Hydrogen Backbone Link
NZTTP Programme

HYDROGEN BACKBONE LINK

CONNECTING SCOTLAND TO EUROPE

Net Zero Technology Transition Programme

Net Zero Technology Centre
Technology Driving Transition

Foreword

The Hydrogen Backbone Link project represents a huge opportunity for Scotland to secure its place on the world stage as a major exporter of green energy. If we act with pace and deliver the backbone, we can place Scotland at the heart of Europe's near and long-term decarbonisation strategy and play a central role in delivering a secure and efficient European hydrogen supply system.

Phase 1 of the project has outlined a credible, direct, and cost competitive route to market as well as a review of the technologies existing and in development that will enable the backbone. When delivered the project will act as a catalyst for green hydrogen production in Scotland providing a direct, low-cost transport option for emerging hydrogen producers.

Technology and innovation will be key to delivering future hydrogen infrastructure, but there are no insurmountable barriers to immediate action. It is imperative we maintain the momentum of the project as we move into phase two, welcoming new partners and collaborating with other major European infrastructure initiatives.

Myrtle Dawes CEO, Net Zero Technology Centre (NZTC)

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1.0

Executive Summary

Scotland, with its vast onshore and offshore renewable resources, has the ambition to become a net exporter of green energy by 2045. The Scottish Government funded Hydrogen Backbone Link (HBL) project is a key early enabler for this, providing cost-effective transportation to market for Scottish hydrogen producers and supporting the transition to a low-carbon energy system.

The HBL project focuses on the critical hydrogen transport infrastructure required to deliver a cost-effective pipeline solution. These transportation options and related technologies are a strategic enabler of the hydrogen energy value chain, complementing hydrogen production technologies.

Three key learnings emerged from this Phase of the project:

Repurposing and Routing – Having reviewed multiple options for existing pipeline repurposing, the study concluded that whilst feasible, the technical complexities of repurposing and the current utilisation for hydrocarbons means that a new purpose-built pipeline route is preferable. The new build pipeline would connect Scotland's east coast with Emden in Germany to deliver a direct link to market at pace to meet anticipated demand growth and with favourable economics when compared to other global sources.

Economics – The CAPEX investment needed to realise this new pipeline is estimated at ca£2.7 billion. The resulting transportation tariff of 32pence/kg will yield a 6% initial rate of return for investors. Balancing the (albeit higher) production and (predicted lower) transportation costs, Scottish green hydrogen will be cost competitive to other globally sourced hydrogen from countries and regions with lower production costs such as Canada, Chile and the Middle East.

Enabling Technology – The technology we need to deliver the backbone is generally well developed, however there remain several key areas where investment is needed to rapidly develop, reduce cost and scale up solutions to enable the system to function. Emerging compressor technologies, such as turbo, electrochemical and compact centrifugal designs require accelerated development and scale up. In parallel, experimental testing of existing meter and valve designs with hydrogen as a test medium is required to verify calibration ranges and confirm the operational limits.

An aligned international effort on research and development into storage solutions at operational, buffer and interseasonal scales is essential to ensure sufficient capacity is available to deliver security of supply.

Delivering the Hydrogen Backbone Link will act as an enabler for both the European and Scottish green hydrogen economies supporting up to 300,000 jobs in Scotland alone by 2045. It will be a critical catalyst for Scottish hydrogen production in the late 2020s and early 2030s removing a major source of project uncertainty by providing a safe and reliable route to market.

The new pipeline could enable Scotland to meet up to 10% of Europe's projected hydrogen import demand by the mid 2030s. Through ongoing investment in additional infrastructure, it could maintain this proportion of export beyond 2045, helping Scottish Government meet its green export ambition and facilitating continental Europe's industrial decarbonisation.

To fully realise this opportunity and capture the mutual benefits of the growing hydrogen market, action is required across six key areas:

- Rapid acceleration of public and private investment to deliver the backbone pipeline
- Continued investment in hydrogen and wind deployments to deliver security of supply
- Develop a National Energy Storage Strategy to deliver an integrated renewables and hydrogen storage system for 2030 and beyond
- Cross border policy and standards alignment to enable safe, efficient export
- Financial support to accelerate technology development and infrastructure deployment to turn vision into reality

2.0

Results

THE OPPORTUNITY:

- Green hydrogen transported via a new pipeline from Scotland will deliver globally cost competitive hydrogen.
- The new pipeline capex spend of £2.7 billion GBP (~3Bn Euros) is significantly cheaper than all other transport options.
- Investors will benefit from a 6% Initial Rate of Return (IRR).
- By the mid 2030s the Hydrogen Backbone Link could provide up to 10% of projected EU import demand.
- Some existing technologies such as valve and flow meter designs are transferrable to hydrogen service with minimal modifications.
- The HBL is a critical enabler for new and existing Scottish green hydrogen projects, de-risking investment decisions and accelerating project deployment.
- The Hydrogen Backbone link would create up to 700 Scottish jobs in the 2030's and act as a key enabler of Scotland's hydrogen economy, supporting up to 300,000 jobs by 2045.

RECOMMENDATIONS:

- Rapid acceleration of investment to deliver the backbone pipeline by mid-2030s.
- Continued investment from government and industrial collaborations in hydrogen and wind deployments to deliver security of supply.
- Develop a National Energy Storage Strategy to deliver an integrated renewables and hydrogen storage system for 2030 and beyond.
- Cross border policy alignment between governments and key stakeholders to facilitate deployment at pace.
- Diversify existing energy skills and ensuring a pipeline of talent throughout the supply chain.
- Technological development and infrastructure deployment to turn vision into reality within the next ten years.

CLOSING THE TECHNOLOGY GAP:

- Rapid development, deployment and scale up of storage solutions at operational, buffer and inter seasonal scales is essential to support the delivery of the hydrogen backbone link.
- Using hydrogen as test medium, experimental testing of existing meter designs is required to verify calibration ranges and confirm the operational limits.
- Emerging compressor technologies, such as turbo, electrochemical and compact centrifugal design, could have a tangible impact on the delivery of the HBL.

3.0

Realising Scotland's green export potential

Low-carbon hydrogen is recognised as a leading global solution in the fight against climate change and has seen exponential global investment from energy rich nations looking to not only decarbonise their own domestic energy needs but also export this commodity to energy hungry regions such as Northwest Europe. Scotland is one such nation, with a vast renewable resource in the form of offshore wind, and an ambition to become a net exporter of green energy by 2045.

Scotland has an Exclusive Economic Zone that covers 462,315km2 and some of Europe's highest capacity factors for offshore wind (circa 60%) with wind power densities ranging from 1000-2000(W/m3). The International Energy Agency (IEA) published its Hydrogen in Northwest Europe report in 2021 which further highlighted Scotland's significant low-cost hydrogen production potential with projected costs of <2.8 Eur/kgH2.

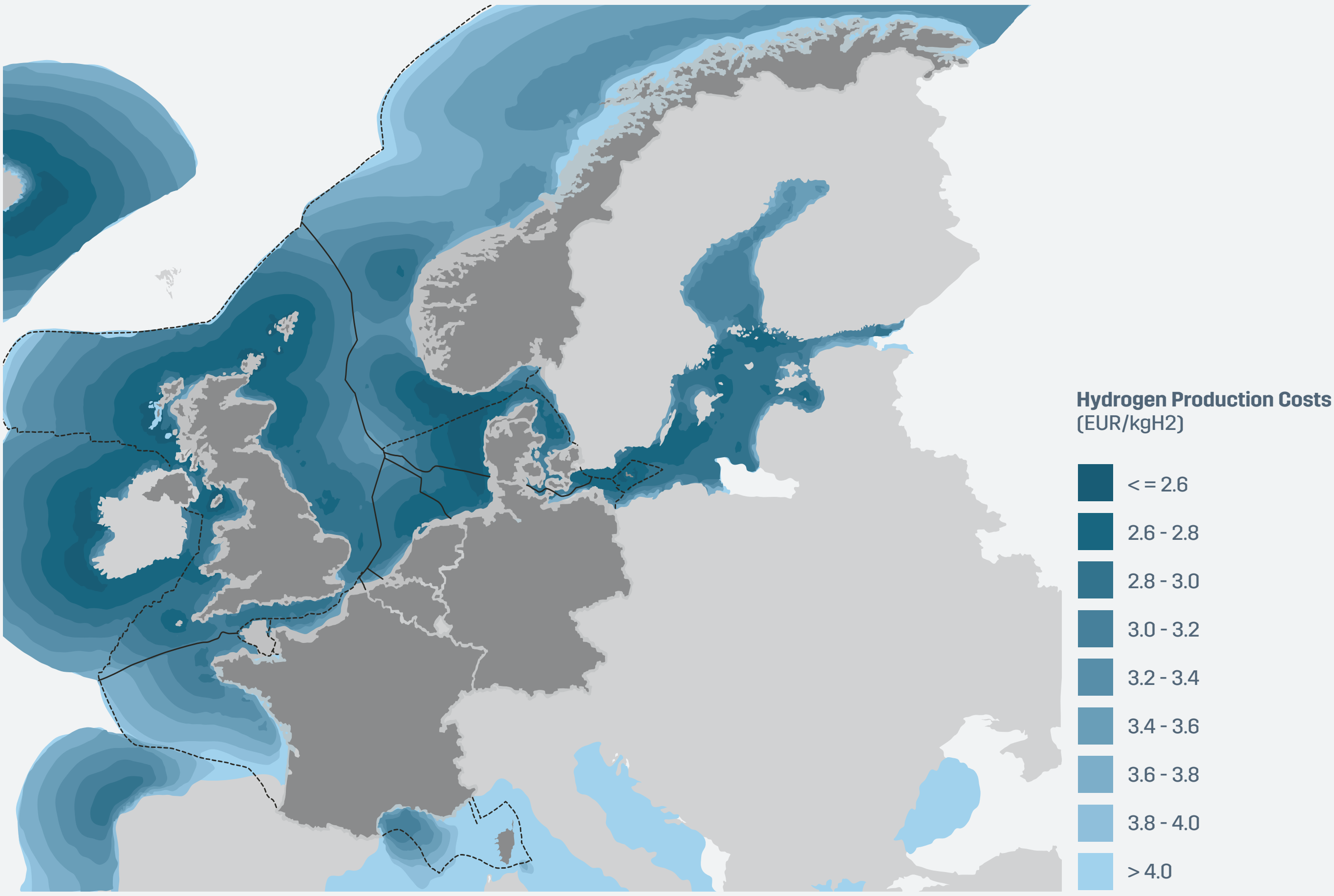

Figure 1: Hydrogen production cost from Offshore Wind adapted from IEA Accelerated 2030 scenario

