030s the deployment of offshore wind may already reach a significant share of its 93 GW potential[5], which will create a need for green hydrogen to integrate and store the large amounts of intermittent wind energy. In the three Baltic states this would create an oversupply of renewable energy, especially during windy periods. For instance, in Estonia, renewable energy production during windy periods could reach four times its projected energy demand. By connecting Baltic energy markets with the rest of Europe, hydrogen could be exported to Central and Eastern Europe. The Baltic sea region and offshore wind also play important roles in the German hydrogen strategy.[6]

In **the UK** by 2035, all five industrial clusters could be connected, resulting in a matured national backbone. In **Ireland**, a hydrogen valley could emerge in the south around the coastal city of Cork, where hydrogen could also be imported by ship.

By 2035, the hydrogen network development would allow for the route from **Italy**, and beyond that North Africa, to expand its reach all the way into north-western and south-eastern Europe. For the latter, a new interconnection from Italy to **Slovenia** would be used, while **Hungary**'s network will enable transport further into south-east Europe. Possible imports into Germany are enabled by the repurposed interconnection between Italy and **Austria** and large diameter repurposed pipelines through Austria, Slovakia and the **Czech Republic**. Slovakia and the Czech Republic could become an important hydrogen hub as hydrogen from the north, south and east could flow through the country. The repurposing could solely happen if natural gas flows were to drop significantly, freeing up one of the parallel lines across Italy, Austria, Slovakia and Czech Republic, while still allowing natural gas transport over this route to the extent needed.

The situation in **Germany** shows a much more dynamic picture in 2035 compared to the 2020 EHB paper. As natural gas and hydrogen may very well be competing for the same pipeline infrastructure, it is unclear as of today whether some of the pipelines shown will actually be converted to hydrogen. An example is the newly suggested route connecting the Ruhrgebiet/Cologne area to the southern parts of Germany. Whether all suggested pipelines will be converted to hydrogen or remain natural gas pipelines largely depends on political support for the scale up of hydrogen and the general market developments of hydrogen and natural gas respectively.

5 DGENER (2019) Study on Baltic offshore wind energy cooperation under BEMIP

6 German hydrogen strategy (2020), available at https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6

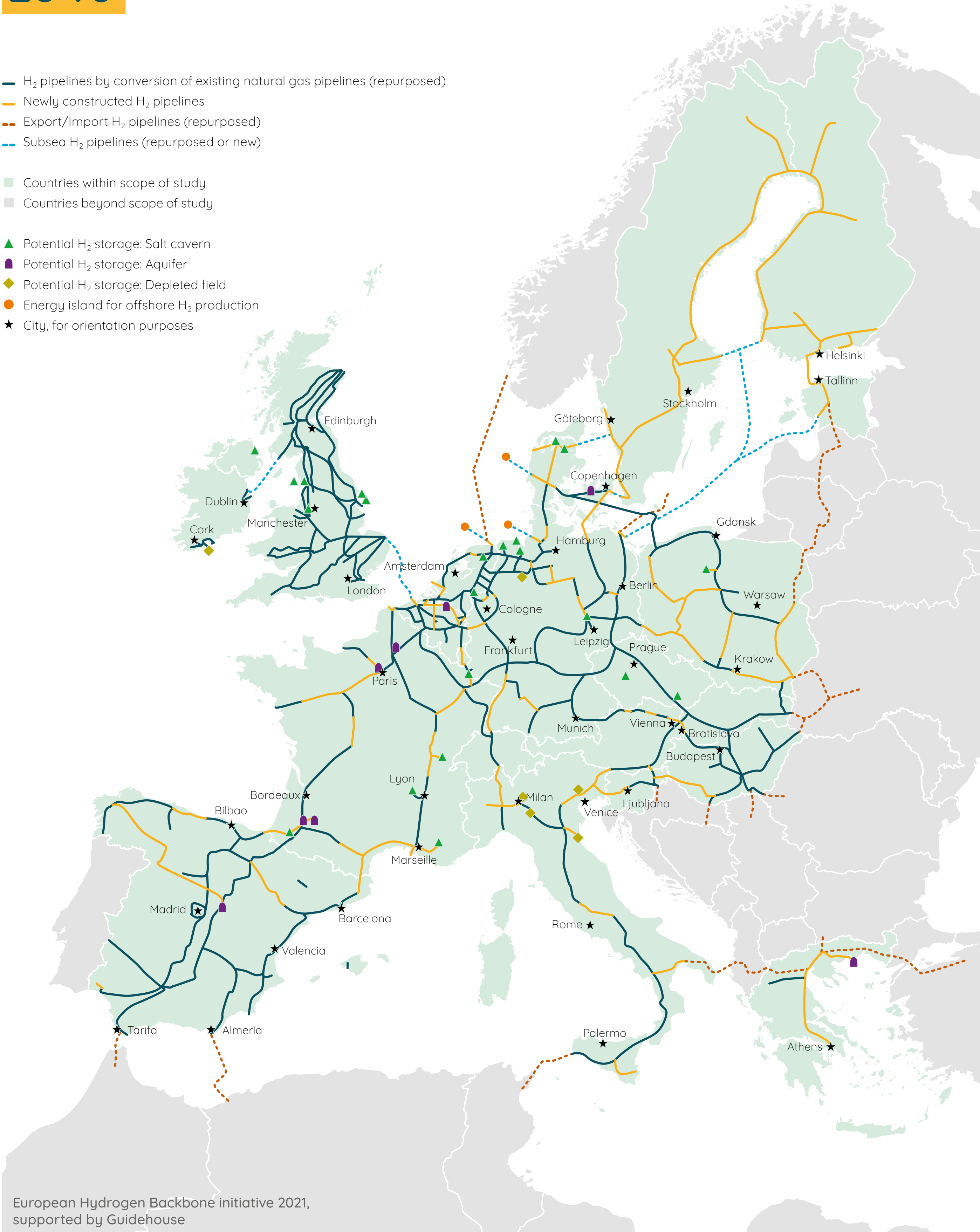
2.3. Mature infrastructure stretching towards all directions by 2040

By 2040, a pan-European dedicated hydrogen transport infrastructure can be envisaged with a total length of around 39,700 kilometres, consisting of 69% repurposed existing infrastructure and 31% of new hydrogen pipelines.

As shown in Figure 4, the network could stretch from Ireland to Hungary and from Spain to the Nordic countries, connecting different regions with different renewable energy production profiles, providing a cost-effective way to transport large amounts of renewable energy to demand centres, and connections to regions with storage capacity. The network would also allow pipeline imports from Europe's eastern and southern neighbours, as well as imports of liquid hydrogen from other continents via Europe's main harbours. This would provide security of supply and enable the creation of a liquid, European market for hydrogen.

Figure 4

Mature European Hydrogen Backbone can be created by 2040



European Hydrogen Backbone initiative 2021, supported by Guidehouse

By 2040, two additional interconnections between **Spain and France** can increase the security of supply and flexibility in the large expected flows of hydrogen from Spain and possibly North Africa into the rest of Europe.

In the **North Sea**, approximately 180 GW of offshore wind power capacity can be installed by 2050. Model studies[7] have shown that its integration in the northwest European energy system would require a smart combination of electricity and hydrogen infrastructure, making use of 80-90 GW of electrolysers in coastal regions. Electricity and gas TSOs in Denmark, Germany, and the Netherlands are already actively collaborating on planning a hub-and-spoke offshore network of energy hubs in an internationally coordinated roll-out[8]. Several MoUs and LoIs between governments in the region, and together with potential connections to the United Kingdom and Norway, extensive offshore hydrogen pipelines and energy hubs acting as an international hydrogen network in the North Sea can be envisioned already in the late 2030s, connecting the countries bordering the North Sea.

Analysis by Energinet confirmed the need for hydrogen to integrate large amounts of offshore wind energy by showing that effective utilization of more than 10 GW of additional offshore wind requires up to 5-8 GW of electrolysis by 2035[9]. Gasunie Germany confirmed a vision on offshore hydrogen production near Helgoland in the North Sea as per 2030. Both plans are shown on the maps. Other plans could not yet be shown on the maps due to uncertainties about locations and timing.

New hydrogen pipeline stretches in **Central, Eastern and Southern Europe** by 2040 would enable pan-European energy system integration and decarbonisation. It would enable a larger role of renewables in a largely coal-based power mix and enable hydrogen supply to decarbonise heavy industry located in central and eastern Europe.

