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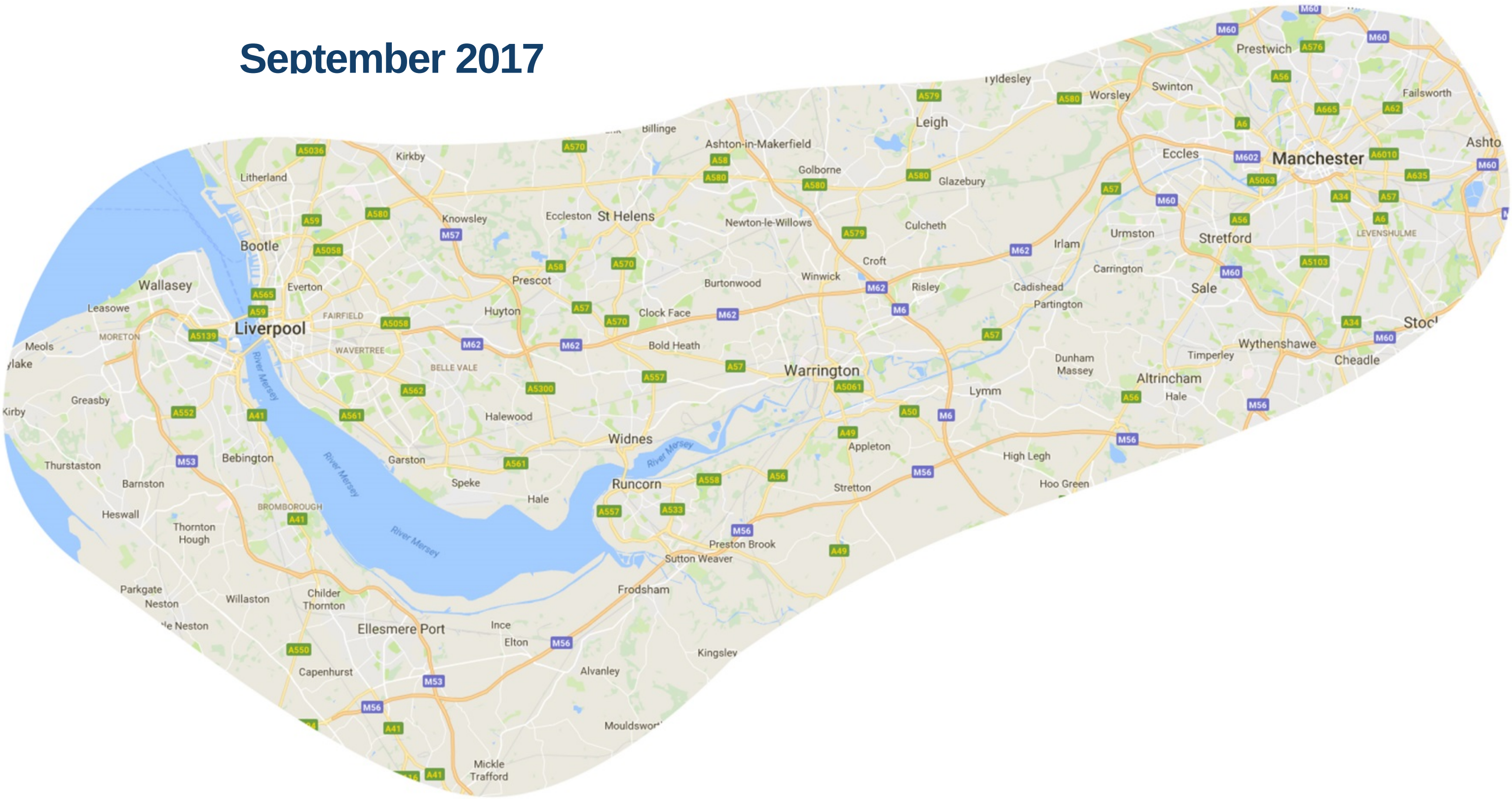
Liverpool - Manchester Hydrogen Hub

Energy to Fuel the Northern Power House

A study for Peel Environmental

September 2017

PEEL



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Foreword

This report has been commissioned by Peel Environmental to provide a high level assessment of the Hydrogen supply and demand chain required for a possible NW Hydrogen Hub. The report is based on reference material from existing literature and dialogue with stakeholders. To demonstrate the range of the hydrogen supply chain the report assesses three scenarios, this has enabled us to model the anticipated hydrogen supply chain with varying levels of political interventions. Each scenario has been modelled to assess the demand for hydrogen, storage and CCS infrastructure required to service each scenario.

The study will be used to assess the potential benefits of a transition to hydrogen economy. Whilst this is a high-level study the aim is to set out a vision of the NW Hydrogen hub as a critical component in the decarbonisation of space heating and transport to support the UK government in delivering the 2050 emissions reduction targets

This study has been prepared using publicly available documentation and data sources, such as published documents and internet sources. All documents and data utilised in preparing this report are referenced in this document. We have not sought to independently verify these data sources, unless explicitly stated in this report.

Executive Summary

The Climate Change Act 2008 established the world's first legally binding climate change target. The UK government aims to reduce greenhouse gas emissions by at least 80% (from the 1990 baseline) by 2050. Moving to a more energy efficient, low-carbon economy will help us meet this target. It will also help the UK become less reliant on imported fossil fuels and less exposed to higher energy prices in the future. It is widely accepted that this will be achieved through a variety of measures which will entail a diverse future energy mix, encompassing renewable power generation, nuclear and decarbonisation of the UK's gas grid and transport sectors. In short there won't be one single "silver bullet"

Recent reports have highlighted that converting the UK's gas grid to hydrogen could play a pivotal role in meeting our emissions reduction target. It is widely accepted that this option is the "least regrets", lowest cost decarbonisation option for the UK's energy consumption.

The use of hydrogen gas as a fuel to power the UK economy isn't a new concept. Prior to the discovery of reserves of Natural Gas in the UK continental shelf, town gas (so called because it was manufactured locally) had provided heat, lighting and power for industry for over 150 years. Town gas consisted of up to 50% hydrogen, along with a blend of other gases including methane and carbon monoxide. In the 1960's and 70's the country underwent a mass conversion from Town gas to North Sea Gas, demonstrating that UK wide conversion is both feasible and achievable.

Due to the regions underlying salt geology, access to Carbon Capture and Storage (CCS) in the East Irish Sea and petrochemical industry expertise, the Manchester – Liverpool corridor has the potential to play a significant role in providing a solution to the United Kingdom's energy trilemma. Furthermore, decarbonisation of the UK's gas network could provide a catalyst for improving air quality. The government's recent announcement, banning the sales of petrol and diesel vehicles from 2040 will mean a radical shift in transport. Hydrogen powered Fuel Cell Electric Vehicles (FCEV) are a proven zero carbon emissions technology. They deliver major benefits over battery powered electric vehicles, in that the user experience is very similar to today's transport options in terms of range and refuelling time. FCEV's are fuelled in a similar manner to today's vehicles and don't need to have their batteries charge from an electric supply point. The single biggest obstacle to the onset of hydrogen vehicles is the lack of a nationwide hydrogen fuelling network, which would be addressed should the UK gas grid be converted to hydrogen gas.