In December 2020, the Scottish Government launched its Scottish Hydrogen Assessment Report outlining the critical role of hydrogen in decarbonising the national energy system. It publicly presented Scotland's ambition to become a net exporter of green hydrogen, with up to 94 twh per annum exported to local markets in Europe by 2045 in the Green Export scenario.

Underpinning this is Scotland's world leading position in fixed and floating offshore wind deployments. It boasts the world's first commercial floating offshore wind park, Hywind Scotland, which started producing electricity in October 2017. The 2023 licensing rounds for seabed rights around Scotland's coast, through both Scotwind and the INTOG leasing rounds, have seen well over 30GW of projects accepted, with more than half being floating wind.

As an early mover, Scotland is positioning itself at the forefront of the transition to net zero with world leading offshore wind deployments and a portfolio of ambitious projects. The Hydrogen Backbone Link (HBL) is a crucial piece of this impressive 'puzzle', providing a cost-effective route to market for Scottish green hydrogen into NW Europe.

The European Union (EU) has given hydrogen a significant role in its future energy strategy. Exacerbated by the ongoing war in Ukraine, 2030 demand is predicted to be 20 million tonnes, of which 10 million tonnes is to be produced domestically and 10 million tonnes will come via imports (EU Hydrogen Strategy).[1]

The HBL project will play a significant role in providing the reliable, safe and stable export of hydrogen into Europe and by the mid-2030s, could account for approximately 10% of NW Europe's total import requirement.

A report by the World Energy Council (WEC) in 2021 suggests that by 2050, the total EU demand for hydrogen and hydrogen-based derivatives could rise from 20 million tonnes in 2030 to 60 million tonnes, or 2,000 terawatt hours in 2050, 50% of which would be met by imports. If Scotland was to meet its green export scenario targets, this would account for 9.4% of the EU's total import demand.

To reach this ambitious target by 2050, Scotland would need to install additional pipeline infrastructure beyond the initial HBL both on and offshore.

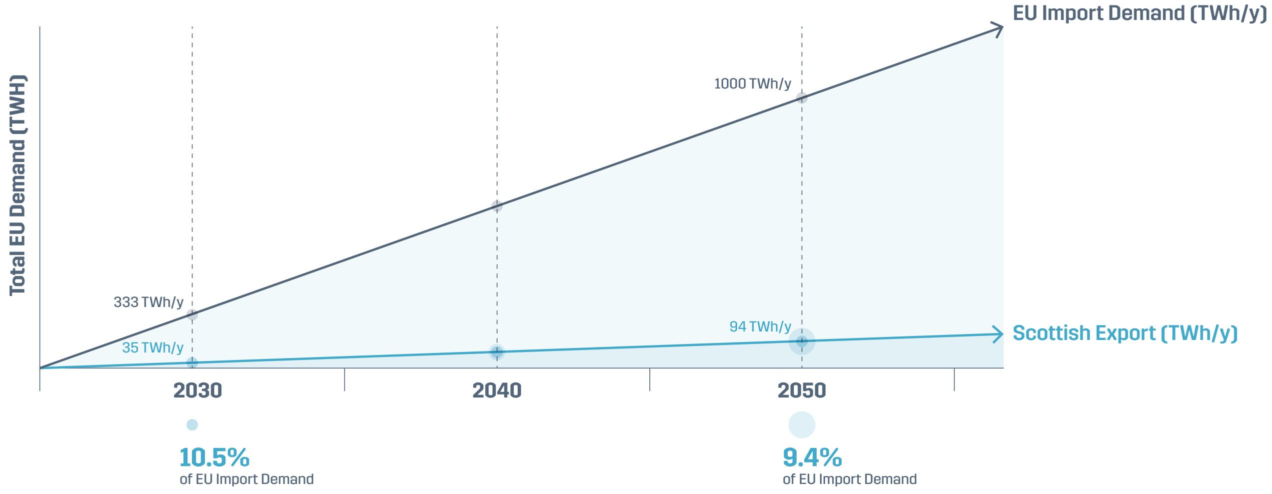

Figure 2: Projection of Scottish export ambition versus European demand

[1] Source: www.energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en#:~:text=The%20ambition%20is%20to%20produce,in%20energy%2Dintensive%20industrial%20processes.

4.0

A project portfolio accelerating the transition

In 2021 the Net Zero Technology Centre (NZTC) was awarded £16.7M of public funding from the Scottish Government's Energy Transition Fund (ETF) to support a programme of seven strategic energy transition projects.

Energy Hub	Energy Hub	Identifying key opportunities and technologies to deliver the nations future low carbon energy requirements
Hydrogen Backbone Link	Hydrogen Backbone Link	Scotland in a leading role for the development of pan-European hydrogen infrastructure
Alternative Fuel Gas Turbines	Alternative Fuel Gas Turbines	Accelerating the development of gas turbines capable of running on clean fuels
Advancing Remote Operations	Advancing Remote Operations	Remote operations to create safer, more efficient and lower carbon operations
Data for Net Zero	Data For Net Zero	Developing analytics to unlock energy transition action and deliver the world's first smart energy basin
OLTER	Offshore Low Touch, Energy, Robotics & Autonomous Systems	Enabling next generation robotics and autonomous systems for the offshore energy sector
Offshore Energy Digital Architecture	Offshore Energy Digital Architecture	Implementing a sector-wide data and infrastructure strategy to enable digitisation

The HBL Project has been allocated 10% of the programme funding, £1.6M of public funds. This will be matched by industry contributions resulting in a total project budget of £3.2M. The project is funded over a three year period up to March 2025.

The HBL project aims to position Scotland in a leading role for the development of pan-European hydrogen infrastructure for export capability. It will address the opportunity for Scotland and the rest of the UK to supply hydrogen to Europe as part of an extensive hydrogen transport and distribution system. Phase one of the project has attracted a strong, active consortium of industry partners who have match funded and contributed to the individual workscopes, ensuring it is industry lead and aligned to drive results and outcomes.

Crown Estate Scotland Oighreachd a' Chrùin Alba

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Shetland Islands Council

SGN Your gas. Our network.

wood.

Wood Mackenzie A Verisk Business

Worley energy | chemicals | resources

XODUS

> **The Hydrogen Backbone link represents a unique opportunity for Scotland to capitalise on our natural resources, engineering prowess and technical skill to support the country's ambition to be a net exporter of Green Hydrogen. Delivering this ambitious project will put Scotland at the forefront of the energy transition.**
>
> **Salman Malik** CFO & MD, EnQuest

5.0

Hydrogen Backbone Link: Route Assessment

With hydrogen set to play a key role in an integrated energy future both for Scotland and globally, reliable and affordable hydrogen transport solutions are fundamental.

The HBL delivers an integrated energy vision with pipeline solutions at the forefront. It provides energy security and resilience, and connectivity throughout the UK and Europe, as well as delivering hydrogen at a globally competitive price.

Two case studies, a **'New Pipeline to Germany'** and **'Routing via Rest of UK'**, were identified and studied to establish the optimal route and pipeline option for the HBL, considering both pipeline re-use and new build infrastructure. In each case, 100% gaseous hydrogen is assumed, with 10GW windfarm capacity. Sensitivities for 2GW and 5GW were also completed.

Case option 1 (A+B): New Pipeline to Germany:

The New Pipeline to Germany Case is a fully new build, accelerated option for the delivery of an offshore hydrogen backbone. Two alternate route options identified for this case are;

- Option 1A which follows a route primarily in the UK sector of the North Sea to the south and west of existing Central North Sea infrastructure.
- Option 1B presented in Figure (below), which follows a route through the Danish and Norwegian sectors close to the existing Europipe I trunkline.

Option 1B is considered the preferred route in a new pipeline scenario as it follows existing pipeline corridors and has lower overall costs compared with Option 1A.