In **Poland**, by 2040 a mature hydrogen network could emerge which would enable the integration of large amounts of (offshore) wind energy up north. This energy could then be transported in the form of hydrogen to possible industrial demand regions in the south, while storage of the intermittently produced energy would be enabled by a salt cavern near the supply in the north. Additionally, the Baltic gas pipeline from **Denmark to Poland** could be repurposed to dedicated hydrogen transport by 2040, respecting long-term natural gas contracts on this pipeline which run until the end of 2037.

In **Austria**, an alternative route to transport hydrogen from east to west or vice versa would be available. The additional possibilities would contribute to the decarbonisation of industry in Austria and to reach the ambitious 2040 carbon neutrality target set by the Austrian government.

In the northwest of Europe, the 2040 pan-European network would also connect **Ireland** with **the UK** to the rest of the European Hydrogen Backbone, by repurposing one of the interconnectors from the UK to Ireland and by repurposing of the IUK interconnector from Belgium to UK. In Ireland, a hydrogen valley could emerge around Dublin, just south of where the repurposed interconnector from the UK would land. In the UK, all options for converting the existing gas network to hydrogen have been shown, however not all of these pipelines will have completed conversion to hydrogen within this period.

7 Guidehouse (2020), for North Sea Wind Power Hub: https://northseawindpowerhub.eu/wp-content/uploads/2020/04/NSWPH-Integration-routes-offshore-wind-2050.pdf

8 NSWPH, 2020, available at https://northseawindpowerhub.eu/category/studies/

9 Energinet, 2020. Available at https://en.energinet.dk/Analysis-and-Research/Analyses/System-perspectives-for-the-70pct-target-and-large-scale-offshore-wind

3. Updated cost of an expanded European Hydrogen Backbone

Total investment costs of the envisaged 2040 European Hydrogen Backbone are expected to range from €43 to €81 billion, covering the full capital cost of building new hydrogen pipelines and repurposing pipelines for the European backbone. The ranges reflect differences in capital cost assumptions, with the greatest uncertainty stemming from compressor costs. Annual operating costs are estimated to be between €1.7 and €3.8 billion[10] when assuming a load factor of 5,000 hours per year.[11] An overview of these costs is given in Table 1. Transporting hydrogen over 1,000 km along an average stretch of the hydrogen backbone, as presented in this report, would cost €0.11-0.21 per kg of hydrogen transported, with €0.16 per kg for the central case.[12] Although marginally higher than last year's estimate this confirms that the EHB is an attractive and cost-effective option for long-distance transportation of hydrogen, taking into account an estimated future production cost of €1.00-2.00 per kg of hydrogen.

The updated investment costs shown in Table 1 and updated transport costs per kg of hydrogen differ from the previous estimate of €27 to €64 billion reported in the 2020 study, with transport costs of €0.09 to €0.17 to transport a kilogramme of hydrogen over 1,000 km. The difference in investment costs and levelised costs compared to the previous EHB report are due to a combination of three factors:

1. **The backbone has expanded in length and scope.** The updated network covers a total distance of 39,700 km across 21 European countries with highly diverse gas infrastructures, compared to 23,000 km across 10 countries in the previous EHB report.
2. **The relative share of repurposed and new pipelines has changed** following the geographic expansion of the network. The enlarged network includes 69% repurposed pipelines, while 75% of the previous shorter network consisted of repurposed pipelines. This change is due to country-specific differences in network topology, expected pipeline availability as well as the creation of new hydrogen networks for renewable energy integration in the Nordics, where today limited gas infrastructure exists. These country-specific factors and developments are substantiated in Annex B of the report.
3. **A more granular assessment of pipeline diameters has been conducted.** Pipeline diameters of gas grids across Europe differ in size. The previous study used a simplified assumption that the entire backbone would consist of large 48-inch pipelines. The updated investment costs as presented in the current report differentiate between 48-, 36- and 20-inch pipelines (1200, 900, and 500 mm respectively). We now estimate that about half of the total network will consist of medium sized pipelines plus smaller stretches of pipelines with a small diameter. Repurposing or building new smaller sized pipelines imply reduced unit capital costs and lower throughput capacities compared to 48-inch pipelines. The breakdown of the European Hydrogen Backbone network by pipeline length, diameter, and type — repurposed or new — is presented in Figure 5.

Additional information regarding the investment and operating cost estimation methodology, including network design considerations such as throughput capacity, compression requirements, and operating pressure are detailed in Appendix A.

10 Not all of these operating costs are additional to current costs of running natural gas infrastructure. For reference, annual operating costs of natural gas infrastructure are around 5% of investment costs.

11 Load factor. This study considers the backbone from an infrastructure investment perspective and does not take a strong stance on the exact level of network utilization. A load factor of 5000 hours per year is deemed reasonable, cognizant of the fact this value will change depending on future market developments – and impact resulting costs accordingly.

12 This corresponds to €3.3-6.3 per MWh of hydrogen (LHV) per 1,000 km with €4.9 per MWh in the central case.

TABLE 1

Estimated investment and operating cost of the European Hydrogen Backbone (2040)

		Low	Medium	High
Pipeline cost	€ billion	33	41	51
Compression cost	€ billion	10	15	30
Total investment cost	**€ billion**	**43**	**56**	**81**
OPEX (excluding electricity)	€ billion/year	0.8	1.1	1.8
Electricity costs	€ billion/year	0.9	1.1	2.0
Total OPEX	**€ billion/year**	**1.7**	**2.2**	**3.8**

FIGURE 5

Breakdown of the European Hydrogen Backbone network by pipeline length, diameter, and share of repurposed vs new pipelines

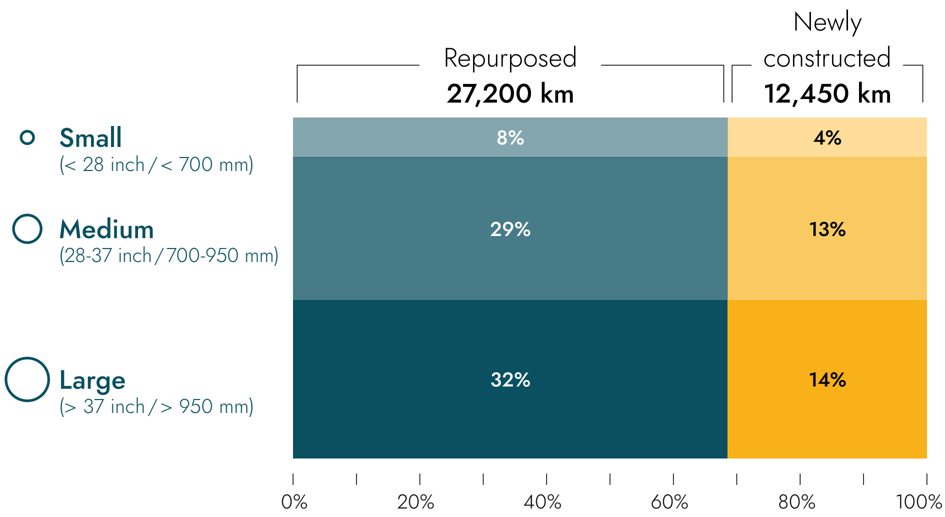


Figure 5 shows that, based on an analysis of the existing gas network, almost 90% of the European Hydrogen Backbone can be expected to consist of medium (28-37 inch, 700-950 mm diameter) and large (> 37 inch, > 950 mm diameter) pipelines. For simplicity, it is assumed that the share of pipeline diameters for newly built hydrogen stretches remains comparable to the current shares in the natural gas network.

Representative unit capital cost figures for small, medium, and large hydrogen pipelines are summarised in Table 2. These figures use 20-inch (~510 mm), 36-inch (~900 mm), and 48-inch (~1200 mm) as models to represent small, medium, and large pipelines respectively. This is a simplification of reality, given that the actual backbone is made up of a continuous range of pipeline sizes. Additional underlying cost assumptions such as compressor costs, depreciation periods, and operating and maintenance costs are also shown and are consistent with those used in the previous EHB report of July 2020. These cost estimates are based on gas TSOs' preliminary R&D efforts with regards to hydrogen infrastructure. The ranges are determined through comparison with experience investing in and operating existing natural gas networks and based on initial experience in pilot projects. Although some dedicated hydrogen components have been tested in pilot projects, no large-scale hydrogen infrastructure exists to date to provide real historical benchmark figures. Equal to the previous results in 2020, these cost estimates are based on running an average single stretch of hydrogen pipeline. They do not incorporate a scenario-based simulation of a full-scale network as is commonly done for network development planning.