Hydrogen buses are currently in operation in a number of cities around the UK. Should hydrogen be developed on a regional basis it provides an opportunity for local authority vehicles, public transport, taxis and local business fleets to reduce their carbon footprint and have a marked impact on improving air quality and reducing premature deaths in the regions towns and cities. The onset of a UK wide or regional hydrogen economy could provide the catalyst for wide spread roll out of hydrogen fuelled public transport.

The development of a hydrogen pipeline linking the cities of Liverpool and Manchester will facilitate the development of refuelling points in the region. Details of the proposed Liverpool-Manchester Hydrogen Cluster and a hydrogen pipeline connecting the cities are set out in the Cadent Gas Report[1].

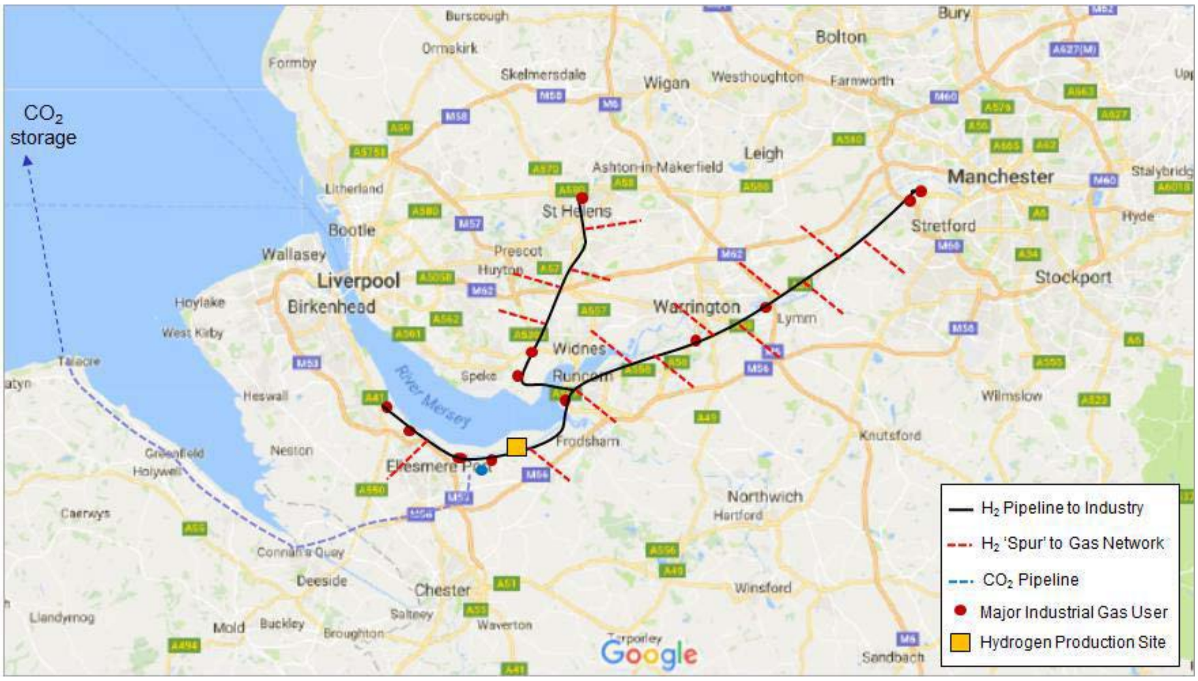

Figure 1 Cadent proposed hydrogen pipeline

Air pollutants, primarily from transport are responsible for approximately 3,500 premature deaths per year in the NW region. Displacement of petrol and diesel in transport by hydrogen has the potential to save thousands of deaths and save the NHS billions of pounds each year.

In addition to the CO2 emissions removed from the earth's atmosphere and the improvements to local air quality, the establishment of a hydrogen hub would provide substantial benefits to the region's economy. The additional regional GVA generated would be up to £3.5 billion by 2035 and in excess of £13 billion by 2050, dependant upon which scenario was implemented. Furthermore, thousands of temporary and permanent jobs would be created within the region. Further details for each scenario are summarised in the table below.

	Cumulative GVA to 2050	Peak Jobs to 2050
Slow Progression	£ 50 Million	70
NW Regional Hydrogen Hub	£1.6 Billion	2,400
UK Wide Hydrogen Economy	£13 Billion	14,000

[1] Cadent Gas Liverpool-Manchester-Hydrogen-Cluster

The UK's gas network operators and government are currently undertaking a range of projects to demonstrate the technical feasibility, costs and relative safety of converting the gas network to either 100% hydrogen or a methane / hydrogen blend, with a view to informing the government's future energy policy. It is imperative that there is support from politicians and industry to position the Manchester – Liverpool region at the forefront of this rapidly developing decarbonisation technology. The development of a North West Hydrogen Hub base at Protos with a new hydrogen pipeline network is an opportunity to achieve significant energy decarbonisation and be the first exemplar project incorporating industrial heat conversion to hydrogen and introducing significant benefits in air quality through hydrogen as a transportation fuel. It will be a significant step in helping fuel the Northern Powerhouse compliant with Government decarbonising and road transport objectives whilst delivering major economic benefits to the region.

1 Introduction

The UK government is faced with an energy trilemma; providing low cost energy to an ever increasing population, ensuring security of supply, whilst meeting the 2050 emissions reduction targets.

Natural gas is the lowest carbon dioxide emitter of all fossil fuels, producing approximately 180mg/KWh CO_2 equivalent when combusted. Natural gas plays a vital role in the UK economy, with more than 80% of heating, 36% of industry and over 40% of all power generation fuelled by Natural Gas[2]. Currently Natural Gas isn't widely used in the transport sector, however advancement in CNG (Compressed Natural Gas) technology has seen an uptake in CNG fuelled HGV's. Recent studies carried out by the UK gas industry have identified the potential to decarbonise the gas sector through conversion of the UK's existing gas network to hydrogen. Northern Gas Networks H21 Leeds City Gate Report[3] demonstrates the feasibility of converting a major city to 100% hydrogen, with a vision for UK wide deployment. More recently Cadent Gas has published the Liverpool – Manchester Hydrogen Cluster study, outlining a project to partially convert the NW gas distribution network to a methane / hydrogen blend to service industry and domestic consumption.

In the transport sector, petrol and diesel will need to be displaced by an alternative decarbonised energy source. The government's recent policy announcement, banning the sale of petrol and diesel cars from 2040 will lead to a transformational change in the transport sector. Electric vehicles will become the most common form of new vehicle sales. EV's require an electric power source, this can be supplied by either batteries, or a hydrogen fuel cell. As the transport sector accounts for over 40% of the UK's energy consumption, replacing petrol and diesel would require a substantial increase in the amount of "green" electricity currently generated. It is widely accepted that, should "green" electric be utilised to displace petrol and diesel the additional power required would mean the transmission and distribution networks would require enormous invest in reinforcement to meet the additional demand.

By contrast, the UK's gas grid is designed and sized for the 1 in 20 year peak 6 minute load. This means that the gas distribution networks have plenty of unused capacity, more than would be required to meet the additional energy transportation requirements to displace petrol and diesel.

Hydrogen is the most common element in the universe, making up three quarters of the mass of the universe. Hydrogen is essential for life and is present in nearly all the molecules in all living things. Hydrogen also occurs in the stars and powers the universe through proto – proton reaction and carbon – nitrogen cycle. However, hydrogen gas in its pure form isn't naturally occurring on earth and currently can only be produced in sufficient quantities as a replacement for Natural Gas through either methane reforming (Steam Methane Reforming / Auto Thermal Reforming) or from water using electrolysis (however "green" hydrogen requires a non – carbon electricity sources).