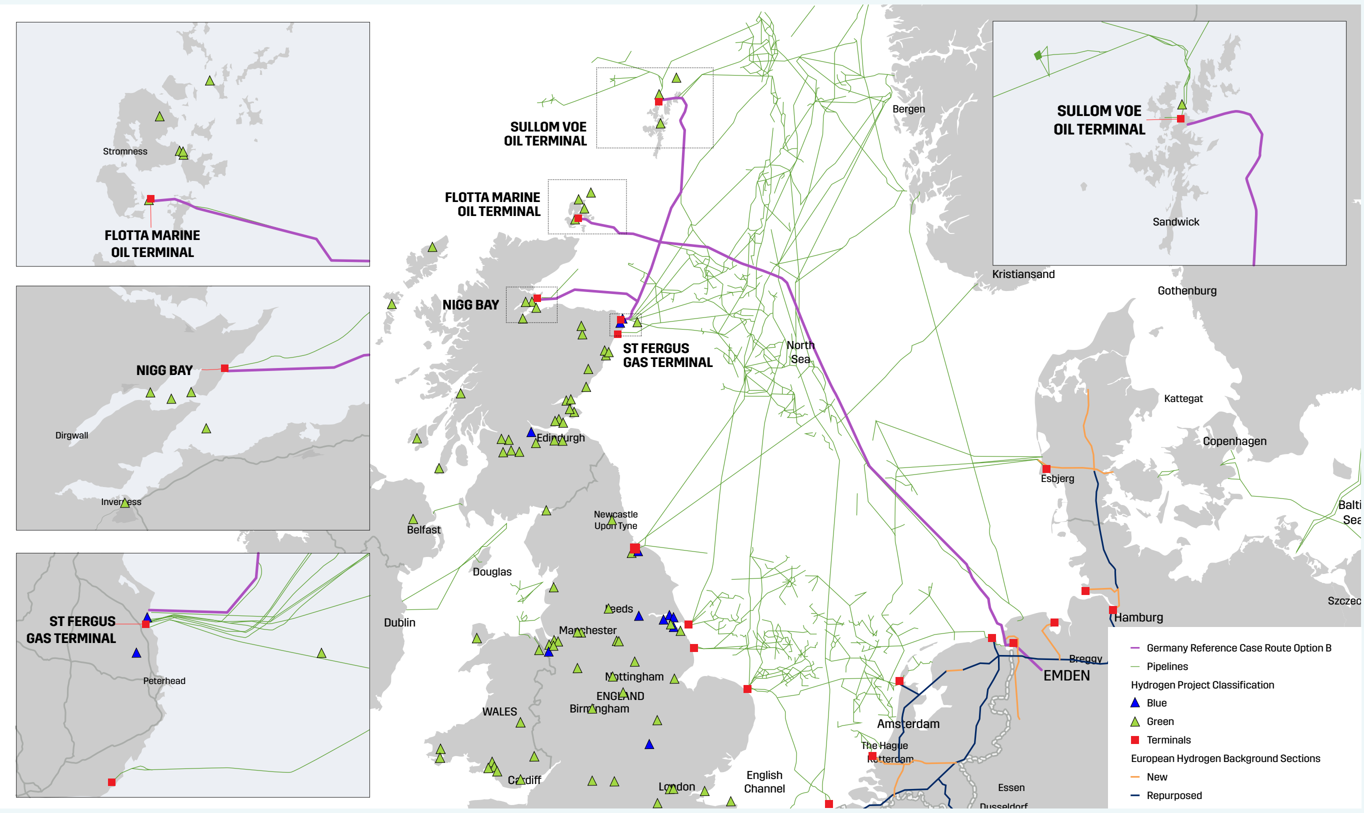


Figure 5 Option 1B - Routing through Danish and Norwegian Sectors

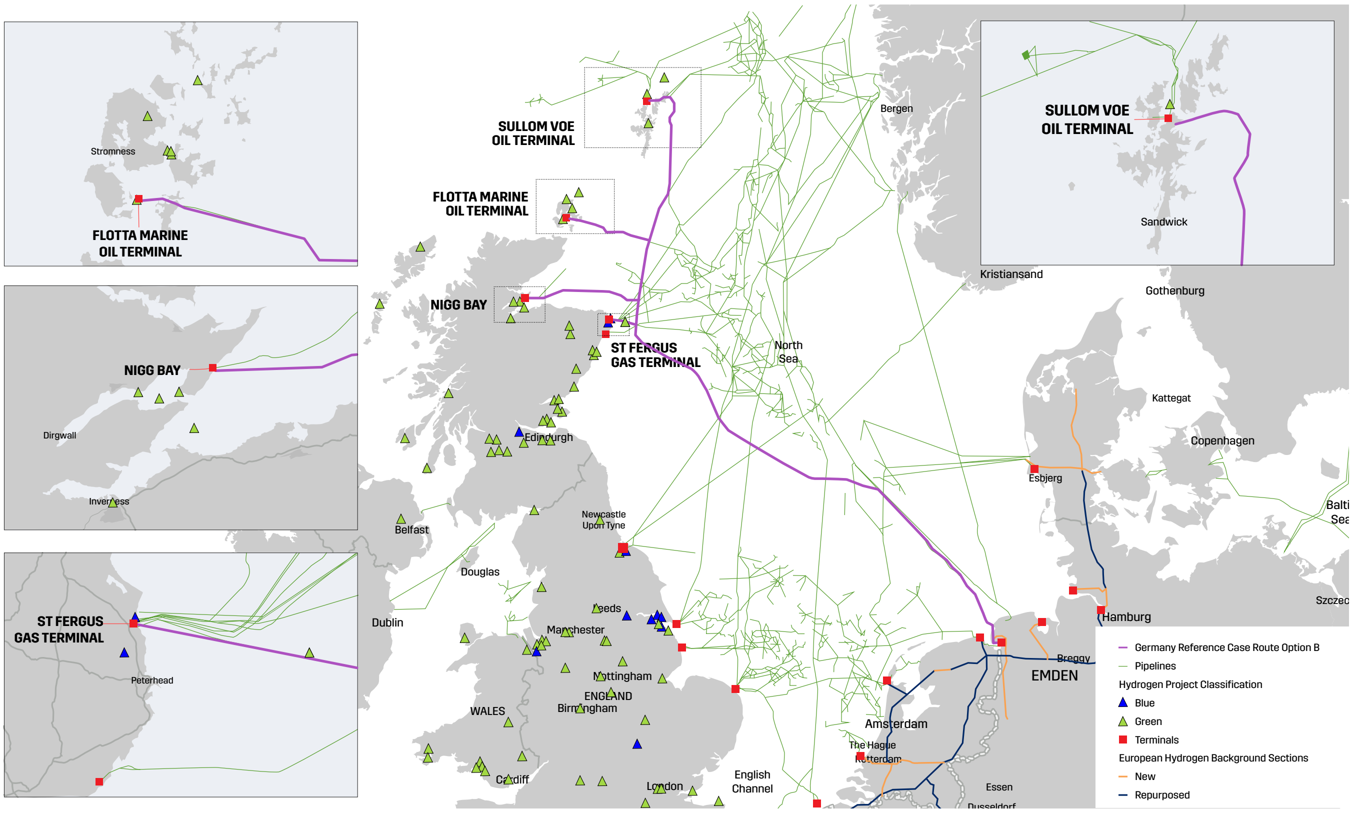


Figure 6: Option 1A, routing through UK sector

Case option 2: Routing via Rest of UK Case

The Routing via Rest of UK identified a UK onshore pipeline network with potential export routes from Scotland via England to the following countries: France, Belgium, the Netherlands, Germany, and Denmark.

The export routes from Scotland proposed under this case consist of a combination of fully new onshore pipeline routing through the UK and partial re-use of existing pipelines to Europe. No options for routes which fully re-use existing infrastructure were identified.

Maps of Options 1B and Option 2 can be found in Figure 5 and 6.

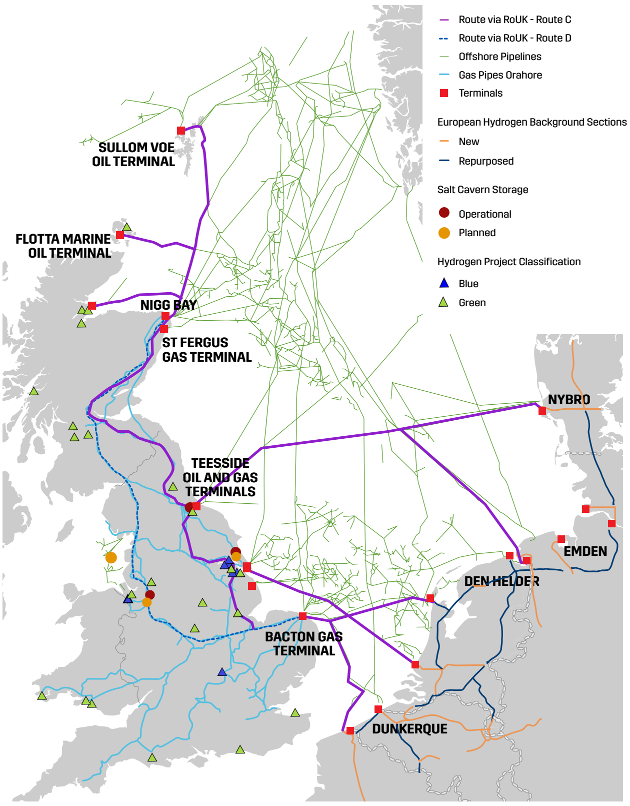


Figure 7: Other routing options via UK onshore network

Option Selection

The best overall opportunity is an entirely new pipeline, direct from Scotland to Europe.