TABLE 2

Cost input ranges used for estimating total investment, operating, and maintenance costs for hydrogen infrastructure. Adapted from the original European Hydrogen Backbone Report (2020)

Cost parameter				Unit	Low	Medium	High
Pipeline Capex, new	Small	< 700 mm	< 28 inch	M€/km	1.4	1.5	1.8
	Medium	700-950 mm	28-37 inch		2.0	2.2	2.7
	Large	> 950 mm	> 37 inch		2.5	2.8	3.4
Pipeline Capex, repurposed	Small	< 700 mm	< 28 inch		0.2	0.3	0.5
	Medium	700-950 mm	28-37 inch		0.2	0.4	0.5
	Large	> 950 mm	> 37 inch		0.3	0.5	0.6
Compressor station Capex				M€/MW$_e$	2.2	3.4	6.7
Electricity price				€/MWh	40	50	90
Depreciation period pipelines				Years		30-55	
Depreciation period compressors						15-33	
Weighted average cost of capital				%		5-7%	
Operating & maintenance costs (excluding electricity)				€/year as a % of Capex		0.8-1.7%	

The inclusion of sub-48-inch stretches — mainly medium-sized pipelines of around 36 inch in diameter — significantly reduces the overall investment cost compared to a case where all pipelines are assumed to be 48 inch in diameter. At the same time, the levelised cost of transport is somewhat higher for smaller pipelines, which raises the overall levelised cost. As a result, transporting hydrogen over 1,000 km along an average stretch of the hydrogen backbone, as presented in this report, would cost €0.11-0.21 per kg of hydrogen transported with €0.16 per kg in the central case.[13]

This price figure represents a blended average across a wide range of pipeline sizes and types – ranging from repurposed 20-inch pipelines to new 48-inch ones – and also reflects their respective distance and capacity-weighted shares within the context of the overall European Hydrogen Backbone.[14] This means that even though smaller pipelines have a higher cost of transport per unit distance, their modest share in terms of length and capacity leads to a modest impact on overall transport costs when considering the pan-European picture.

The cost ranges reflect uncertainties in the estimate of the cost of the European Hydrogen Backbone as a whole. Depending on circumstances, the costs for individual stretches can be lower or higher than the range indicated.

13 This corresponds to €3.3-6.3 per MWh of hydrogen (LHV) per 1,000 km with €4.9 per MWh in the central case.

14 The blended levelized cost of €0.11-0.21 per kg per 1,000 km is calculated by multiplying the estimated levelized costs for each pipeline diameter by their respective capacity- and distance-weighted shares, i.e. the relative amount of hydrogen transported by that pipeline size across the entire backbone. A detailed breakdown of levelized costs for each pipeline size and their respective capacity- and distance-weighted shares are shown in Appendix A Table 4.

Appendix A. Updated costs

The updated cost estimates are the result of a series of hydraulic simulations conducted by gas TSOs. The modelled scenarios cover a range of point-to-point pipeline transport cases with varying input parameters — selected by TSOs — including pipeline diameter, operating pressure, and design capacity. Note that these analyses, while thoroughly conducted, are not exhaustive and merely serve as high-level approximations of what would happen in a real network. Regarding inlet (starting) pressure, operating (maximum) pressure, and compression requirements to achieve these, there are no standardised rules or benchmarks for these as of today. Views on these key parameters differ amongst TSOs and depend on project-specific planning considerations, and in reality pressures may differ from the figures reported in this study. Hence, given the simplifying assumptions made in the analyses, these results should not be considered as representative of a fully optimised, actual meshed pipeline grid. Key results are summarised in the tables below.

TABLE 3

Overview of unit capital costs for different pipeline transport scenarios

Pipeline diameter	Repurposed / new	Design / capacity	Inlet pressure	Operating pressure	Pipeline Capex	Compression Capex
mm / inch		GW H_2 (LHV)[15]	bar	bar	M€/km	M€/km
1200 / 48	Repurposed	13	40	80	0.5	0.62
	New	13			2.8	0.62
900 / 36	Repurposed	3.6	30	50	0.4	0.14
	New	4.7			2.2	0.32
500 / 20	Repurposed	1.2			0.3	0.09
	New	1.2			1.5	0.09

'Small' pipelines, as defined in this study, make up about 10% of the backbone in terms of length and typically only cover modest distances, up to 200 km, at a time. For this reason, levelised costs are expressed per 1,000 km for medium and large pipelines but per 200 km for small pipelines. In addition, newly built 'small' pipelines would likely only be constructed in niche situations, e.g. where they are needed to connect two existing repurposed natural gas pipelines of the same size.

15 We choose to report LHV as it is customarily used in energy system analyses, including in studies published by the EC. Note that some experts recommend using HHV for electrolysis as it is a closed system and LHV for fuel cells.

TABLE 4

Overview of levelised cost of pipeline transport assuming 5,000 full load hours for different scenarios

Pipeline diameter	Repurposed / new	Design / capacity	Inlet pressure	Operating pressure	Levelised cost of transport		Capacity- & distance-weighted share
mm		**GW H_2 (LHV)**	**barg**	**barg**	**€/kg/ 1000 km**	**€/kg/ 200 km**	**% of backbone**
1200	Repurposed	13	40	80	0.08	–	33%
	New	13			0.16	–	25%
900	Repurposed	3.6	30	50	0.11	–	19%
	New	4.7			0.30	–	13%
500	Repurposed	1.2			–	0.05	6%
	New	1.2			–	0.14	3%

TABLE 5

Breakdown of estimated lengths by pipeline size and shares of repurposed and new pipelines of the Europe Hydrogen Backbone (2040)

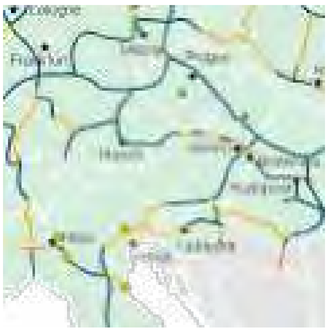
	Length, km			Sub-total	% share
Size	**Small** (< 700 mm)	**Medium** (700-950 mm)	**Large** (> 950 mm)		
Repurposed	3,200	11,500	12,500	27,200	69%
New	1,450	5,300	5,700	12,450	31%
Sub-total	**4,650**	**16,800**	**18,200**	**39,650**	**100%**

Appendix B.
Country-specific developments

The evolution of a hydrogen network in the maps presented above illustrates a vision. Further detailed modelling and a flow study is needed to define the shape, size and ordering of hydrogen infrastructure, alongside policy support, development of hydrogen markets and hydrogen supply scaling up. The evolution of a hydrogen network in these maps illustrates one of many repurposing scenarios. This shows a scenario for the development of a dedicated hydrogen infrastructure. The EHB initiative considers blending and deblending hydrogen in/from natural gas for transportation purposes as a suitable step especially during the 2020s and early 2030s towards a dedicated hydrogen pipeline transport network.

TABLE 6

Country narratives

Country	Background	Hydrogen infrastructure development
Austria (GCA and TAG) 	Austria's current transmission gas network is operated by two TSOs, TAG and GCA and stretches over ~1,700 km. TAG mainly transits natural gas from the eastern border with Slovakia towards Italy. GCA's network serves a dual function and simultaneously transits gas mainly from Slovakia towards Germany, Hungary and Slovenia and provides gas for domestic customers in Austria. In the future both TSOs expect to transport hydrogen. Austria has an ambitious target to produce 100% of its electricity from renewable sources by 2030 and a carbon neutrality target by 2040, although enabled partly by its hydro sources, solar PV and wind will need to scale up substantially. Future hydrogen use will increase in Austria with its industry presence in fuels, chemical and steel. However, the main driver for the emerging hydrogen infrastructure, especially for TAG's network, would be to transit green hydrogen from North Africa via Italy or Ukraine into North Western Europe via NET4GAS's (the Czech Republic) and GCA's network. GCA's network would next to the transit role also serve residential and industrial customers.	In 2030, a first step towards a dedicated hydrogen network could be reached via blending and deblending into/from the existing infrastructure connecting Slovakia, Hungary, Slovenia, Italy and Germany. By 2035, one of TAGs parallel pipelines could be repurposed to transit hydrogen in both directions (from north to south and vice-versa). Furthermore, 3 interconnectors from Italy, Slovenia and Hungary could already emerge enabling H_2 transportation from North Africa and Ukraine to Slovenia, Hungary and Germany via Slovakia and Czech Republic. By 2040, an additional interconnector to Germany could be added by entirely looping GCA's WAG pipeline offering an alternative transport route of Ukrainian H_2 to Germany (Slovakia to Germany). Upon completion, Austria's grid would be ready to serve as a hydrogen hub in the region. Bidirectional hydrogen transportation possibilities at all interconnection points would be in place. In addition, GCA's network would also transport H_2 to Austrian (industrial) customers, such as one of Europe's largest steel plants in Linz, which is already running trials for hydrogen-based steelmaking and a large refinery located near Vienna.