Unlike Natural Gas, when pure Hydrogen is mixed with oxygen and combusted it produces no harmful CO_2 emissions, only heat and water. When used in transport to power electric fuel cell vehicles, hydrogen produces no harmful NO_x or particulates emissions, known to be responsible for up to 40,000 deaths in the UK and costing the NHS £16b each year[4]. The transport sector accounts for

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[2] www.gov.uk/government/uploads/system/uploads/attachment_data/file/632523/Chapter_4.pdf

[3] Northern Gas Networks H21Leeds City Gate Report

[4] www.nhs.uk/news/2016/02February/Pages/Air-pollution-kills-40000-a-year-in-the-UK-says-report.aspx

40% of total energy consumption and 25% of all the UK's CO_2 emissions. Hydrogen has the potential to dramatically reduce greenhouse gas emissions and improve air quality in our towns and cities, helping to reduce premature deaths in the UK.

This report builds on the previous studies undertaken by the gas industry and explores the potential for the development of a Hydrogen fuelled economy in the Liverpool – Manchester region to fuel the Northern Power House concept. To help understand what a future NW hydrogen economy could look like we have developed three credible scenarios. In each scenario, we examine the political drivers and policy decisions required to provide the promote a hydrogen economy in the North West, the demand for hydrogen generated in each scenario, where in the region Hydrogen production could be situated and the benefits in greenhouse gas emissions reduction, air quality improvements, job creation and GVA for the Liverpool – Manchester corridor.

2 Scenario Characteristics

2.1 Scenario Selection

To enable an understanding of how a future NW Hydrogen economy may look we have developed three scenario models;

1. Slow Progression
2. NW Regional Hydrogen Hub
3. UK Wide Hydrogen Economy

These scenarios have been developed following an initial assessment of the factors most likely to make each scenario a future reality. Having identified the set of factors we considered to be most influential, we constructed three distinct scenarios with the objectives of ensuring that:

1. We identify the political and socioeconomic conditions required to act as a catalyst for each scenario;
2. The demand for Hydrogen in each scenario, subdivided by demand type;
3. The Hydrogen chain infrastructure required to support each scenario; and
4. The regional benefits each scenario could deliver.

The sections below provide a brief overview of each of the scenarios, contrasting them in terms of political and policy drivers, supply and demand characteristics and regional benefits.

2.2 Slow Progression

In this scenario, we assume there are no regional or national policy decisions to stimulate the onset of a Hydrogen economy. The impact of the lack of political direction means there is very little uptake of Hydrogen across any of the end use vectors. Corporate social and environmental policy is the only driver in the conversion of industrial processes from Natural Gas to Hydrogen.

In this scenario decarbonisation of UK energy consumption would need to be delivered from electricity generated through renewable sources of power generation, including nuclear. This would require an enormous increase in power generation from low carbon sources. Furthermore, the UK electric transmission and distribution networks would require extensive reinforcement and investment to meet the additional demand for space heating, industry and transport. Households would have to endure a transformational change in their existing heating systems from Natural Gas to all electric. As the government recently announced the complete ban on petrol and diesel vehicles by 2040, all cars, vans public transport and HGV's would need to switch to battery powered or hybrid petrol/electric vehicles. A recent report by KPMG, 2050 Energy Scenarios[5] commissioned by the Energy Network Association (ENA) identifies an all electric future as the most expensive decarbonisation option with the greatest impact on consumers.

[5] KPMG 2050 Energy Scenarios July 2016

2.3 NW Regional Hydrogen Hub

In this scenario, we have used the Cadent Gas, Liverpool – Manchester Hydrogen Cluster Report[6] as the basis for the hydrogen supply chain model.

We assume there is explicit local governmental support for the development of a NW Hydrogen hub to fuel a regional Hydrogen economy. Furthermore, we anticipate a level of devolution of powers and fiscal budgets from central government to the Liverpool and Manchester regional authorities, with set targets for reducing CO_2 emissions to support the UK government in achieving the Climate Change Act 2008 targets. Regional "carrot and stick" initiatives could be required to stimulate the transition from natural gas consumption to hydrogen. Hydrogen would be produced at large scale within the region using established SMR / ATR technologies, with small scale production from constrained renewable power generation utilising electrolysis and other green and brown hydrogen technologies. CO_2 would be permanently sequestrated in depleted oil and gas fields under the East Irish Sea. Compatible industries would convert to hydrogen, surplus hydrogen would be blended into either the local gas distribution network or the National Transmission System (NTS), negating the need for storage to service peaks and troughs in demand.

The wide availability of hydrogen would enable the use of hydrogen in transport, displacing petrol and diesel in targeted fleets. Local Authorities, public transport, taxis and large utility fleets would switch to hydrogen fuel cell vehicles and hybrid hydrogen/petrol cars, improving air quality in the regions towns and cities.

This scenario has no direct impact on domestic gas consumers and will therefore have the highest levels of public acceptability. Cadent Gas has recently published their technical report, The Liverpool Manchester Hydrogen Cluster, which demonstrates the feasibility of this scenario at an affordable cost.

Due to the fact that hydrogen only carries approximately one third of the energy by volume of natural gas, the net amount of CO_2 abated from domestic heating is substantially less than in our third scenario, however this option could be scaled to partially meet the demand of a UK wide hydrogen economy. Following the government policy announcement banning the sale of new petrol and diesel cars after 2040, as the hydrogen production generated by this scenario could be used to displace petrol and diesel fuels in the transport sector we believe this scenario represents a "least regrets" option and could greatly enhance the Northern Power House concept.

2.4 UK Wide Hydrogen Economy

In this scenario, we have used the Northern Gas Networks, H21 Leeds City Gate Report[7] as the basis for modelling the hydrogen supply chain. Due to the NW regions geological potential for salt cavity storage and access to CCS in the East Irish Sea, in this scenario we envisage the NW region would be one of a small number of areas in the UK suitable for the development of large scale hydrogen production to supply a UK wide hydrogen economy

This scenario would require central government to set a clear future energy policy, with hydrogen playing a central role in decarbonising domestic heating and industry. Furthermore, UK wide availability of hydrogen through the existing gas distribution networks would allow a nationwide

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6 Cadent Gas Liverpool-Manchester-Hydrogen-Cluster

7 Northern Gas Networks H21Leeds City Gate Report

network of hydrogen fuelling stations to be established, enabling the uptake in hydrogen Fuel Cell Electric Vehicles (FCEV). Domestic consumers could install hydrogen fuelled micro CHP (Combined Heat and Power) appliances, reducing the reliance on centralised power generation to support decarbonisation of the power sector.

This scenario would mean a level of disruption to consumers during the conversion process, however this would be substantially less disruption than would be experienced in conversion to all electric heating. NGN's H21 Leeds City Gate Report sets out a vision for incremental roll out of a UK wide hydrogen conversion programme, KPMG's report, 2050 Energy Scenarios[8] concludes this option to be the lowest cost option for meeting the 2008 Climate Change targets.