This is the result of an option selection exercise that compared case options 1 and 2, with weighted drivers such as schedule, operability and overall cost used to complete the exercise. Option 1, New Pipeline to Germany, was ranked as the optimal solution, with greater than 20% difference in score compared to case option 2.

Option 1B – The Detail

The premise of establishing a new pipeline route was to utilise a single larger bore pipeline, namely the backbone, which would start from one of the four identified Scottish hydrogen production hubs, including additional smaller bore pipelines, namely spurs, to connect the other three Scottish hubs to the backbone pipeline.

This option connects Flotta to Emden via the large bore pipeline (backbone), with spurs from Sullom Voe, Cromarty Firth and St Fergus. Most of the existing North Sea oil and gas assets are avoided by routing northwards and then eastwards of the Central North Sea infrastructure. This results in the majority of the backbone section being located outside of the UK sector, and instead going through Norwegian and Danish sectors.

In the UK sector, the proposed route follows the corridors laid by the following existing pipelines; PL11 (P/C Tee to Flotta), FLAGS (PL002), SIRGE (PL2764). On approach to Emden, the route follows the Europipe I and the 36" Gas H-7 BP Emden corridors down from the Ekofisk field.

This route closely follows most of the ScotWind leasing sites to the north of St Fergus, as well as the German offshore windfarms namely BorWin, DolWin, HelWin, and SylWin, allowing for potential future connections to wind-powered offshore hydrogen electrolysers.

"The proposed route with a fully new-build pipeline following existing North Sea infrastructure allows for accelerated delivery of green hydrogen from multiple Scottish producers to export markets in Germany and beyond. The proximity of the route to multiple wind farms areas allows for potential connectivity to wind powered offshore hydrogen electrolysers in future."

Thomas Atherton Senior Energy Developments Consultant, Xodus Group

6.0

An Economic Solution

The economic case for hydrogen pipelines versus other maritime transport, such as ship transport by liquid organic hydrogen carriers, ammonia or methanol, is well publicised. In cases where hydrogen is being transported less than 3000km, pipelines provide by far the cheapest and safest transport option from producer to consumer.

Detailed economic analysis conducted by Wood Mackenzie examined the costs associated with deploying and operating a new build pipeline from Scotland to Europe using the Case Option 1 New Pipeline to Germany routing.

The analysis targeted an initial rate of return (IRR) of 6%, based on the 10 GW case with CAPEX spend of 2.7 bn GBP. The resulting tariff based on a 90% pipeline utilisation was £0.32/kg of hydrogen.

In the **base case analysis**, the implied tariff is **£0.32/kg**

A 40% increase or decrease in **development capex** implies a tariff of **£0.44/kg** or **£0.21/kg** respectively

A 40% increase or decrease in the **operating costs** implies a tariff of **£0.34/kg** or **£0.31/kg** respectively

Adjusting the **hydrogen supply build-up period** from 5 years to 10 and 1 year implies a tariff of **£0.39/kg** and **£0.30/kg** respectively

Reducing the plateau utilisation of the pipeline from 90% to 75% and 60% increases the implied tariff to **£0.38/kg** and **£0.48/kg** respectively

A 2GW scale pipeline (as opposed to the 10GW modelled in the base case) increases the implied tariff to **£0.96/kg**, three times the 10GW value.

A 6% IRR has been targeted in the base case analysis with 8% and 4% cases run as sensitivities. The rate of return targeted for investment will be shaped by government support and project finance.

Investment Risk & Cost of Capital

A clear national long-term vision with a sector road map and a stable policy environment will reduce market uncertainty around hydrogen, whilst government financial support will reduce investment risk. In combination, these can reduce the cost of capital for a project. Taking the view that the Hydrogen Backbone Link will be a strategic national infrastructure investment, it is worth understanding the impact that the cost of capital has on the project. The IRR sensitivity shows:

- **At 4% the implied tariff is £0.25/kg**
- **At 8% the implied tariff is £0.41/kg**

The estimated Capex spend over a 35 year life of pipeline is 2,79bn GBP with sustaining Capex of 90 million GBP and Opex of 843m GBP.

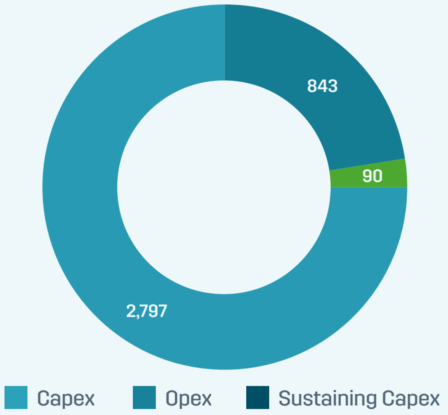


Figure 8: 35 year Capex and Opex spend on proposed pipeline

Hydrogen Supply Build-up

A key variable for pipeline economics is the rate at which the hydrogen supply, and therefore revenue, materialises through the first decade of pipeline operations. The quicker this is, the lower the tariff that needs to be charged to achieve a 6% IRR.

For a natural gas project, a pipeline is typically sized to the field or fields that will be supplying it, which can then be brought onstream in quick order so that the pipeline rapidly reaches capacity. Given the majority of hydrogen supply is expected to be fed with green hydrogen (with some blue hydrogen potentially coming through the St Fergus spur) this will require large scale offshore wind developments, associated infrastructure and matching hydrogen generation capacity across all four supply hubs – Flotta, Sullom Voe, Cromarty Firth and St Fergus. Assuming that all, or much of this, will come onstream as the pipeline is brought online is unrealistic, so part of the project modelling scope was to understand how the hydrogen supply build-up assumptions impact the implied tariff.

Years	Capacity Build-up by Year
1	90%
3	20%, 60%, 90%
5	20%, 40%, 60%, 80%, 90%
10	10%, 15%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%

Our base case assumes a 5 year build up, combined with other factors to result in a tariff of 0.32 pence per kg.

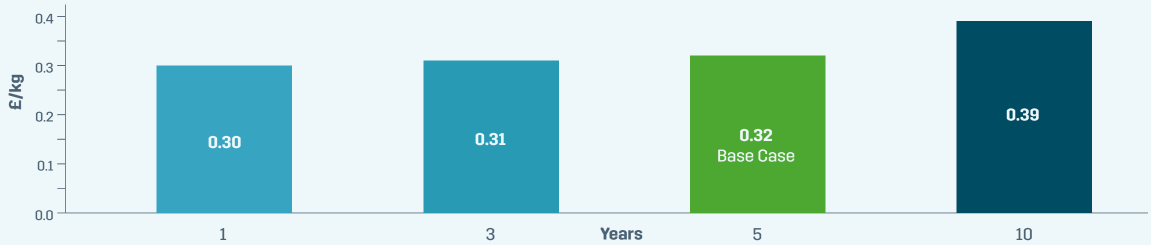


Figure 9: Hydrogen supply build up scenarios with bases case highlighted

Source: All diagrams Wood Mackenzie, Xodus Report

7.0

Export Economics: Scotland on the Global Stage

Once transportation costs are accounted for, green hydrogen, transported via pipeline from Scotland, could be cost comparable to other globally sourced hydrogen.

The International Energy Agency (IEA's) Future of Hydrogen report from June 2019 highlighted global levelised cost of hydrogen (LCOH) costs from a combination of renewables including wind and solar. While other regions globally will undoubtedly have lower production costs when compared with Scotland, such as Chile, the Middle East, North Africa and Australia, where combined solar and wind projects will achieve higher efficiencies, Scotland has a geographical advantage in terms of its proximity to European markets.

When transportation costs are considered, Scotland's moderately higher production cost is balanced out by its low cost of transport – 32p or 36 euro cent per kg compared to > 1£/€ per kg, meaning that domestic hydrogen production in Northern Europe will be cost competitive.

	Scotland	Middle East, North Africa, Chile...
H_2 Production	€2.6/kg	€1.7/kg
H_2 Transport	€0.4/kg	€1.4/kg
H_2 to EU Customer	€3.0/kg	€3.1/kg
Security of Supply	+	–
Shared Ownership	+	–

Table 1: Comparison of Scottish production and transport costs with other key global competitor regions

As well as the cost of the hydrogen, security of supply will play a huge factor in early decision making. Pipelines offer an increased level of certainty for larger volumes of hydrogen transport over shipping.