Country	Background	Hydrogen infrastructure development
Belgium (Fluxys) 	Fluxys Belgium is the owner and operator of gas transmission, storage and LNG regasification facilities in Belgium. The network consists of 4,000 km of pipelines and 18 interconnection points with neighbouring countries and import facilities. Fluxys has adapted the steps towards the long-term vision of the hydrogen backbone in Belgium to reflect the discussions with Belgian industrial players to identify production and consumption potential and with policymakers. However, the timing of the investments for new pipelines and repurposed pipelines depend on the evolution of natural gas demand and the uptake of hydrogen demand.	The Belgian national backbone is expected to emerge through developments in and around the industrial clusters in Antwerp, Ghent, and along the industrial valley in Wallonia. Given the proximity between Antwerp and Rotterdam, port-to-port interconnections with the Netherlands are likely. In addition, inter-connections with France and Germany provide Belgium access to hydrogen from/to neighbouring countries. Hydrogen demand in Belgium in 2040 is expected to exceed production capacity. Imports and exports with all neighbouring countries including the UK – if technical and economic conditions are right – and imports through the Zeebrugge terminal could shape the North-Western European hydrogen market by 2040 and beyond.
Czech Republic (NET4GAS) 	Czechia's gas TSO, NET4GAS, operates around 4,000 km of pipelines consisting of three major branches of double or even triple pipelines which serve for international transit - connecting Germany, Slovakia and Poland - while also covering domestic demand. NET4GAS sees the gas infrastructure as an enabler of decarbonisation in the energy sector and expects to transport hydrogen (and other renewable or decarbonised gases) in the future. Due to its geographical position, NET4GAS will remain an important transit TSO as it can transport hydrogen from an Eastern direction (e.g. from Ukraine via Slovakia), from a Southern direction (e.g. from North Africa via Italy and Austria) as well as from the North-West (e.g. Germany). The Czech Republic is currently developing its own hydrogen strategy. Potential utilisation of hydrogen is expected in carbon intensive and hard-to-abate industrial processes such as ammonia, cement, steel production or fuels and transportation. But also, in the power production and (district) heating sectors there is an increased interest in hydrogen as an energy carrier.	There are several long-term gas transmission contracts in place. The major contracts expire at the beginning of 2035 and in 2039, respectively. The possibility for hydrogen transportation from the Eastern border with Slovakia to the Western border with Germany is shown in the updated maps in 2035. This option would - under certain circumstances still to be analysed - allow for hydrogen imports from Ukraine and North Africa already in 2035 by connecting major non-EU supply sources and regions with the hydrogen demand centres in the EU. In addition, the Gazelle pipeline could provide a large-scale connection for hydrogen transportation between the Northern and Southern regions of Germany. For 2040, as there might be additional hydrogen demand in the industrial regions close to the Polish border, a new connection to the hydrogen backbone might have to be analysed.

Country	Background	Hydrogen infrastructure development
Denmark (Energinet) 	Denmark's electricity and gas TSO, Energinet, owns and operates a gas transmission pipeline grid of around 925 km, with cross border connections to Germany and Sweden. An expansion with the Baltic Pipe connecting Norway, Denmark with Poland will be in operation from 2022, expanding the pipeline grid to approx. 1,250 km. Energinet owns and operate two gas storages, one cavern and one aquafer storage. In the view of EU's climate ambition, Energinet sees a need for coordinated and holistic planning of energy infrastructure across electricity and gas, including new energy carriers such as hydrogen. Energinet welcomes and is active in the work undertaken by European TSOs with regards to identifying possible hydrogen cross-border networks, which can bridge the regional disparities between renewable hydrogen generation and demand for hydrogen across Europe. Denmark has set out a 70% greenhouse gas emissions reduction target by 2030. Power-to-X is an integral part of the government's plan to install two energy islands of 3 respectively 2 GW in 2030. Analyses show that effective utilization of more than 10 GW of additional offshore wind require up to 5-8 GW of electrolysis by 2035. Several electrolysis projects are underway in Denmark, which indicates an installed capacity of around 3 GW in 2030. This includes a 1.3 GW plant outside Copenhagen and two projects in Northern and Southern Jutland linking the west coast (wind production) to industrial clusters and hydrogen storage facilities in the east and north of Jutland. Additionally, an announced bilateral cooperation agreement with the Netherlands includes a €135 mln Dutch investment in large-scale Power-to-X plants in Denmark, ensuring that both countries fulfil their 2020 renewable energy targets	By 2030, Initial development of the Danish backbone consists of constructing new pipelines parallel to the existing natural gas network, connecting hydrogen producers and industrial clusters with large scale storage facilities. Beyond 2035, Denmark seeks to draw upon its significant offshore wind resource in combination with electrolysis to attract new industries, such as e-fuels. The energy islands will be the drivers for the expansion of the hydrogen infrastructure. As such, the national backbone expands throughout the 2030s into several directions. The eastern route is extended all the way to the Copenhagen region by retrofitting the existing pipeline and connecting to Sweden. A northern connection also emerges from west which includes access to the cavern storage and towards demand areas in Sweden. In addition, the southern part of the gas in Jutland (interconnection with Germany) can be retrofitted and a new transmission pipeline could be constructed from Copenhagen area southwards toward Germany. Also, the Baltic Pipe could be repurposed as a supply connection to Poland. The 2040 map shows many possible developments for hydrogen transport, which ones to be realized depend on the societal economic value and demand situation in the future. The development will co-exist with the biomethane grid. Also, by 2040 the Danish energy island in the North Sea should be scalable to 10 GW, for which offshore production of hydrogen can be envisioned and a radial hydrogen pipeline connection from the energy island to the national onshore hydrogen network.

Country

Estonia (Elering)

Background

Estonia's electricity and gas TSO, Elering, operates a pipeline grid of 977 km, including the recently built subsea interconnector with Gasgrid Finland.

With offshore wind potential of 7GW and 24TWh[16], Estonian offshore wind energy potential alone will far exceed its domestic electricity demand (link). Without the introduction of green hydrogen, the offshore wind production and installed capacity may not even reach its full potential due to large amounts of energy which could be curtailed during high wind periods. Connecting the national backbone to the European Hydrogen Backbone supports system integration of large volumes of offshore wind, enabling a relatively small country to supply multiple potential demand regions across Europe. Estonia could also act as a transit corridor for hydrogen that would be produced in Finland. The benefits of realising the Baltic sea offshore- and Nordic onshore wind potential would not only be regional. Connecting the Baltic region with Central Europe with an offshore pipeline would enable Europe to increase its energy self-sufficiency and energy security. Green hydrogen would allow for integration and storage of the offshore wind and transport this green energy to hard-to-decarbonise regions in Central (Eastern) Europe.

Locally, hydrogen could enable Estonia to complete the phase out of fossil oil shale-based power plants by 2035. Hydrogen pipeline network could enable the use of hydrogen in dispatchable power plants, thus guaranteeing the security of supply for electricity.

Hydrogen infrastructure development

In the beginning of the 2030s, the first offshore windfarms are expected to be present west of Estonia, in the Baltic Sea[17]. Due to the large volumes of energy produced in offshore wind farms, compared to the relatively small electricity demand in the Baltics, hydrogen production could be economically feasible early on. This renewable energy oversupply could open a possibility to export green hydrogen to Central Europe with an offshore pipeline already in 2035. As such an offshore pipeline would be a great undertaking for a small country like Estonia, the realization of an offshore pipeline like this would largely depend on the demand side interest for green hydrogen produced within the EU and political will. Additionally, hydrogen could be needed to integrate the large amounts of offshore wind energy penetrating the Estonian Energy system, hereby it could also provide seasonal storage and complement the electricity grid, which is also operated by Elering.

By 2040 further offshore wind power expansion is expected together with hydrogen production in western Estonia. Also, an interconnection with Latvia emerges to connect Finland and Estonia with Eastern Europe through the other Baltic states.