2.5 Scenario Comparison

The graphs in the following section compare the impact of each scenario across a range assessment criterion. The "Baseline" is the current documented hydrogen demand associated with CF Fertilisers[9]. This is included since it illustrates scale of current hydrogen production and is also included in the CO_2 emissions abatement if it is connected to CCS. A more detailed analysis is presented in subsequent sections.

2.5.1 Hydrogen Demand

Fig 2.1 shows the calculated hydrogen demand for each of the 3 scenarios and compares them to the current documented hydrogen generation and CF Fertilisers. Scenarios 2 and 3 will both require large scale hydrogen generation capacity

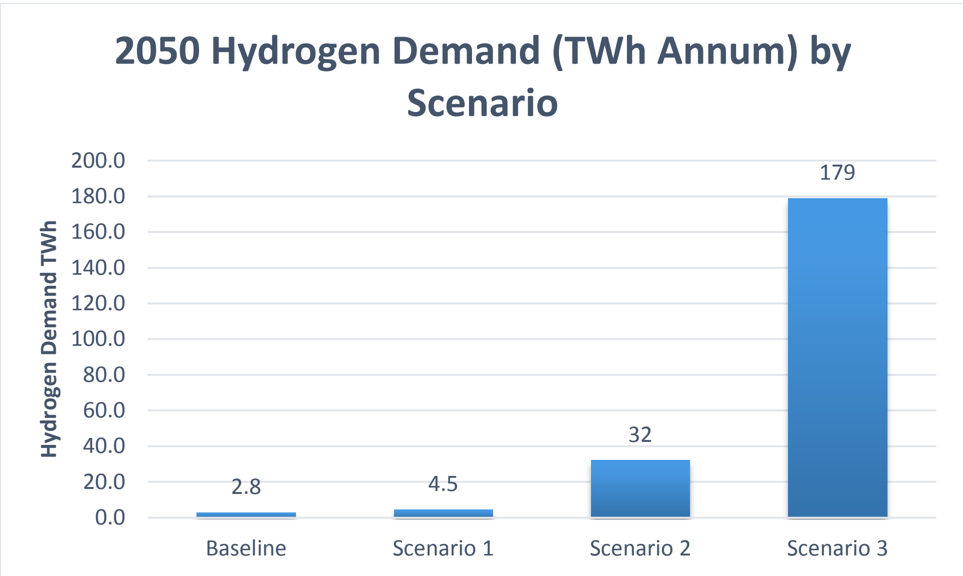


Fig 2.1 Hydrogen Demand by Scenario

8 www.energynetworks.org/assets/files/gas/futures/KPMG%20Future%20of%20Gas%20Main%20report%20plus%20appendices%20FINAL.pdf

9 Cadent Gas Liverpool-Manchester-Hydrogen-Cluster

Fig 2.2 splits the demand by sector for each scenario. The conversion of domestic heating and the additional demand for hydrogen in transport make up the majority of the increase in total demand from Scenario 2. .

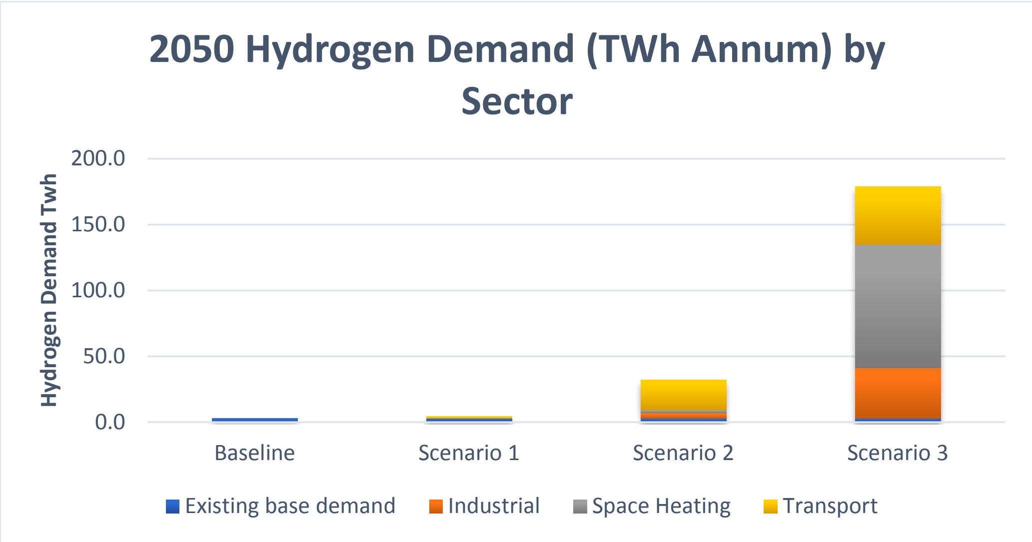


Fig 2.2 Hydrogen demand by Scenario and Sector

2.5.2 CO_2 Abated

In Fig 2.3 CO_2 abatement by scenario in the Liverpool – Manchester area for different years is presented. As above this clearly demonstrates the scale of the difference between the 3 scenarios.

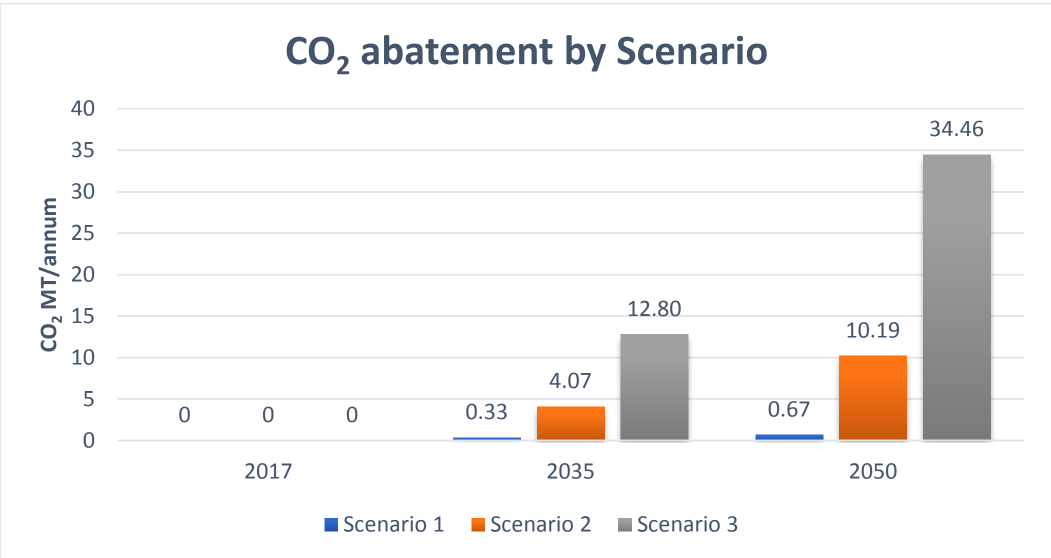


Fig 2.3 CO_2 abatement by Scenario

2.5.3 Air Quality

The following charts calculate the anticipated improvements in air quality in the L – M region from the forecast reduction in road transport emissions in each scenario.

NO_x and particulates are widely accepted as the emissions from the transport sector, most damaging to health. In the following section we plot the anticipated reductions in NO_x and PM_{10} particulates attributable to the uptake of hydrogen vehicles in each scenario.

Scenario 1 assumes that there is a small uptake of hydrogen vehicles, driven by the governments 2040 transport policy, but this is very limited by the restricted availability of hydrogen.