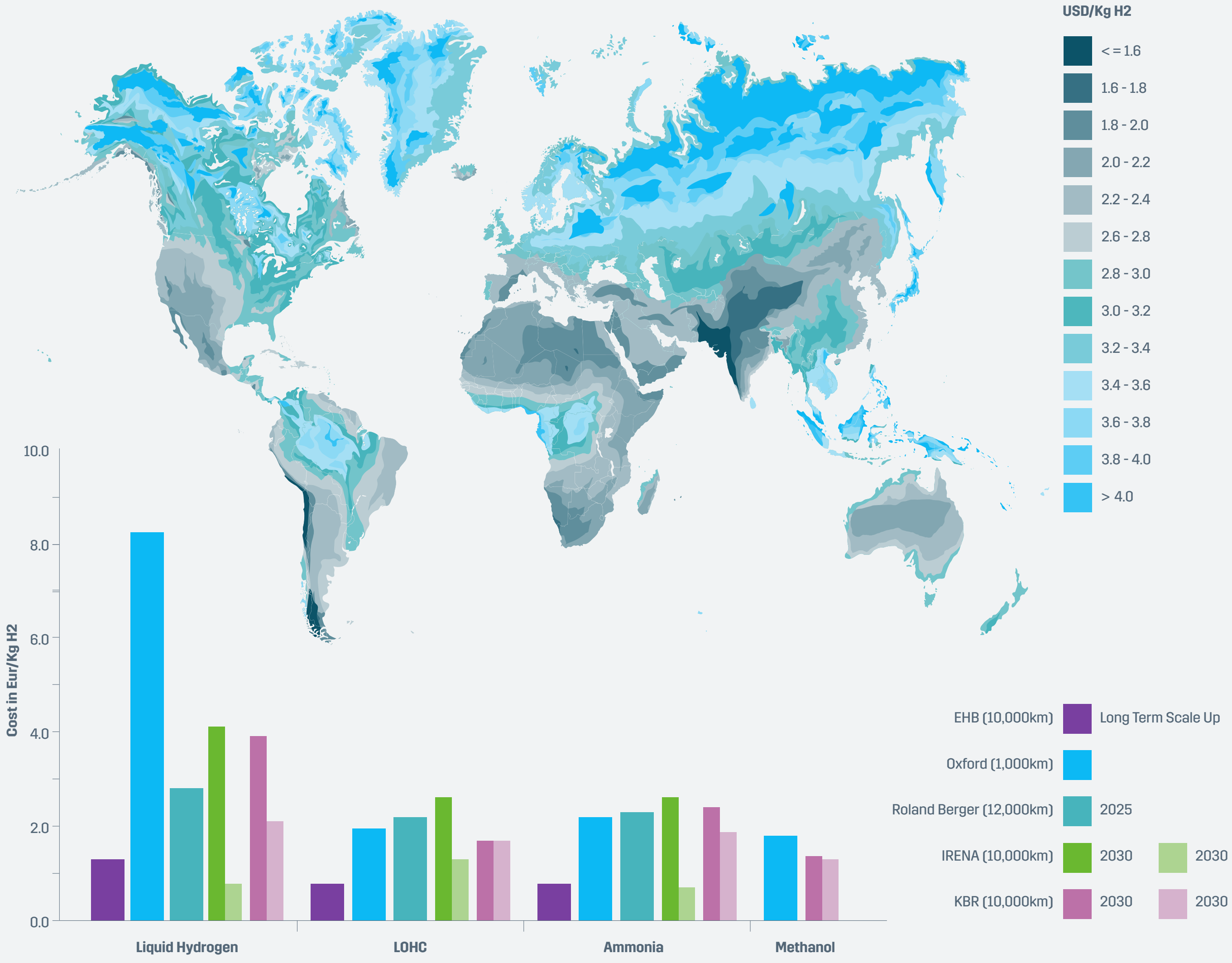


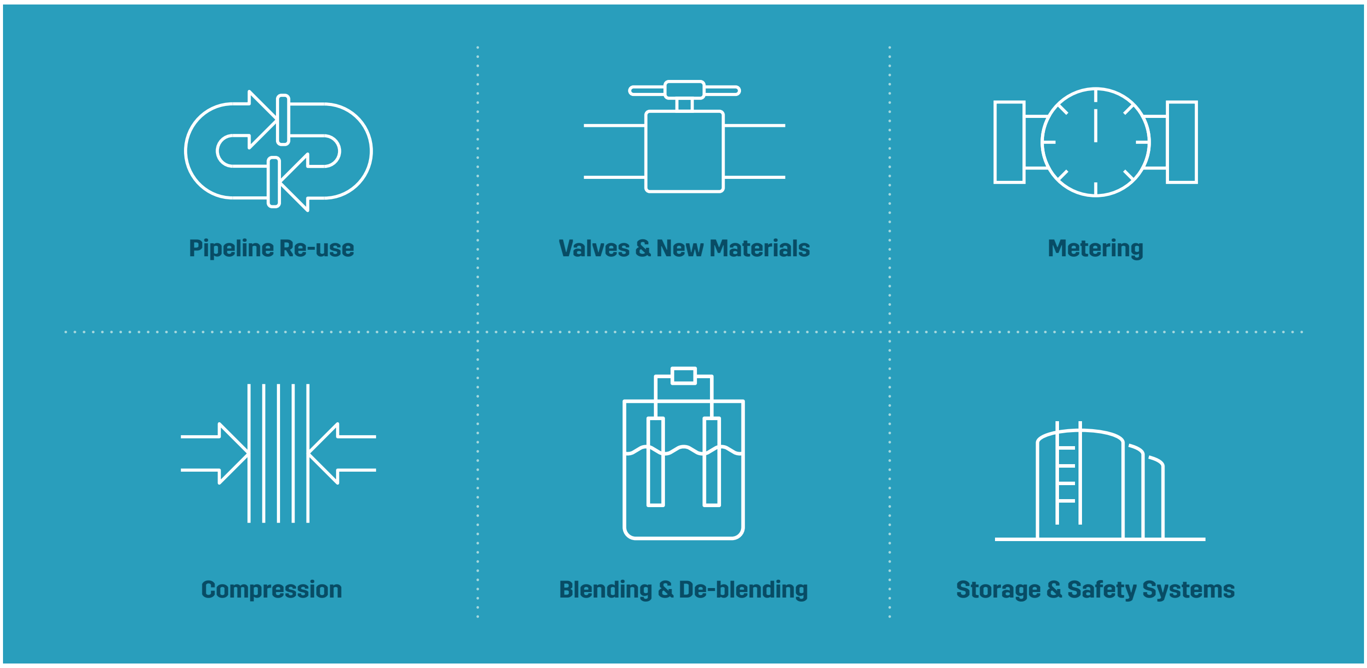
Figure 10: Adapted from IEA Future Hydrogen Report – Global hydrogen production costs and transportation costs across 4 vectors

> **“We were delighted to partner with the NZTC to help fund this important study and offer our technical and commercial expertise. The report clearly points to Scotland playing an integral role in a future pan-European hydrogen infrastructure, linking into locations in England, such as Teesside, and endorses the technical viability of an export pipeline to Europe.”**
>
> **Kellas Midstream**

8.0

Delivering the Backbone: Enabling Technology

To successfully deliver an offshore hydrogen pipeline system, several supporting and ancillary technologies are required. Within the HBL project, pipeline re-use, valves and new materials, metering, compression, blending and de-blending, storage and safety systems were all studied to understand the current technology status, emerging technologies required and remaining gaps to support the delivery of the overall pipeline system. Each area is explored further in this section.



> **"The research undertaken by NZTC and our delivery partners has not only shone a light on Scotland's significant green hydrogen production and export potential, but identifies what is needed from an investment and technology development perspective. We're harnessing innovation to ensure Scotland is a key player on the global hydrogen stage and is an integral part of helping the EU achieve its decarbonisation goals."**
>
> **Jason Paterson** Innovation Manager, Net Zero Technology Centre

8.1 Pipeline Re-Use Analysis

The options identified in the HBL project include partial re-use of existing offshore pipelines, shown in Figure 11 as the green portion of offshore pipelines.

With no existing offshore hydrogen pipelines in operation, implementing a change of use from natural gas to hydrogen would be a first. ASME B31.12 remains the governing hydrogen-specific code presenting a flexible design approach to pipeline re-use with two options:

Option A: Prescriptive Design Method: Uses a lower design factor up to 0.5 times the original design parameters and applies a material performance factor dependent on material grade and pressure. This factor is applied to penalise the use of embrittlement-sensitive high-grade steels.

Option B: Performance-Based Design Method: Identifies more stringent material performance criteria and allows for use of a design factor up to 0.72. No material performance penalisation is applied for higher-grade steels.

Within Option B, the material and testing requirements are challenging and require destructive tests to be performed to qualify existing pipelines. This includes fracture mechanics test data at a minimum of 1-mile intervals. Such tests would require the cutting of weld samples and rectification welding of replacement linepipe. There are significant costs and risks associated with cutting into a pipeline, particularly offshore, in terms of engineering, installation, and commissioning. Based on the published test reports, even modern high-grade pipelines showed mixed results in meeting Option B requirements. It therefore seems unlikely that existing natural gas pipelines will be able to meet such limitations. Consequently,the reduced stress operation under Option A looks to be the most realistic re-use case.

CASE STUDY

Of those pipelines relevant to the HBL project, data was gathered on the SIRGE and CATS lines. A desktop assessment was completed to determine their suitability for repurposing in line with the ASME options outlined above. In both cases, SIRGE and CATS would be able to meet the design factor requirements set out within the options. However, current studies can only apply Option A criteria, requiring further tests to validate Option B.

Integrity is one of the essential pillars of the safe operation of the pipeline. An accurate history of pipeline utilisation is essential in establishing a baseline condition for the repurposing study. Considering the track record of both SIRGE and CATS pipelines, it can be reasonably assumed that both pipelines are in good condition.