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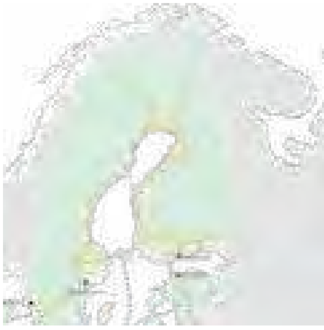
16 EU, 2020, Study on Baltic offshore wind energy cooperation under BEMIP
17 Euractiv, 2021, The untapped green energy potential of the Baltic States

Country

Finland (Gasgrid)



Background

Finland's gas transmission system operator (TSO) Gasgrid Finland owns and operates a network in the south of Finland of 1,300km and a subsea interconnector into Estonia with Estonian gas and electricity TSO Elering. Finland has an ambitious carbon neutrality target already for 2035. A hydrogen network could support the development of a carbon neutral energy system in Finland by providing intermediate energy storage and efficient transport of renewable energy from supply sources to the demand locations. In a later stage the hydrogen network could also be connected to multiple markets across Europe and make Finland a hydrogen exporter. Finland has significant onshore wind potential and possibility to utilise heat from electrolysis process for production of district heating – factors supporting competitiveness of hydrogen production. The potential for wind power is significant and 70 GWs of inquiries for wind power have been made already[18] to Fingrid (electricity TSO in Finland), who is envisioning 25 GW of wind power already by 2035[19] in one of its scenarios. Thus, Power-to-X production could have a significant potential in Finland that should be further investigated.

In addition, Finland is relatively close to the Central European countries with expected significant increase in hydrogen demand. In parallel, demand for clean hydrogen in Finland could grow and scale rapidly in industry, considering the 2035 carbon neutrality target and strong presence of steel, chemicals, and fuel production. In addition, the need for energy system integration is a key driver of a hydrogen network in Finland. Furthermore, land and water availability further add to the large potential of hydrogen production in Finland.

Hydrogen infrastructure development

By 2030, the Finnish hydrogen network could develop around first hydrogen valleys in the south and south west of Finland (Kymenlaakso & Uusimaa and Southwest Finland & Satakunta) and north-west (Bothnia Bay area) with an interconnector to Sweden in the last one mentioned. The development of hydrogen valleys could emerge due to envisioned significant use of hydrogen in industry (low-carbon fuel production, chemicals, steel, mining) and possibility to utilise clean energy resources for hydrogen production. Hydrogen networks could connect producers and consumers, enable utilisation of wind power potential located at the west coast, provide possibilities for intermediate energy storage and create a hydrogen market. An interconnection to Sweden could create a Finnish-Swedish market at the Bothnia Bay area.

By 2035, Finland would achieve its carbon neutrality targets and could become a hydrogen exporter. National hydrogen valleys are connected, and a national hydrogen network could be developed. A connection along the west coast of Finland enables more extensive utilization of wind for hydrogen production and aids the energy transfer from north to south. Also, another interconnector to Sweden could be developed with direct subsea route crossing the Gulf of Bothnia and Åland Island. Åland Island has the target of becoming a society scale demo of an energy system running 100 % on renewables. A possible subsea interconnector to Estonia connects Finland to the Baltics and to potential demand markets in central, northern and eastern Europe.

By 2040 up north, the hydrogen grid extends further north, and potentially also additional north-south pipelines are developed. Expansion of the Finnish hydrogen network facilitates accelerated deployment of wind power to fully utilize the potential enabled by great land availability in the northern and eastern parts of Finland. Further expansion of the network could also aid transmission of energy from north to south of Finland.

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18 Available at https://www.tekniikkatalous.fi/uutiset/fingrid-saanut-70000-megawatin-verran-tuulivoiman-hanketiedusteluja-vastaisi-44aa-olkiluoto-3-ydinvoimalaa/0f88bec8-5831-4532-9ce7-653d066f0d2f)

19 Fingrid, 2020, Network Vision, available at https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/kantaverkon-kehittaminen/fingrid_network_vision.pdf Fingrid, 2020, Network Vision, available at https://www.fingrid.fi/globalassets/dokumentit/fi/kantaverkko/kantaverkon-kehittaminen/fingrid_network_vision.pdf [1] EVwind, 2021, available at https://www.evwind.es/2021/02/05/iberdrola-strengthens-its-commitment-to-offshore-wind-energy-and-acquires-3-gw-in-ireland/79178#:~:text=Ireland%20has%20ambitious%20climate%20change,of%20potential%20for%20offshore%20development.

Country

France (GRTgaz and Teréga)

Background

France's current gas network is operated by GRTgaz which operates 23,000 kilometres of pipelines and Teréga, which operates a 5,000 km network in the south-west. The networks serve industry, power and residential customers while GRTgaz also transits gas to Switzerland, Italy and Teréga transports gas to and from Spain. Both TSOs are convinced that hydrogen and biomethane, next to electrification, will play an important role in the future French energy system. GRTgaz have ongoing hydrogen projects such as mosaHYc, Jupiter 1000, Hyfen, while Teréga is involved in trials around hydrogen storage as HyGéo project and studying a hydrogen dispatchable power plant (Lacq Hydrogen project).". The "France Hydrogène" association study estimates French hydrogen demand to increase to approximately 110 TWh/y by 2040.

Hydrogen infrastructure development

The majority of France's future hydrogen backbone would exist of repurposed pipelines, hereby providing a cost-effective way to transport hydrogen. By 2030, regional dedicated hydrogen networks will emerge around industrial clusters, with existing fossil hydrogen production or consumption, in Dunkerque, in the Seine Valley from Le Havre to the vicinity of Paris, and around Lyon, Lacq and Marseille. These first regional hydrogen networks will foster the achievement of the French Government ambition, issued in September 2020, which aims to reach 6.5 GW of electrolysis capacity installed in 2030, to decarbonise industrial and mobility uses. The hydrogen cluster around Dunkerque will be supplied with decarbonised hydrogen from offshore wind, as well as low-carbon hydrogen. This cluster will also co-benefit from the hydrogen valleys in Belgium and the Netherlands. In the east of France, a regional cluster will also develop at the border between France, Germany, and Luxemburg with the commissioning of the mosaHYc project. The southern clusters in Marseille-Fos and Lacq are also expected to have access to green hydrogen from solar PV and Mediterranean offshore wind. Lastly, dynamic development of green hydrogen for fuel cell projects and industrial uses is expected to continue and to lead to a need for a dedicated hydrogen pipeline in the region surrounding Lyon. By 2035, additional hubs emerge near Saint Nazaire/Nantes, Bordeaux and along the Mediterranean coast, powered by offshore wind or low-carbon electricity and combined with the evolution of Seaports activities. Those hubs will connect to Region of Paris, and to Lyon along the Rhone Valley, thus enabling the decarbonisation of existing grey hydrogen consumptions and the development of new hydrogen uses in mobility (road, inland navigation, rail, airports). The North-West of France will also be connected to the East of France and to the Region of Paris via the retrofitting of existing gas pipelines. This will enable interregional transit and an easier integration of renewable electricity in the energy system, and it will bring flexibility to the system. The French network will also allow a transnational transit from Spain to Belgium, Germany or Luxembourg. By 2040, a mature network has emerged of mostly repurposed pipelines which has 3 interconnectors with Spain, while also connecting to Belgium, Germany, and Switzerland. The three interconnectors to Spain enable security of supply and flexibility in the large expected flows of hydrogen from Spain and possibly North Africa into the rest of Europe. On the west side another stretch also provides a different route within France to transport hydrogen, while also serving local customers and industry on the way. In the south, Teréga's storage locations could provide another way to store the intermittent production of green hydrogen, hereby enabling a stable and secure hydrogen supply further up north.

Country

Germany (ONTRAS and OGE)

Background

OGE, headquartered in Essen, operates the largest German gas transmission system spanning 12,000 kilometres. Two thirds of natural gas consumed in Germany flow through OGE's pipeline system, comprising about 100 compressor units and about 1100 exit points. The OGE 2030+ strategy aims to secure the OGE transmission business in the long run and prepares the pipeline network and numerous compressor stations for new gaseous energy carriers. OGE actively support the European gas market and work together with the European distribution network operators to create the prerequisites for transnational.

ONTRAS Gastransport GmbH is a national gas transmission system operator in the European gas transport system based in Leipzig. ONTRAS operates Germany's second-largest gas transmission system, with approximately 7,500 km of pipelines and about 450 interconnection points. ONTRAS links the interests of transport customers, dealers, regional network operators and producers of regenerative gases.

With the National Hydrogen Strategy (NWS) of the German government aims to create a coherent framework for action for the future production, transport, and utilization of hydrogen and thus for corresponding innovations and investments. The German government will intensify the cooperation with countries around the North and Baltic Seas, primarily to accelerate hydrogen production from offshore wind. It also regards hydrogen as a foundation for strenghtening energy partnerships beyond Europe.