Scenario 2 assumes that, with local government policy initiatives and support for the L – M hydrogen cluster, hydrogen is readily available within the region with local authority vehicles, public transport and industry fleets converting to hydrogen. We anticipate a greater uptake of FCEV's in this scenario, however wider uptake is hampered by the lack of a wider national network of hydrogen fuelling stations

Scenario 3 assumes that central government energy policy means there is a national hydrogen network, meaning that hydrogen fuelled electric vehicles are the predominant mode of transport across the UK.

The following diagrams demonstrate the level of improvements in the regions air quality attributable to the contribution of hydrogen road transport in each scenario.

There are further opportunities for hydrogen to play a significant role in improving air quality across further transport vectors, such as rail and shipping however we consider there currently isn't sufficient information to allow us to model these impacts within this report.

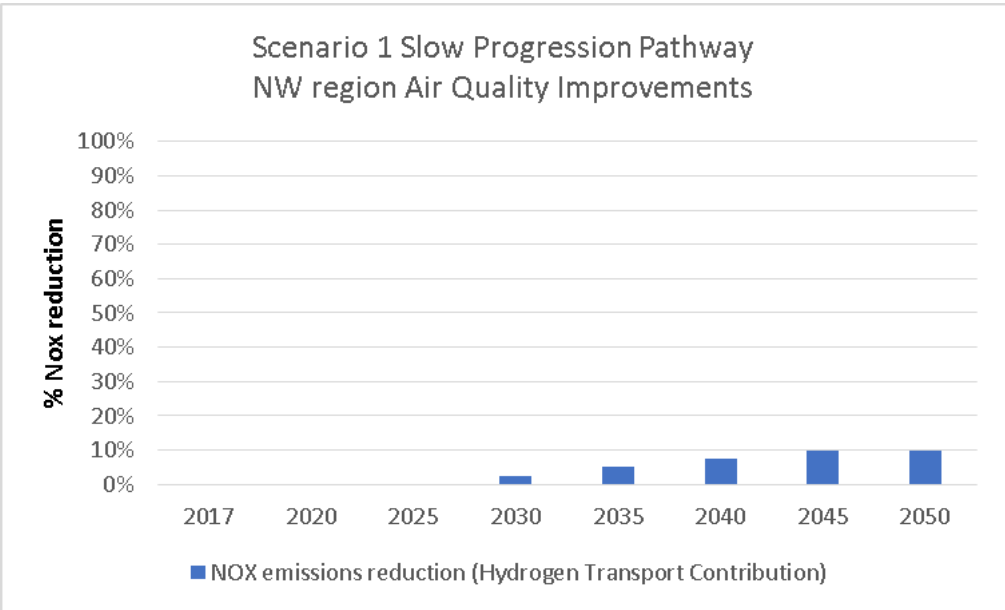


Fig 2.4 Scenario 1 NOx improvements

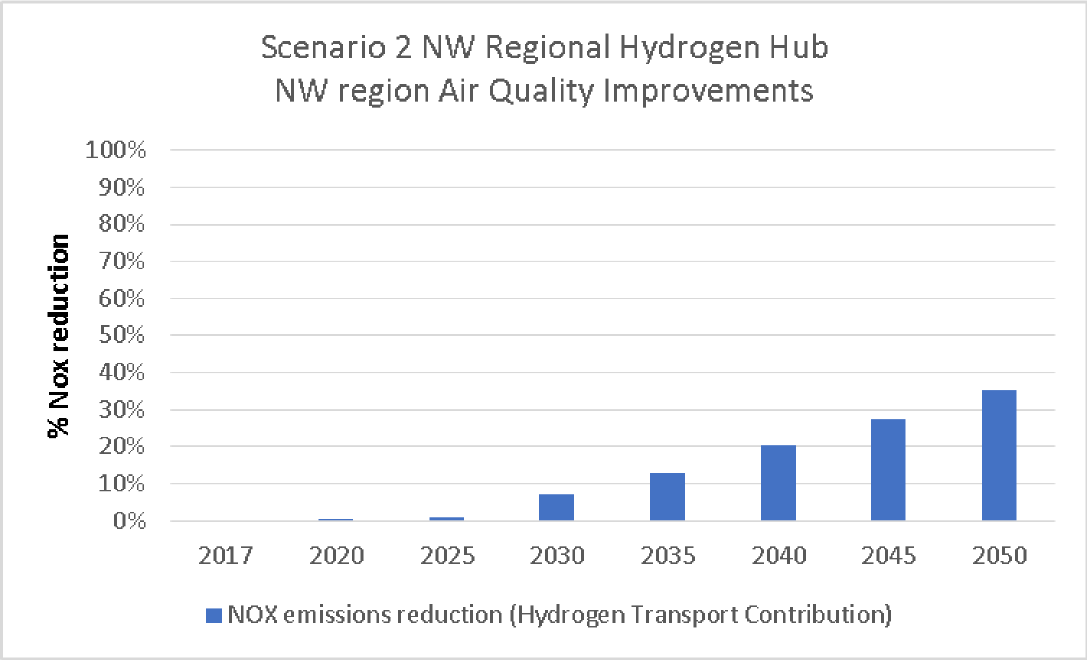


Fig 2.5 Scenario 2 NOx improvements

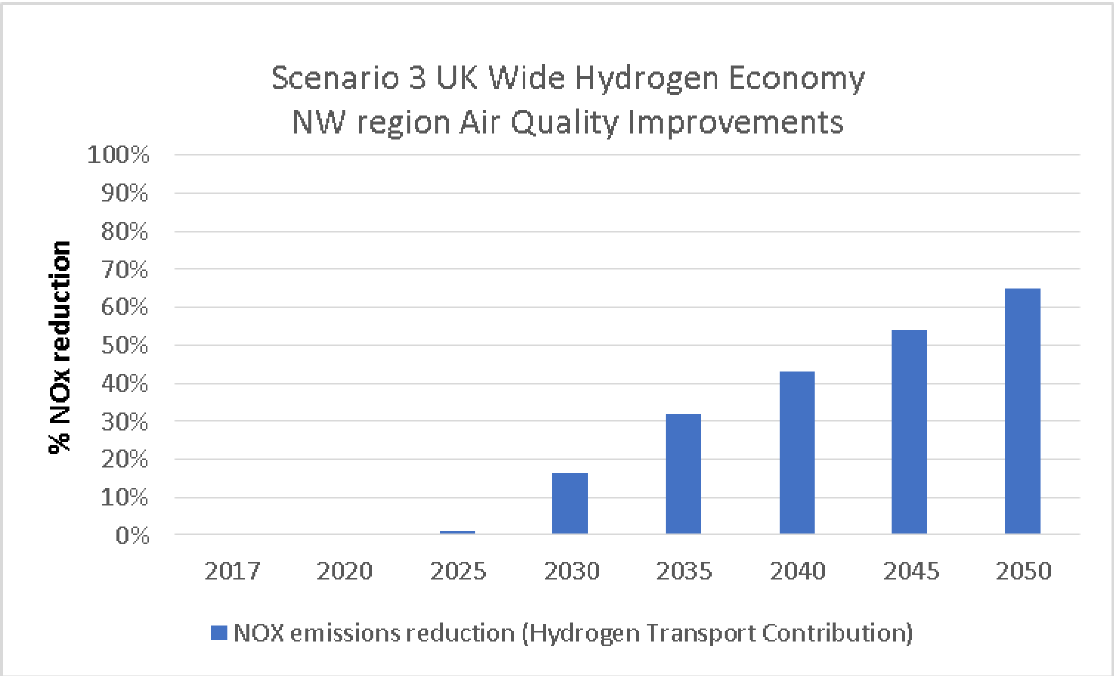


Fig 2.6 Scenario 3 NOx improvements

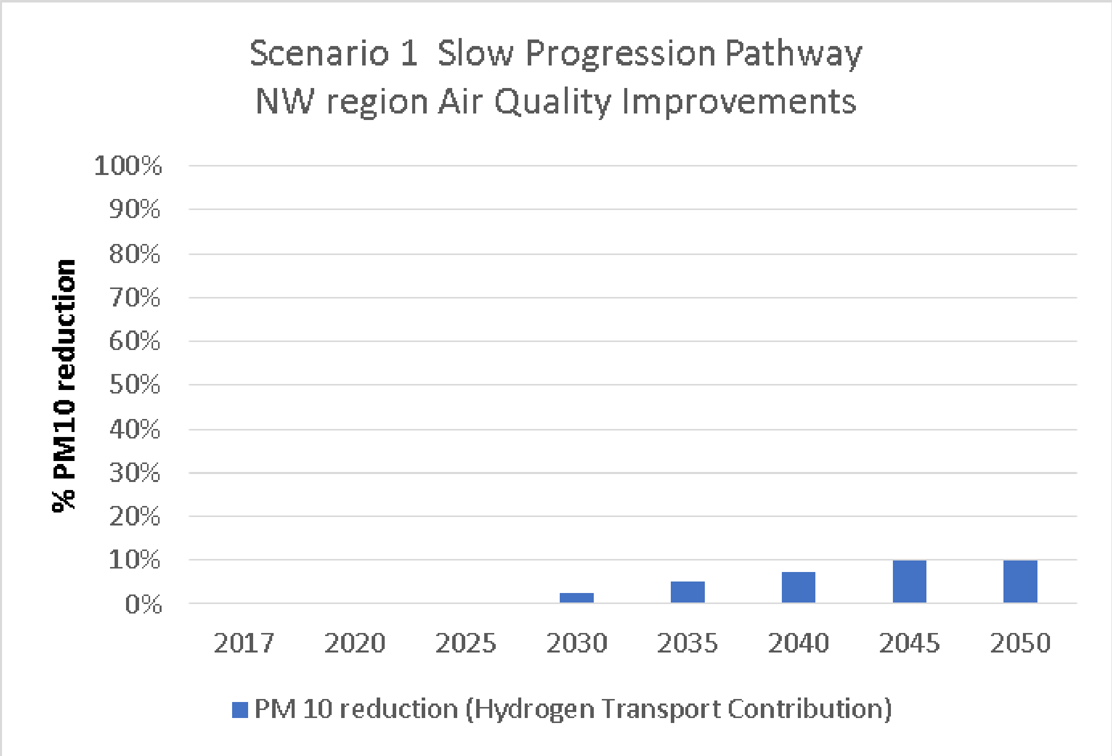