Pipeline	Option A (barg)	Option B (barg)
SIRGE	82.0 ✓	152.2 ✓
CATS	96.6 ✓	179.3 ✓

Table 2: SIRGE and CATS pipeline re-use assessment

Next Steps

The following criteria and their impact on re-use should be explored further: expansion, on-bottom roughness, collapse, allowable bending stress, lateral stability, buckling, fatigue, dropped objects, and trawl impact.

Undertake testing on representative portions of pipeline to determine their suitability for hydrogen service.

Undertake further research into fatigue in re-used pipelines for hydrogen service in order to bridge the substantial knowledge gap in this area.

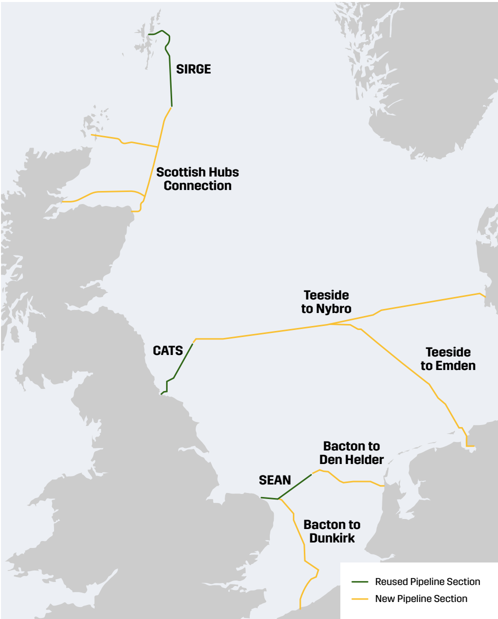


Figure 11: Pipeline re-use analysis

8.2 Valves and New Materials

To support the safe and efficient operation of a hydrogen pipeline, robust valves and complementary materials are required.

FutureGrid, a project being undertaken by the National Grid, is currently working to collate data about valve types and valve materials throughout the UK in anticipation of a change to hydrogen or a hydrogen-blend service. Early data indicated ball valves are most prevalent, with exact percentages to be published when available.

The work undertaken in the HBL study determined that current valves, including ball valves, operational in natural gas infrastructure, are suitable for hydrogen gas, provided they currently demonstrate good integrity. However, valves currently in natural gas service that demonstrate leaks, will likely leak hydrogen at a greater rate of up to three times volumetrically, with wear on the valve seals creating the highest risk point for leakage.

There are no significant signs of incompatibility of current valve materials with hydrogen gas transport.

CASE STUDY

Innovative designs related to hydrogen transport focus mainly on eliminating fugitive leaks and the use of new materials and coatings, such as elastomers. New valve technologies focus on overcoming leaks by reducing the stress concentration on the stem or by removing the stem altogether.

One technology being developed by Actuation Lab, in collaboration with the National Manufacturing Institute Scotland (NMIS) and the University of Strathclyde, looks to prevent hydrogen leaking from valves by developing a new valve mechanism, the Dragonfly valve.

The Dragonfly valve is being developed with operating torque requirements low enough to allow magnetic couplings to be used to provide non-contact, maintenance-free torque transmission into the valve body. This completely eliminates the valve stem and any associated leak paths.

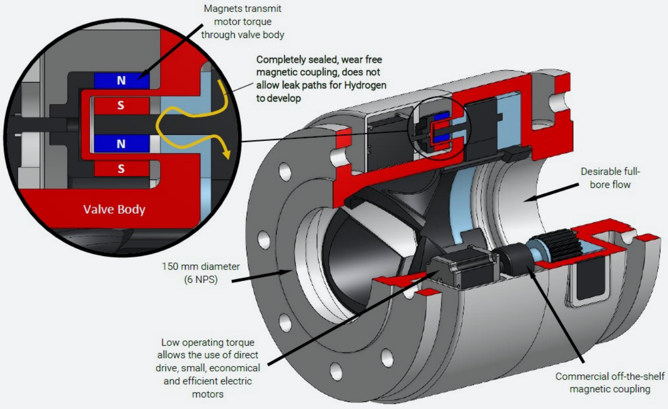


Figure 12: Dragonfly Valvet

Although magnetic couplings are an established technology used within pumps, there is a knowledge gap around how to design magnetic couplings for use with valves, an application that is typically higher pressure, yet lower RPM than existing pump applications. In addition, for hydrogen service, these coupling designs must use materials that do not suffer from hydrogen embrittlement.

Next Steps

Work with industry is required to fill gaps in standards and in the qualification and testing requirements for valves in hydrogen gas transport service.

While the current standards and regulations address hydrogen-specific damage mechanisms, the guidance for material selection, qualification and testing methodology is not established.

8.3 Metering Systems

Several types of metering systems can be used for hydrogen or hydrogen blends, with many existing designs suitable for this service. These include Coriolis, differential pressure, clamp on ultrasound, thermal mass and turbine types.

It is also possible to re-use meters from natural gas systems for non-fiscal hydrogen applications such as general flow management and monitoring where the uncertainty tolerance is reasonable. It is not recommended however to use repurposed meters in fiscal applications due to the potential calibration uncertainty.

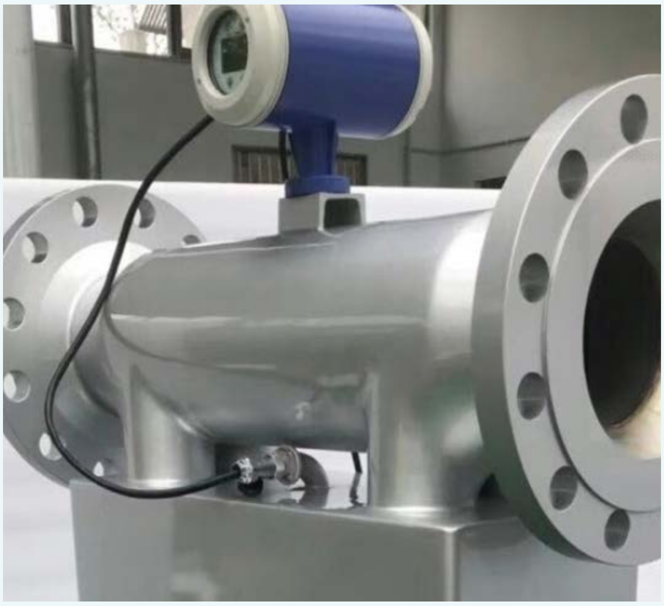


Figure 13: TUV sud pipeline coriolis meter

CASE STUDY

The EURAMET Meterology for Hydrogen Vehicles 2 (MetroHyVe) Joint Research project, a consortium consisting of NEL, METAS and CESAME EXADEBIT, has been studying the use of existing Coriolis flow meter designs for hydrogen service.

METROLOGY for HYDROGEN VEHICLES 2

Coriolis flow meters are based on the principle of Coriolis forces which are present when translational and rotational movement occurs simultaneously. The meters consist of flow tubes that are vibrated at their natural frequency with electrical pick offs at the inlet and outlet measuring any shift. When flow is applied, the Coriolis forces produce a “twisting” in the tubes resulting in differentials in inlet and outlet measurements. By measuring these “twists”, a mass flow rate can be calculated.

Their project used an air nitrogen mix for the initial testing, highlighting the requirement for hydrogen to be available for innovation and technology development across the UK. Tests showed errors within the +/- 1% range, which was subsequenlty confirmed in deployment conditions with hydrogen useage in a hydrogen refuelling station. This project will support implementing procedures and processes for hydrogen flowmeters, with additional scaled up testing required for the size of flowmeters appropriate for the HBL.

Next Steps

Although it is theoretically possible to use both existing flow meter designs for hydrogen service, further experimental testing is required with hydrogen as a test medium to confirm the operational limits of the meters. This will also support cost and performance analysis to ensure the most cost effective solutions are being deployed across the HBL project.

8.4 Compression Systems

A key component of a hydrogen transport system is compression. Understanding existing compressor design and its applicability to large scale hydrogen transport will be essential in the delivery of the HBL.

Compressors operate based on volume, resulting in a considerably higher compression horsepower requirement to move comparable quantities of energy in the form of hydrogen when compared to a natural gas system. For centrifugal compressor systems, this results in a blade tip speed three times that observed in natural gas service. As a result, the overall practicality and costs associated with using compressors designed for natural gas for hydrogen, is considered unviable.

At present, reciprocating compressors are the most commonly recommended for hydrogen transport. However, current reciprocating compressors are costly, are subject to excessive wear, have poor reliability, and often use lubricants that can contaminate the hydrogen. Despite these challenges, many thousands of reciprocating hydrogen compressors are in reliable service in refineries and petrochemical plants worldwide.

Research is currently under way to minimise moving parts and to address wear through new designs (centrifugal, linear, guided rotor, and electrochemical) and improved compressor materials. Examples of emerging technologies include turbo centrifugal compressors being developed by Siemens, which look to overcome tip speed challenges and electrochemical compression systems which are high pressure, compact designs with no moving parts.

CASE STUDY

Elliot Group, an established designer, manufacturer and service provider for hydrogen industrial compressors, is developing an integrated centrifugal compressor system specifically for hydrogen systems. Their Flex-Op prototype is comprised of three to four individual centrifugal compressors arranged around a single multi-pinion gearbox improving the head, flow, reliability and operational flexibility capabilities of existing hydrogen compressors.