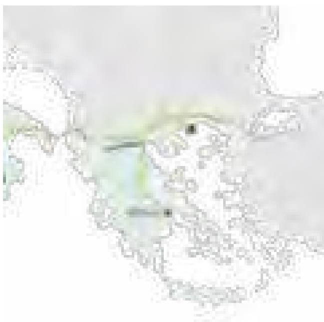
German transmission system operators plan to determine the need for entry and exit capacity as part of the network development plan process in order to be able to provide the necessary transport capacities. Studies estimate the 2040 hydrogen demand for Germany at over 300 TWh (GfC's Decarbonization Pathways Study; DENA - Pilot study on integrated energy system transformation). Regarding sources of hydrogen an increase in domestic production as well as additional imports of hydrogen from the Netherlands, Norway Denmark and Russia, as well as from Southern Europe are expected. The European Hydrogen Backbone creates additional import opportunities from across the continent, e.g. green hydrogen from Spain or North Africa.

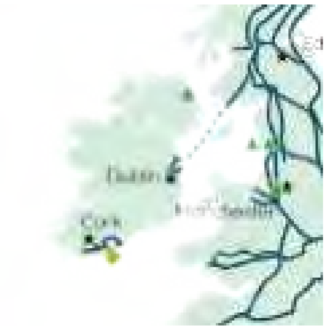
Hydrogen infrastructure development

As part of the network development plan process (2020-2030), the German transmission system operators queried specific projects for the generation or use of hydrogen by means of a market partner query. For 2030, the market participants asked for 1 GW of green hydrogen feed-in capacity. The exit capacity requested for the same point in time was significantly higher with 3 GW. This should be based on an annual hydrogen requirement of around 20 TWh for industrial purposes only. To close the gap in the entry-exit balance for H_2 in 2030, the network operators envisage hydrogen imports from the Netherlands, the connection of cavern storage facilities and additional feeds from wind farms that are equipped with electrolysers. The plans for the German H_2 start grid 2030 foresee pipeline connections to the Dutch H_2 grid.

Since the market partner query is the first broad-based query for future hydrogen transport needs, it can be assumed that further requirements will become apparent in the coming years. This also corresponds to the view of the German government expressed in the national hydrogen strategy, which forecasts hydrogen requirement of 90-110 TWh for 2030. In the updated map for 2035, an accelerated repurposed connection from the Czech border is possible in order to import hydrogen from the south and east via the Czech Republic to Germany.

In the Western part, a pipeline has been added which is mainly repurposed with the aim to connect the industrial cluster of the Ruhr and Cologne/Bonn area with areas in South-Western Germany. As of current data that pipeline connection might still be needed for natural gas, depending on development of demand and policy decisions. By 2040, multiple new interconnections emerge to Belgium, Switzerland and Austria, further enhancing the security of supply.

Country	Background	Hydrogen infrastructure development
Great Britain (National Grid) 	National Grid owns and operates the National Transmission System in Great Britain, a network consisting of approximately 7,660km of pipelines. The UK government has targeted at least 5 GW hydrogen production capacity and 40 GW offshore wind by 2030, with four low carbon industrial clusters established. A dedicated hydrogen transmission system is expected to emerge in Great Britain (the island consisting of England, Scotland and Wales) initially through the phased repurposing of existing natural gas transmission pipelines to join GB's largest industrial clusters (Grangemouth, Teesside, Humberside, Merseyside and South Wales). This will provide resilience to the clusters and could support the conversion of some industries outside of these clusters. The initial development of the emerging hydrogen backbone in GB aims to utilise and repurpose pipelines to transport hydrogen, whilst still maintaining the security of supply on the existing natural gas transmission system. Further conversion of remaining pipelines will likely develop at a later stage and may require small sections of new pipelines to enable the transition.	By 2030, up to four of the five industrial clusters could be connected and will form the basis of a GB hydrogen transmission backbone. Due to the sensitivities around industrial cluster developments, National Grid Gas does not hold any views on the phased sequencing of which industrial clusters are likely to connect first as it relates to this study. Additionally, there may be connections to St Fergus in north Scotland and Bacton on the east coast, providing additional hydrogen supplies which could help integrate the large amounts of renewable energy from offshore wind. By 2035, it is possible that all clusters could be connected. A converted pipeline to Bacton, located on the east coast, could enable future hydrogen flows across the interconnectors between GB and Belgium and GB and the Netherlands once ready. Further repurposed pipelines may start to emerge between 2035 and 2040, including a connection to Moffat, enabling hydrogen to flow across the interconnector between GB and Ireland alongside natural gas flows. As hydrogen production scales, further expansion of this hydrogen network will occur throughout the 2040s enabling a greater reach across industrial, power, transport and domestic heating sectors. The maps represent the selection of pipelines that could have started the hydrogen repurposing process but may not have completed full conversion by the date on the map. Sequencing and formally defined routes have not been determined, therefore some of these pipelines could be converted in the following 5 to 10-year period.
Greece (DESFA) 	Greece's TSO is DESFA, which operates a relatively new network of 1,456km. Greece's excellent conditions for both wind and solar power would allow the complete phase out of coal-based power plants by 2028 or even earlier. There are plans to increase installed capacity of Wind Power to 7 GW and Solar PV to almost 8 GW, as stated in its NECP. This may lead to the need to use hydrogen in dispatchable power. The two main industrial clusters, in Thessaloniki and Athens, are potential large demand sources for hydrogen. In addition, according to the recently developed Master Plan for the decarbonisation of the lignite production area of West Macedonia, there is the large potential of hydrogen production in the region This potential stems from the expected deployment of large scale PV plants, along with the potential for the use of hydrogen locally or its transportation through the new hydrogen-ready pipeline DESFA is deploying in the region.	By 2040, Greece's two main industrial clusters in Athens and Thessaloniki would be connected, with new pipelines following the existing natural gas route, repurposing existing pipelines can also be an option depending on market conditions. Storage could be available in the form of an aquifer near the Island of Thasos. The connection to Europe could either go through the seas using the TAP pipeline or via South East Europe. The potential hydrogen cluster in West Macedonia will also be connected to Thessaloniki, near the existing connection to TAP, through the new, hydrogen-ready pipeline in the region, which is currently under development.

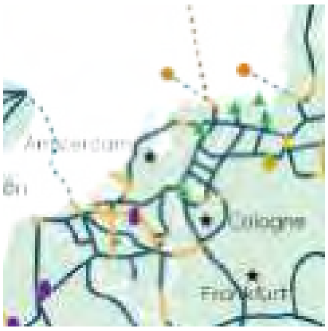
Country	Background	Hydrogen infrastructure development
Hungary (FGSZ) 	FGSZ, Hungary's gas grid operator, operates a mature network of 5,874 km. The network is partially for domestic use, while playing a recently changed transit role from Ukraine to South Eastern Europe. The flows reversed partially and decreased slightly with opening of the LNG terminal on the Croatian island Krk in 2021 and with the gradual opening of the new Balkan routes. Therefore, part of the network might become available at an early stage to be repurposed for green hydrogen transport from Ukraine into the coal-based regions in South Eastern Europe and to the West via Slovenia. Hungary has set a carbon neutrality target for 2050 and targets 6 GW of Solar PV to be installed by 2030. The solar PV potential sits mainly in the south and could lead to variable oversupply of renewable energy, especially if the second nuclear plant in Hungary materializes and operates in parallel with the current nuclear power plant. The current nuclear power plant will be phased out a couple of years after the start of the new plant.	By 2030, changing gas flows make part of the network available to be repurposed for hydrogen transport. This could mean the repurposing of the interconnector with Ukraine which would connect the Hungarian market to the large potential hydrogen supply from Ukraine. The rest of the network connects several industrial customers in the steel, chemical, and fertilizer sector. By 2035, Hungary could already have a mature - mostly repurposed - hydrogen network with in total 6 interconnections to the Ukraine, Austria, Slovenia, Serbia, Romania, and Croatia. This would connect Slovenia and the mostly coal based nations in South-East Europe to Ukrainian hydrogen, effectively making Hungary a green hydrogen transit country enabling the decarbonisation of heavy industry in South-East Europe and the transition away from coal. Interconnections to Slovenia and Austria would, already by 2035, connect the energy systems of South-eastern Europe and North-western Europe. By 2035, a 7th interconnection to Slovakia would add to the market liquidity and security of supply of hydrogen.
Ireland (GNI) 	Gas Networks Ireland (GNI), operates a network in Ireland of 2,477 km of transmission pipelines and 12,044 km of distribution and 2 subsea interconnectors from Moffat in Great Britain to just north of Dublin on Ireland's east coast. Ireland has 30GW of offshore wind projects already in the pipeline and plans 5GW[20] of offshore wind to be operational by 2030. Large amounts of intermittent offshore wind production, particularly off the Atlantic west coast could result in electricity grid congestion and curtailment for a country of Irelands' scale. Green hydrogen production and integration with the gas network could provide a way to maximise Irelands wind energy potential, as a store of energy, as an alternative to imported hydrogen and potentially in peak production periods enabling hydrogen export. While scale hydrogen from offshore wind in Ireland is still developing, Ireland could import hydrogen, initially for the power sector providing zero carbon support to intermittent renewables and later for transport, industry and heating. This could be achieved mainly through repurposed existing gas pipeline network, and possibly some new bespoke hydrogen pipelines.	By 2035, a hydrogen "valley" network could emerge around the city of Cork, on Irelands' south coast. Supply resilience for this mainly green hydrogen cluster would be assured with supplementary imported hydrogen which could be either tanker or interconnector sourced (via a hydrogen pipeline direct to the continent). By 2040, one of the 2 Moffat interconnectors from the UK could be converted for 100% hydrogen transport and some relatively small-scale reconfiguration of the Dublin gas transmission network could enable local, scale, hydrogen – fired power generation. The other Moffat interconnector could sustain resilient supply to the remaining unconverted network, it no longer having to serve the Cork cluster and Dublin power generation loads. Development of these dedicated hydrogen networks provide for accommodation of and ready market access for scale green hydrogen and could create the potential for future (through the 2040's) extended gas network conversion to hydrogen, hydrogen consumption for residential heating and industry and ultimately green hydrogen export to Great Britain or beyond.