Fig 2.7 Scenario 1 PM_{10} improvements

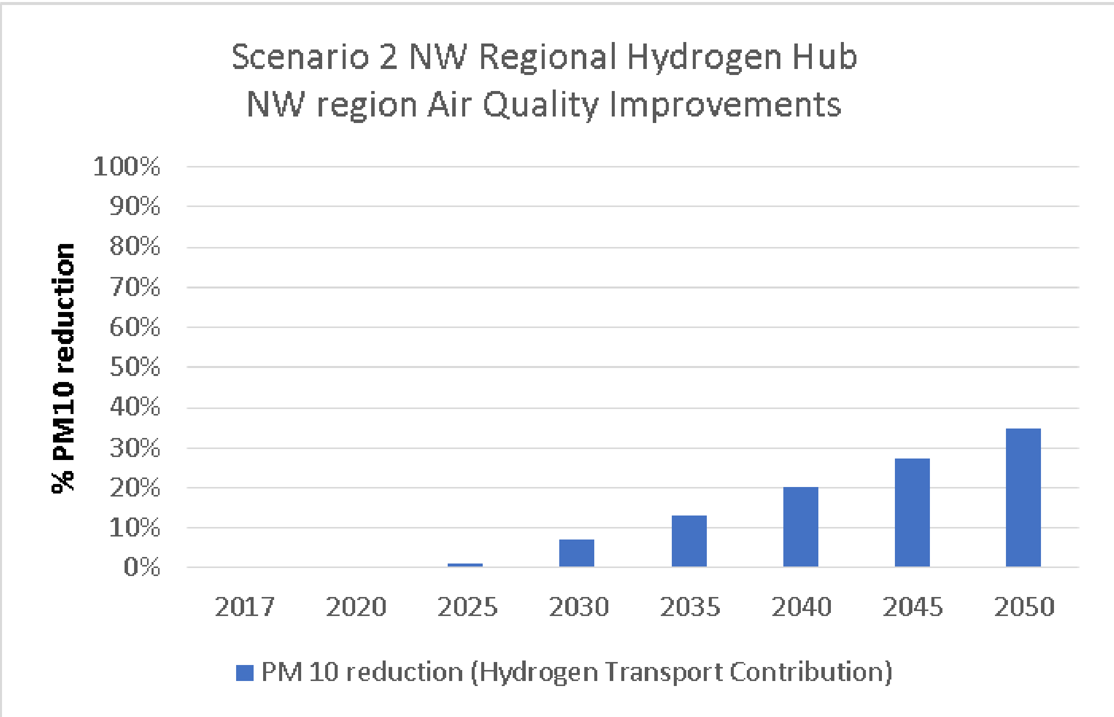


Fig 2.8 Scenario 2 PM_{10} improvements

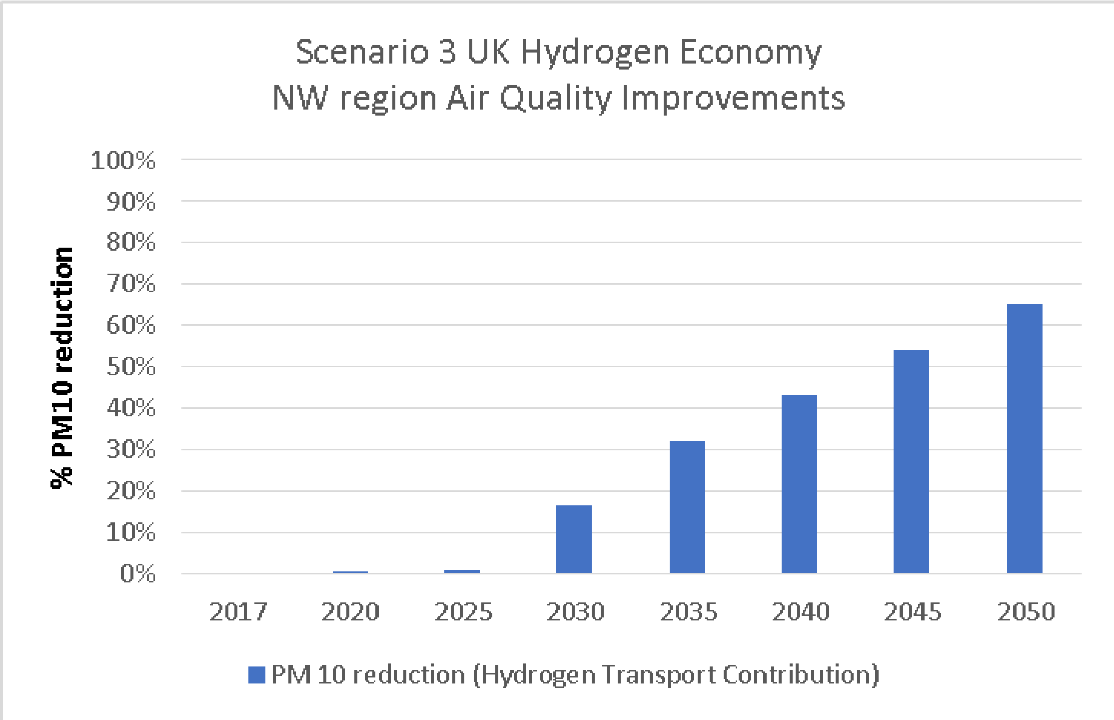


Fig 2.9 Scenario 3 PM_{10} improvements

3 Hydrogen Supply Chain

3.1 Overview

The diagram below details the components of the hydrogen supply chain;

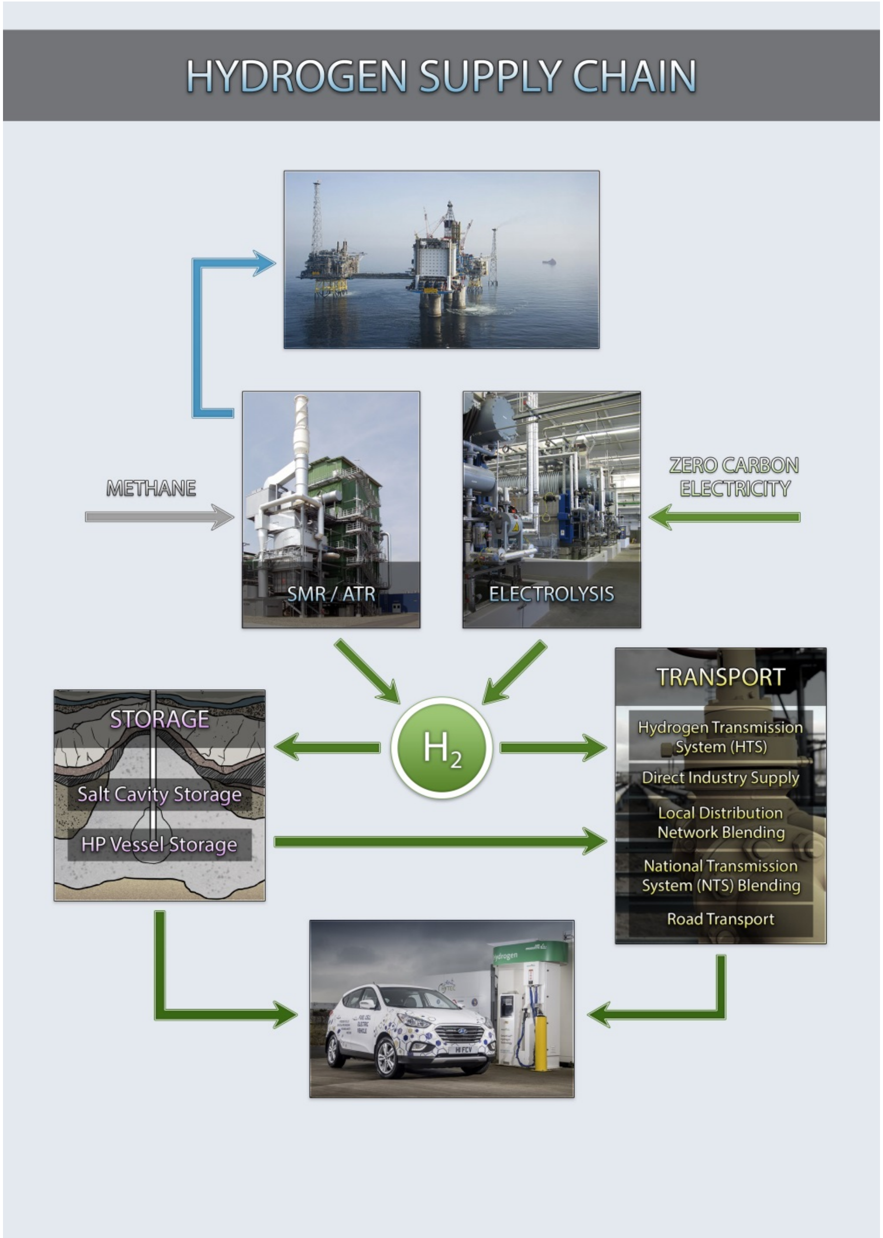


Fig 3.1 Hydrogen supply chain overview

Steam Methane Reforming

Steam Methane Reformers (SMR) convert natural gas to hydrogen gas in a three-stage process. First natural gas is heated with steam under pressure in the presence of a catalyst to produce carbon monoxide, hydrogen and a small amount of carbon dioxide. Next, in a water gas shift reaction, the carbon monoxide and steam again in the presence of a catalyst are reacted to produce carbon dioxide and more hydrogen. Finally, in a pressure swing adsorption phase carbon dioxide and any impurities are removed from the gas stream to leave hydrogen as the product gas.

Steam methane reforming is the most widely used process for the generation of hydrogen. It produces a high purity hydrogen stream but is energy intensive due to the large amount of heat required.

The chemical reaction for SMR is $CH_4 + H_2O \rightarrow CO + 3\ H_2$

The water gas shift reaction is $CO + H_2O \rightarrow CO_2 + H_2$

The combined reaction is therefore $CH_4 + 2\ H_2O \rightarrow CO_2 + 4\ H_2$