The integrated design, with three to four casings, allows up to forty impeller stages to fit into a footprint that traditionally only fits up to ten. Originally designed for high-pressure ratio and high-flow compression, it has enough flexibility to allow individual compressors to either run in series or in parallel, or both.

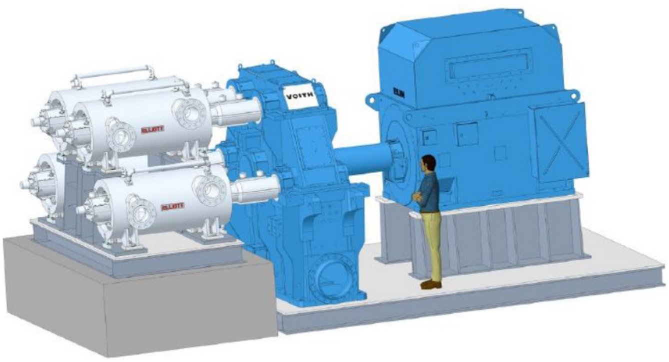


Figure 14: Flex Opp arrangement

Next Steps

Emerging technologies, such as turbo, electrochemical and compact centrifugal design, could have a tangible impact on the delivery of the HBL. Ongoing project works should support the development of technology in this area.

In parallel, industry standards for offshore deployment of hydrogen compressors are required.

8.5 Blending and De-Blending

Injecting a percentage of hydrogen into an existing operational natural gas network is described as blending, with studies ongoing to address operational and technology challenges for a variety of hydrogen blend percentages. The most advanced of the study work considers 20% hydrogen blend owing to the suitability of existing infrastructure to be operated at this level without impacting on end users.

With initiatives such as HyDeploy, HyNet and FutureGrid ongoing, blending hydrogen into the existing gas distribution network is relatively well understood and the pilot trials conducted to date have developed a strong evidence base. Work is ongoing within the scopes mentioned to provide insight into large scale blending solutions.

CASE STUDY

Global industrial gas and chemical company Linde has partnered with Evonik to develop HISELECT, the world's first full-scale plant to separate hydrogen from natural gas streams. The facility in Dormagen, Germany, utilises Evonik's membrane technology coupled with PSA to produce high purity hydrogen from a natural gas pipeline containing a blend of hydrogen.

De-blending hydrogen, effectively removing the hydrogen gas from the natural gas blend, however, is less well defined as the user supply and demand is not apparent. As a result, the technologies that support this are mostly in their infancy and on a small scale. There are however two large scale technologies available in this area; pressure swing adsorption (PSA) and cryogenic separation.

The blended feed gas contains between 5% and 60% hydrogen. The membranes extract hydrogen from the blended streams, achieving up to 90% concentration. PSA technology is then applied to achieve a purity of hydrogen up to 99.9999%.

Next Steps

Blending technologies are reasonably well understood, and although deblending technology development is still needed across the sector, given the HBL pipeline will transport 100% hydrogen, it is not a technology required to deliver this project.

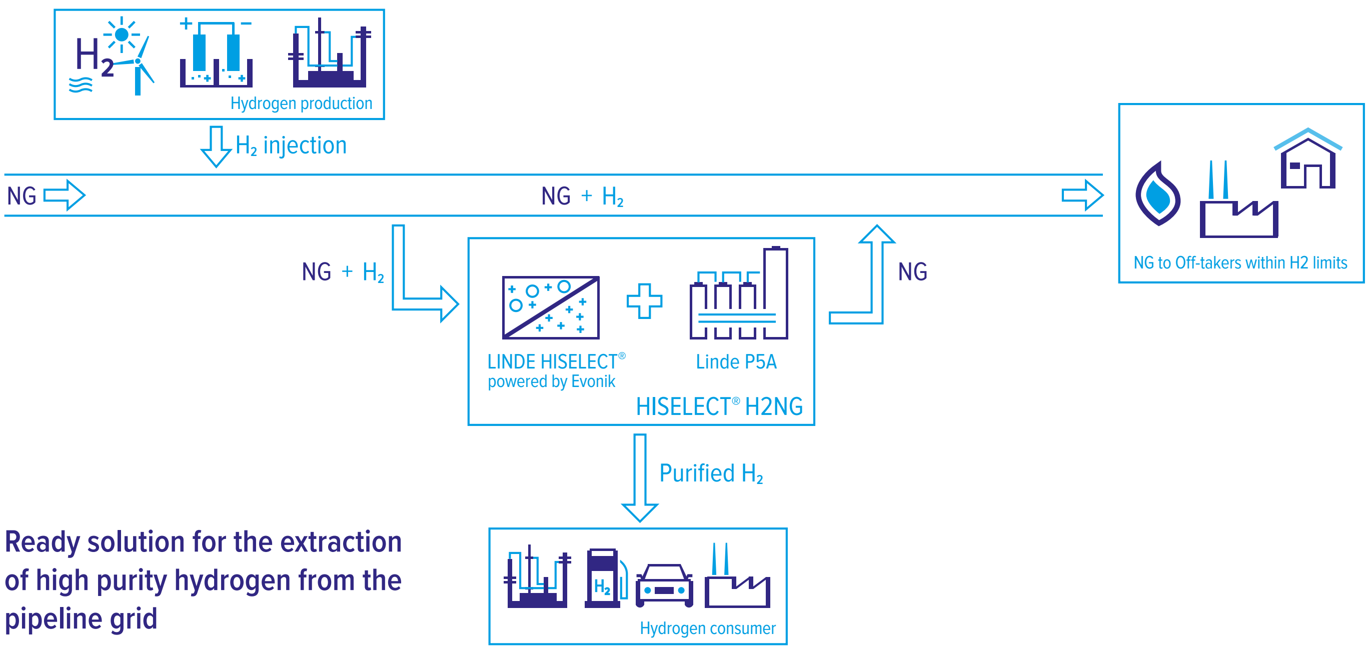


Figure 15: Hydrogen deblending process Linde

8.6 Storage Solutions

Storage solutions which provide operational (hours), buffer (weeks) and inter-seasonal (months) flexibility will be essential in the delivery of a hydrogen transport system. Aside from the technologies needed to deliver the HBL project, the integrated storage required throughout Scotland and the UK to deliver a future hydrogen energy system remains one of the key challenges in the nascent market.

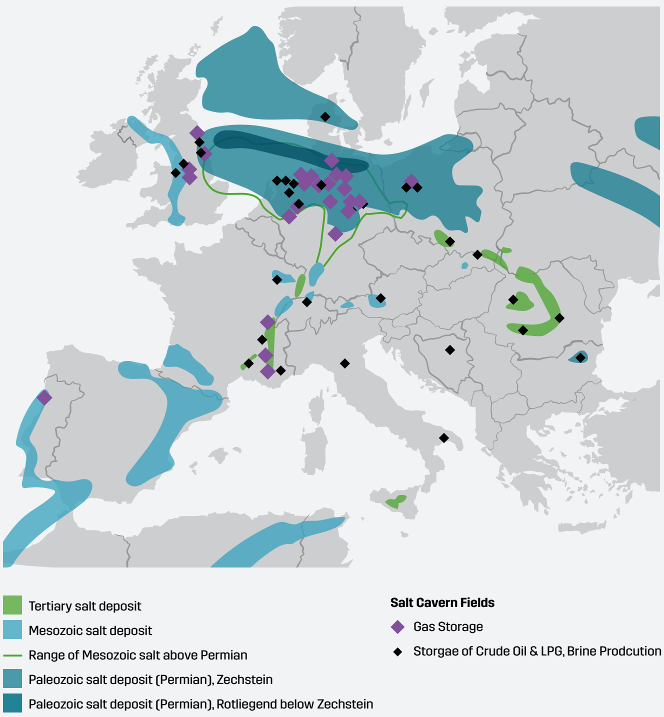
Inter-seasonal storage options exist in subsurface infrastructure such as salt caverns and depleted oil and gas fields, with the UK boasting the third largest salt cavern storage potential across Europe.

The storage of natural gas in such geological structures is a well understood and established process, and hydrogen storage in salt caverns is ongoing within the UK as part of the Teeside cluster development.

The learnings from early salt cavern storage trials will be critical to addressing the overall integrated storage challenge, with research ongoing into the suitability of different geological formations for hydrogen storage. The sites will require assessment from both environmental impact and land use planning perspectives, but this is likely to be under existing legislation.

Repurposed offshore pipelines, cryogenic liquid storage tanks and subsea storage tanks all have the potential to provide scalable solutions that could address small scale inter-seasonal or larger buffer storage. Cryogenic storage is well understood and operational globally, however both repurposed pipeline and subsea storage tank solutions are in their infancy, considered to be Technology Readiness Level* (TRL) 4 and 3 respectively.

Other technologies which could store hydrogen as an alternative vector, such as liquid organic hydrogen carriers or Hydralite, could be used to store hydrogen within existing infrastructure such as oil storage tanks and tend to have favourable handling and storage characteristics. However, these tend to come with an overall energy penalty given the energy vector conversion.