20 EVwind, 2021, available at https://www.evwind.es/2021/02/05/iberdrola-strengthens-its-commitment-to-offshore-wind-energy-and-acquires-3-gw-in-ireland/79178#:~:text=Ireland%20has%20ambitious%20climate%20change,of%20potential%20for%20offshore%20development.

Country	Background	Hydrogen infrastructure development
Italy (Snam) 	Snam owns and operates the National Transmission System in Italy, with over 32.500 km of transportation network in use and 17 bcm of storage capacity. The Italian guidelines for the national hydrogen strategy foresee that by 2030 hydrogen could make up 2% of Italy's final energy demand. This demand will be mainly concentrated in industrial clusters located in the North and in some areas of the South. The Italian national backbone will connect these clusters with green production facilities in the Center and South and blue production facilities that may emerge in the North. There is also the possibility of tapping into additional renewable capacity at favourable cost from North Africa. The extended infrastructure will help the country in meeting the target set by the national strategy and deliver green and low carbon hydrogen to industrial clusters in the North of the country (Pianura Padana) and drive the creation of other hydrogen valleys in the South (Sicily, Puglia). Most of these developments will likely happen in conjunction with a switch from fossil sources to hydrogen, thus allowing the use retrofitted existing natural gas pipelines and pivoting on the availability of parallel routes. As the industry scales up and costs fall, the grid will be extended in order to connect with other markets (Austria, Germany, Eastern Europe) and maximize the corridor role Italy may play in supplying Europe with cost-competitive green hydrogen coming from North Africa.	By 2030, The Italian backbone may stretch from Sicily till the hydrogen valley of Emilia Romagna supporting an accelerated development of hydrogen in the country as indicated by the Guidelines on the Italian National Hydrogen Strategy. These developments will be coupled with the potential to import hydrogen from Tunisia, fully exploiting the cost advantage of solar production and land availability in Northern Africa. Most of these developments will consist of repurposed natural gas pipelines as a result of the availability of parallel routes. Hydrogen could potentially be transported both from North Africa and from injection points in Southern Italy to industrial clusters in the South and potentially integrating the blue production in the North that could serve industrial uses in the area. By 2035, the connection to Austria may already allow hydrogen from North Africa to be used in Northern Europe, provided that gas consumption would be gradually replaced by hydrogen and gas security of supply and balancing needs were guaranteed. On the Eastern side, the interconnection to Slovenia connects two large potential supply regions - Ukraine and North Africa. By 2040, an interconnection to Switzerland could be added to provide another connection to North-Western Europe.
Luxembourg (Creos) 	Luxembourg's network operator, Creos, operates a network of 2.130 km with interconnections to Belgium, France and Germany. It mostly serves residential clients, but also serves industry mostly located in the South of Luxembourg. In the longer-term, Luxembourg could also serve as transit of hydrogen, while use of hydrogen in other sectors beyond industry could also pick up.	By 2040, a north south connection could emerge, if a significant decrease in both residential and industrial gas flows allow it, and hydrogen demand picks up A new pipeline would be built connecting to Belgium at Bras to the MosaHyc project near Remich at the German border. Another option might be a repurposed pipeline, if the structure of end customers would no longer justify continuing the conventional operation and provided that security of supply of the customers can be guaranteed. The network of Luxembourg would connect Germany to Belgium and thus in the future could also serve a transit role.

Country

Netherlands (Gasunie)



Background

In the Netherlands Gasunie operates and owns a gas network of approximately 11,700 kilometers.

The most ambitious project Gasunie worked on in 2020 concerns the development of a national transport network for hydrogen, the 'hydrogen backbone'. For this network, Gasunie is repurposing existing gas pipelines as these become available due to declining demand for natural gas. This backbone could be in place as early as 2026. Thanks to this hydrogen infrastructure, the Netherlands and northern Germany can be the market leaders in Europe for the global hydrogen market, just as they are now for natural gas. This hydrogen backbone connects the large industrial hubs to factories that will soon be producing blue and green hydrogen. This will enable major companies to wean themselves off natural gas, massively reduce their carbon footprint and maintain jobs, their export strength and innovation capacity for the Dutch economy.

As an independent network operator, Gasunie wants to transport hydrogen from various providers to the large industrial clusters in the Netherlands through a newly developed hydrogen backbone with nationwide coverage. Together with TenneT and the Ministry for Economic Affairs and Climate Policy, Gasunie is exploring the possibilities through a study called HyWay 27, named for the year when the backbone is supposed to be ready. This study will answer the question whether and on what conditions part of the existing gas infrastructure can be used for hydrogen transport and storage. The first results of this study will be available over the course of 2021, so that an investment decision can be made in time.

Hydrogen infrastructure development

By making maximum use of the existing natural gas transport infrastructure, the national hydrogen backbone can have a capacity of approximately 10-15GW by 2030. The first regions in the Netherlands where hydrogen transport infrastructure can be built are the Rotterdam-Rijnmond region (2024) and the northern Netherlands region (2025). The province of Zeeland, the Amsterdam-IJmond region and the province of Limburg will follow after that. The national backbone can be ready by 2027 and used as a pipeline ring by 2030, whereby the connection to seaports will also be an important point.

In collaboration with foreign network operators, neighbouring industrial areas can be connected to each other and the Zuidwending hydrogen storage facility. A hydrogen partnership agreement was signed with EWE, northern Germany's largest regional energy distribution company. EWE operates large natural gas caverns, making them predestined to be part of the future large-scale hydrogen storage landscape. By mutually aligning plans for hydrogen transport and storage, joint Dutch and northern German hydrogen infrastructure is very much a possibility. Additionally, green hydrogen will be used to integrate large amounts of offshore wind energy, particularly in the north of the Netherlands. Here the North Sea Wind Power hub expects to build 180 GWs of offshore wind by 2050 and a vital role is foreseen for hydrogen to integrate the large amounts of energy into the system and provide seasonal storage.

Country	Background	Hydrogen infrastructure development

Poland (GAZ-SYSTEM)

Background

Poland's grid operator GAZ-SYSTEM operates a large and increasing network of 11,056 km of gas pipelines, connecting to Germany, the Czech Republic, Belarus, Ukraine and in the future also Denmark, Slovakia and Lithuania, to accelerate the switch from coal to gas, foster competition, market integration and ensure security of supply. Natural gas and its infrastructure will play a pivotal role in the Polish energy transformation by contributing to emission reduction by allowing a switch away from coal. An increase in gas demand is expected until the 2030s.

Poland has recently published a draft Hydrogen Strategy aiming for 2 GW of installed electrolyser capacity by 2030. Moreover, the Polish government has also published ambitious offshore wind capacity targets of 5.9 GW by 2030 and 11 GW by 2040.

The draft Polish Hydrogen Strategy indicates the need to build a hydrogen highway, which in its main objectives is to connect the north with the south and the emerging hydrogen valleys.

Poland is the third European country in terms of current hydrogen demand (1 million tons), mainly located in the industry in the South plus industrial clusters across the country. A hydrogen backbone in Poland would be crucial to transport energy produced offshore in the North to the demand regions in the South and other consumption centers, while also opening the possibility of green hydrogen imports from Scandinavian wind and decarbonise hard-to-abate heavy industry. Import from other directions such as Ukraine, could be considered, once production ramps up.