Typically, the SMR technology is suited to individual units being around 150 - 250MW, however 500MW single train units are already in operation.

Fig 3.2 Steam Methane Reformer (Linde Group)

Technology	Steam Methane Reforming (SMR)
Endothermic reaction	30 – 50 bar (DeltaHf + 206 kj/mol
Developed	1940s
Process	Fired heater with catalyst tubes inside
Single line capacity	150,000 – 200,000 Nm3/h
Efficiency	70%
CO2 capture	Up to 90%

Table 3.1 SMR Technical Summary

Auto Thermal Reforming

Auto Thermal Reforming (ATR) is an alternative to SMR. As opposed to SMR, ATR is an exothermic process. In ATR air or oxygen is added to a natural gas steam mix to produce hydrogen, carbon monoxide and water.

A second stage water gas shift reaction is then carried out as in SMR to produce carbon dioxide and hydrogen.

There is no requirement for a pressure swing adsorption stage as the hydrogen from the second stage will be at >98% purity which is acceptable for power generation or heating.

The chemical reaction for ATR is $CH_4 + ½ O_2 \rightarrow CO + 2 H_2$

The water gas shift reaction is $CO + H_2O \rightarrow CO_2 + H_2$

The combined reaction is therefore $CH_4 + ½ O_2 + H_2O \rightarrow CO_2 + 3 H_2$

If oxygen is used rather than air there is no requirement to remove nitrogen from the hydrogen stream.