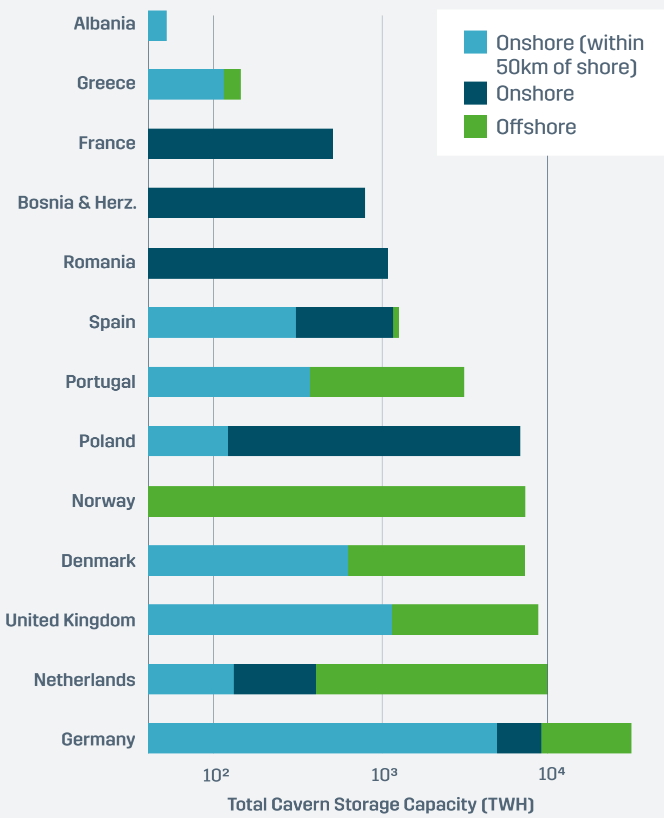


Figure 16: Onshore and Offshore storage

*TRLs were originally developed by NASA as a method of measuring the maturity of space exploration technology.

8.7 Storage Solutions

Storage Technology	Scale	TRL Level
Cryo-compressed storage	Small	5
Liquid ammonia storage	Small Medium	9
Line pack	Medium	3
Subsea storage tanks	Medium	3
Liquid hydrogen shipping tankers	Small Medium	9
Carbon 280 Hydrylite	Small	6
GKN Hydrogen	Small	9
Liquid Organic Hydrogen Carrier (LOHC) Hydrogenious	Small	9
Salt caverns	Large	9
Repurposing existing oil and gas storage tanks	Large	4
Liquid hydrogen storage	Large	9
Depleted oil and gas reservoirs	Large	4
Repurposing offshore pipelines	Large	4
Subsea salt caverns	Large	4
HyDUS	Small	3
HYSTORSYS	Small	9
HEOS	Small	5/6

CASE STUDY

The Rough gas field located 29 km offshore from Easington in the southern North Sea is being considered for hydrogen storage. Rough is operated by Centrica Storage Ltd and ceased natural gas storage in 2017, before being brought back online in 2022.

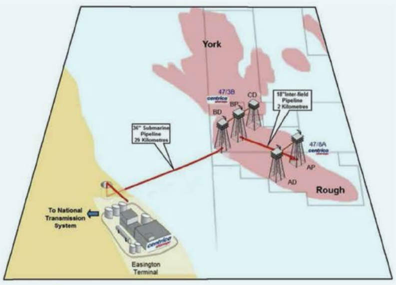
It is estimated that the Rough field can provide up 10TWh of hydrogen storage to be brought online in phases of ~3TWh making it the largest storage facility in the UK. Centrica's long-term aim is to turn the Rough gas field into the largest long duration energy storage facility in Europe, capable of storing both natural gas and hydrogen.

Next Steps

Currently, there are no large utility scale cryogenic liquid hydrogen storage tanks available. The largest cryogenic hydrogen storage tank has a capacity of 40,000 m³. However, only the design phase has been completed and the tank has not been constructed. Additional technology development is required in this area to accelerate the deployment of this critical technology.

Although it was not considered in the initial scope of work, purification technologies post-storage remains a gap. This is particularly important when geological storage solutions are considered as impurities and are likely to be introduced into the system.

Continue to investigate the feasibility of using existing pipelines for storage.



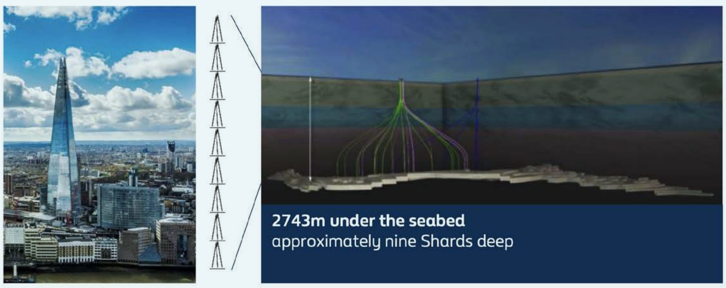


Figure 17: Technology Readiness Level across assessed technologies

Source: www.centrica.com/media/5790/rough-investor-and-analyst-presentation.pdf

8.8 Safety System Analysis

Safe operation and maintenance of gas transmission systems is inherent in today's energy system across Scotland and throughout the UK. Although operated currently with natural gas, many of the principles for a hydrogen system are similar. Through an operational safety comparison with natural gas, we can identify key safety areas for additional study for hydrogen service.

Hydrogen is a colourless, odourless and tasteless gas. It has a low density of 0.09 kg/m3 compared to 0.72 kg/m3 for natural gas at standard temperature and pressure. This results in the volumetric energy density of hydrogen being approximately a third of that of natural gas.

When considering transportation via pipeline, this means that higher volumetric flow rates would be required to ensure the same calorific value of gas being delivered.

Additionally, methane is only flammable within a range of 5 – 15% volume, whereas hydrogen's flammable range sits between 4 – 75.6% volume. The ignition energy required to create a hydrogen flame is also lower than that of methane, 0.02 mJ compared to 0.29 mJ. Hydrogen gas also has a greater capacity for leakage owing to its smaller molecule size.

These properties generally result in a higher risk level for hydrogen than that of natural gas. However, as with natural gas, safe operation can be achieved with appropriate mitigation factors.

Owing to the hydrogen properties outlined above, integrity management is essential in an operational hydrogen transmission system. The key challenges to maintain this for hydrogen pipelines are: selection of an appropriate inline inspection regime, expected gas velocities and tool selection appropriate for the level of feature detection required.

Leak detection systems typically deployed for natural gas pipelines should be adequate in detecting hydrogen leaks along the route of the pipeline, except for leak detection tools that work on the principle of detecting low temperatures as a leak. Such tools wouldn't work for hydrogen pipelines as there is no Joule Thompson cooling effect associated with hydrogen gas.

Additionally, Magnetic Flux tools, commonly employed for natural gas pipelines, are expected to be suitable for use on hydrogen pipelines, for the purposes of confirming any internal or external wall loss owing to corrosion. Tools are being developed to manage the high flow velocities in hydrogen and control the speed of the tool.

Hydrogen gas can cause a significant deterioration to the mechanical properties of metals. This effect is referred to as hydrogen embrittlement leading to an increase in fatigue crack growth rates and a decrease in fracture toughness under static loading. This risk can be managed by using low-grade steels, low stress design and hardness testing. Alternatively, for larger high-volume gas transmission lines, codes allow the risk to be managed by using higher grade steels, high stress design, toughness testing in hydrogen, and Elasto Plastic Fracture Mechanics.

CASE STUDY

At Spadeadam, DNV is carrying out vital research work, in collaboration with National Grid as part of the Future Grip project, to understand how to operate gas networks under 100% hydrogen conditions.

A purpose-built, one kilometer polyethylene MicroGrid, which is representative of a typical gas distribution network, is being used to test operational gas procedures to understand any changes which need to be made to convert the network to 100% hydrogen.

Next Steps

Despite there being technologies and systems suitable for hydrogen transmission systems, the equipment needs to be qualified and certified for hydrogen service. Further work is needed in this area to provide standards for these systems and regulations to qualify them too.

9.0

Conclusions

Phase one of the Hydrogen Backbone Link has established a credible marine pipeline export route to mainland Europe, a first critical step in ensuring that Scottish green hydrogen plays a significant role in Northwest Europe's decarbonisation journey.

By the mid 2030s Scotland could meet up to 10% of Europe's predicted hydrogen import demand via the backbone link and through continued investment in additional infrastructure, maintain this proportion of EU exports beyond 2045, meeting the Scottish Government's green export scenario ambition.

There are no insurmountable technical barriers to pipeline transport of hydrogen, however investment is needed to rapidly develop, reduce cost and scale up solutions. Investment in testing and qualification for existing systems is required to ensure compatibility with gaseous hydrogen as well as rapid development in the next generation of compressors.

An aligned international effort on research and development into storage solutions at operational, buffer and interseasonal scales is essential to ensure sufficient capacity is available to deliver security of supply.

The transition is happening at pace. For Scotland to capitalise on this opportunity, rapid acceleration in technology development and infrastructure deployment is needed to propel the hydrogen backbone link from vision to reality within the next decade.

> **"The Scottish Government recognises the importance of developing hydrogen pipelines to unlock Scotland's export potential. We want to work collaboratively with partners across Europe to advance infrastructure which ensures security of supply in Europe and positions the North Sea as a centre for low-cost hydrogen production. The Scottish Government supports the Hydrogen Backbone Link project because it gives valuable insight into the viability of repurposing or developing new pipelines. This can help us understand any barriers where government support is required to unlock investment and realise Scotland's export potential."**
>
> **Neil Gray** Scottish Government Energy Secretary

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