However, due to the specificity the Polish energy transition, it is important to bear in mind a certain fluidity concerning the timeframes.

Hydrogen infrastructure development

A possible scenario is that Poland's hydrogen network would be in place around 2035. Mainly around the offshore wind potential in the North and the industrial clusters in the South, Center and West. An interconnection to Germany would allow to integrate the emerging Polish hydrogen network with the rest of Europe. Additionally, the connection to storage in a salt cavern could be envisioned to enable offshore wind energy to be stored and re-used later in periods of low wind speeds. Hereby providing a valid alternative for gas or even coal peaker plants. It shall play an important role to connect industrial clusters. Post 2040, all industrial clusters are to be connected, while also the North South connection would complement the integration of large amounts of renewable energy in the North from offshore wind. Repurposing is not always on option due to increasing demand on natural gas, technical constraints and age existing networks.

Meanwhile, the vision of the Hydrogen Highway outlined in the Polish Hydrogen Strategy could be implemented. In the post 2040 perspective, interconnections to Denmark through the Baltic Pipe and Lithuania (via GIPL) in the East opens up import routes of hydrogen produced from (offshore) wind in the Nordics and Baltics. Via the East of Poland hydrogen could be imported from the Ukraine and possibly even transited into East Germany in a cost-efficient manner.

One important factor to take into account in developing a hydrogen network is the growing consumption of natural gas, which will still require large parts of the Polish transmission system until 2040. Any solution concerning repurposing/retrofitting will be carefully assessed on a case-by-case basis, due to technical limitations and heterogeneity of existing network. An analysis of such potential in the area of materials has already been initialised by GAZ-SYSTEM - mapping of potential is in progress, as is the analysis of the transmission system itself and its possible cooperation with hydrogen.

Slovakia (Eustream)

Background

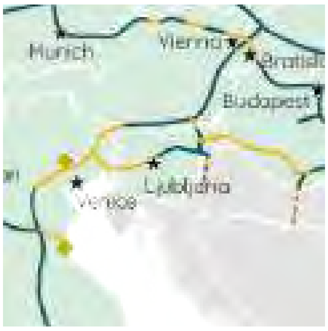
In Slovakia, Eustream operates a main east-west 450 km backbone network of 4 and sometimes 5 large diameter pipelines, while the total length of Eustream's network is 2,230km. Eustream's network connects Ukraine to the rest of Europe, thus its role is mainly a transit country. In the future a similar role is foreseen, only this time for large amounts of green hydrogen which could potentially be supplied from Ukraine. The large parallel pipelines would provide a very cost-efficient way of transporting energy, as it would mean substantial savings of the most important cost factor in hydrogen transport – compression.

Hydrogen infrastructure development

By 2035 - in an optimistic scenario for hydrogen supply from Ukraine or North Africa taking off – the timeline could allow the repurposing of one of its large diameter pipelines from Ukraine in the East to the Austrian and Czech networks in the West.

In the beginning with green hydrogen flows still picking up, the lower capacity of hydrogen flowing the repurposed network would also serve the currently coal-based steel industry in the region near Košice and chemical industry near Šala.

Repurposed interconnections to Hungary in 2035 and Poland in 2040 would connect multiple markets and provide security of supply.

Country	Background	Hydrogen infrastructure development
Slovenia (Plinovodi)  	Plinovodi, the TSO of Slovenia, operates a network of 1,195 km, for domestic use while also playing a transit role from Austria to Croatia and Italy. For both using a doubled main backbone from its capital Ljubljana into the east which then stretches north into GCA's and TAG network in Austria. With the LNG terminal in Croatia on the Krk Island, up and running since beginning of 2021, planed new interconnection with Hungary and other changes, the transit role will change. As a result, one of the pipelines of the main backbone could be repurposed for hydrogen. Slovenia has nuclear energy and Solar PV installation is expected to increase. About one third of its electricity comes from coal. The coal fired power plant could be replaced in the future by a gas-fired power plant, thus providing another possible opportunity for the hydrogen. A hydrogen network could be used to serve industry users and power plants with available green hydrogen via Austrian and FGSZ's network or with North African green hydrogen via SNAM's network, as well as from domestic production. While the hydrogen network could also play a transit role, connecting sources of demand and supply, and integrating the energy systems in Italy, Austria, Hungary and Croatia.	By 2035, a regional backbone could emerge. The current main gas pipeline is doubled and together with the changing gas flows due to changes on energy markets, new interconnection with Hungary, and upgrade of connection with Croatia, it enables the repurposing of parallel natural gas pipelines. Thus, the domestic production and consumption can be connected. There would be hydrogen interconnections from Slovenia to Hungary and Italy which connects the national hydrogen markets, but also major green hydrogen supply sources (e.g. North Africa). The connection to Austria and possibly Croatia would ensure that the European Hydrogen Backbone becomes an integrated hydrogen network stretching from South-Eastern to North-Eastern Europe.
Spain (Enagás) 	Enagás operates an extensive gas transmission network in Spain that comprises over 11,000 km of gas pipelines. This network has six international connections: two with Africa via Tarifa and Almeria (linking with the Magreb and Medgaz gas pipelines, respectively); two with Portugal via Badajoz and Tuy; and another two with France via Irun and Larrau. The Spanish Hydrogen Roadmap recognises that renewable hydrogen is a key sustainable solution for the decarbonisation and the development of a high value-added green economy. For 2030, the strategy foresees an installed capacity of 4 GW electrolysers and a series of milestones in the industrial, mobility and electricity sectors. The hydrogen pipeline network in Spain is based on a high-level analysis and it would enable the coexistence of both natural gas and hydrogen for a defined period, optimising the use of current infrastructure to serve potential demand in industry and guaranteeing security of supply. At the same time the backbone aims to harness the significant potential of Spain´s solar PV and onshore wind resources, which could enable the exportation of green hydrogen to other European countries. Hereby, also ensuring the role of Spain as a transit country, with pipeline infrastructure to transport low cost hydrogen produced in North Africa to demand centres in Western Europe.	By 2030, industrial clusters within reach of the proposed parallel network and therefore relevant for initial development of the backbone are along the Mediterranean coast and in the center and north of the peninsula. Later, the development of the network will guarantee cohesion between the different demand regions, also integrating the multiple supply points that will be distributed across the geography. Spain's long-term ambition is to be one of the main hydrogen suppliers in Europe, building on its significant large-scale solar PV and wind and hybrid potential to produce green hydrogen. The national backbone will enable this by connecting to France through the existing connections by Larrau (2035) and Irún (2040) and creating a new route through Catalonia by 2040. Connections to North Africa can be made from 2035 to complement national supply with imports from the south to cover the demand in Central Europe.

Country

Sweden (Nordion Energi)

Background

The Swedish climate target is to reach net-zero emissions of greenhouse gases by 2045. The decarbonisation efforts necessary for this goal to be achieved are many and the visionary and ambitious scenario of a dedicated hydrogen backbone not only supports this goal, but it brings additional robustness to the entire energy system. The backbone would aid the transmission of energy from north to south creating a sustainable, flexible, and balanced energy system.

During the late 2020s, the Swedish backbone emerges on the coastal region in the south-west of the country with an interconnection to the Danish grid. Chemical and petrochemical industries situated close to the backbone are the drivers of hydrogen demand. Given the absence of parallel piping infrastructure, dedicated hydrogen pipelines will have to be newly built.

Given the nature of Sweden's geography, terrain, and location of industrial clusters, hydrogen island grids are starting to arise and are subsequently connect via regional networks.

Hydrogen infrastructure development

By 2030, significant industrial use of hydrogen is expected, and the total energy demand requires large scale-up of RES and transmission solutions. Large onshore wind parks situated mainly in scarcely populated areas, and offshore wind parks emerge across the country. The southern backbone stretches further north not far from the Stockholm region of Sweden, linking industrial demand centres and cities in southern and central Sweden. In the most northern parts of Sweden an additional backbone emerges with an interconnection to the Finnish backbone. The transforming mining and steel industries are the main drivers behind the hydrogen demand in the most northern parts of the country.

By 2035, the southern and northern backbones connect, creating a hydrogen corridor across the country, linking the backbones of Denmark, Sweden, and Finland to the European hydrogen backbone. A new energy transmission network from north to south would be a reality. An offshore connection across the Gulf of Bothnia, via an energy island, would be the second possible interconnection between Sweden and Finland.

By 2040, a second interconnection (offshore) from Denmark could emerge via the Kattegat sea area, which is the fourth possible interconnector for Sweden.