ATR is best suited to large installations with single train capacity of 1-2 GW. This is 4-5 times the size of a typical SMR.

Fig 3.3 Auto Thermal Reformer – Air Liquide

Technology	Auto Thermal Reforming (ATR)
Exothermic reaction	40-80 bar (DeltaHf - 35 kj/mol
Developed	1940s
Process	Air or oxygen added to natural gas – steam mix
Single line capacity	400,000 – 600,000 Nm^3/h
Efficiency	75-80%
CO_2 capture	95%

Table 3.2 ATR Technical Summary

Electrolysis

Electrolysis can be used to generate hydrogen. In electrolysis, hydrogen is produced by passing electric current through water to produce hydrogen and oxygen. There are a number of different types of electrolysis cell with proton exchange membrane cells (PEM) and Alkaline being the most widely available commercially. If the power source for the electrolysis is from a renewable source such as wind or solar then the energy produced can be stored as hydrogen and then used when required.

Equation – $2H_2O$ + electrical energy -> $2H_2 + O_2$

In alkaline electrolysis, a reaction takes place in a solution of water and 30% potassium hydroxide. When voltage is applied between the electrodes reactions occur at the cathode and anode. At the cathode electrons are taken to give OH^- and H_2 molecules. The OH^- ions then travel through electrolyte to the anode where they combine and give up electrons to produce water, electrons and O_2.

The membrane between the anode and cathode prevents hydrogen and oxygen recombining.

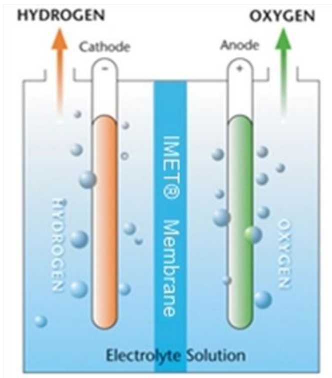


Fig 3.4 Alkaline Electrolysis (image sourced from Hydrogenics[10] webpage)

In a PEM electrolyser, an ionically conductive solid polymer is utilised. When a voltage is applied between the electrodes oxygen in the water gives up an electron at the anode to make protons, electrons and O_2. Hydrogen ions then travel through the proton conducting polymer to the cathode where they take on an electron and become H atoms which then combine to H_2.

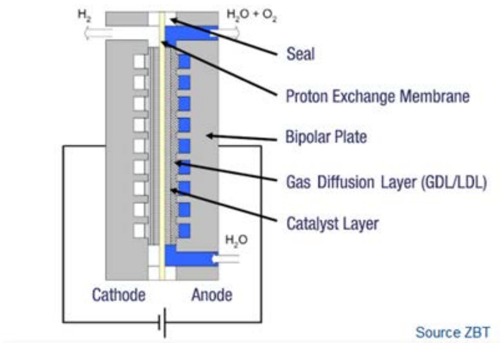


Fig 3.5 PEM Electrolysis (from Hydrogenics)

10 http://www.hydrogenics.com/technology-resources/hydrogen-technology/electrolysis/

Electrolysis is an established technology that was first developed in 1800 and is utilised in numerous applications worldwide. Electrolysers come in a variety of sizes. Historically large electrolysers up to 2.5MW scale were utilised in local hydropower for chemical production. A new wave of relatively small scale units producing up to around 200 Nm^3/h in a single unit have been developed to supply fuel cells in local networks.

Technology	Electrolysis
Power required	5.2 kWh/Nm^3 (source Hydrogenics – includes all utilities)
Developed	From 1800 commercially from 1920s
Process	Voltage applied to water
Efficiency	70% - 80%
Single line capacity	Up to 200 Nm3h for a single unit
CO2 capture	None produced

Table 3.3 Electrolysis Technical Summary

Figure 3.6 Megawatt Scale Hydrogen Production By Electrolysis

Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) is a method for capturing carbon dioxide emissions and storing them in wells in depleted oil fields. Without CCS in place any hydrogen production utilising natural gas will not have a positive impact on decarbonisation.

SMR and ATR can operate without CCS this would have the impact of concentrating the CO_2 emission to a single point source rather than at the point of use as would currently happen.

Overview of Technology

The CCS process involves capturing the emissions, conditioning the gas, transportation via pipeline onshore, transporting via pipeline offshore, injection and finally storage.

If hydrogen is generated via SMR or ATR then carbon capture and storage needs to be provided to "decarbonise" the system.

There are two likely methods of capturing carbon with SMR

1. Post combustion capture of CO_2. This would use a flue gas scrubbing column with MEA (monoethanolamide) to produce two output streams a CO_2 lean flue gas and a concentrated CO_2 stream. This would typically capture 90% of the CO_2. This is the simpler of the 2 methods. The CO_2 rich MEA liquid is then heated with steam from the SMR to drive off the CO_2. The CO_2 can then be dehydrated, compressed and sent onto the transport pipeline.

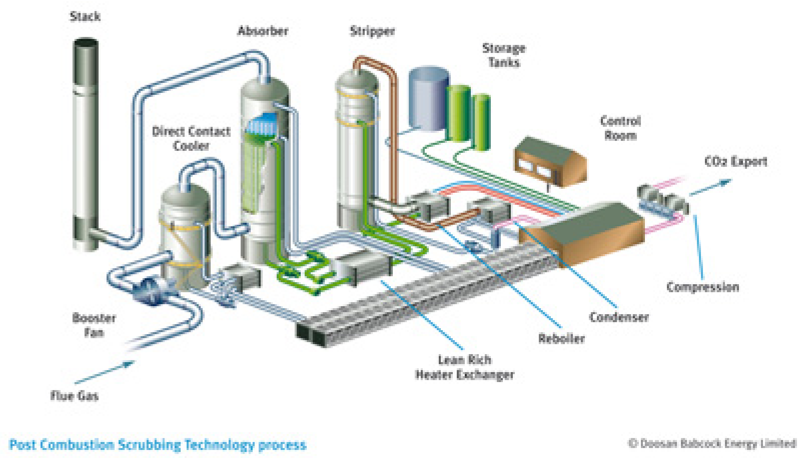


Fig 3.6 Post Combustion Carbon Capture (Doosan)

2. Capture the CO_2 within the SMR system after the water shift reaction and before the pressure swing adsorption step.

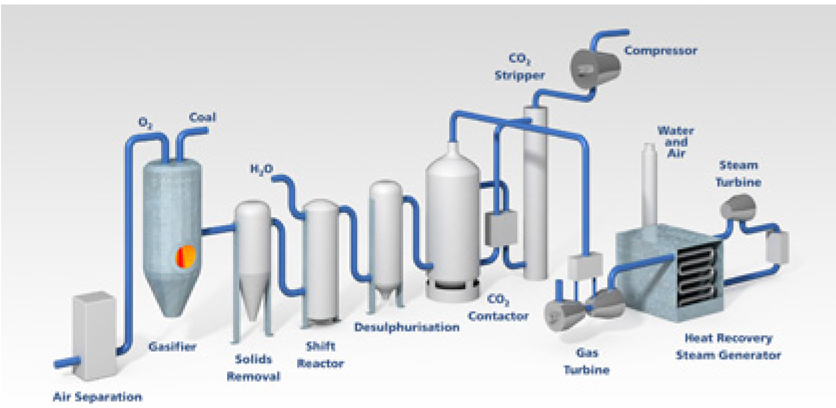


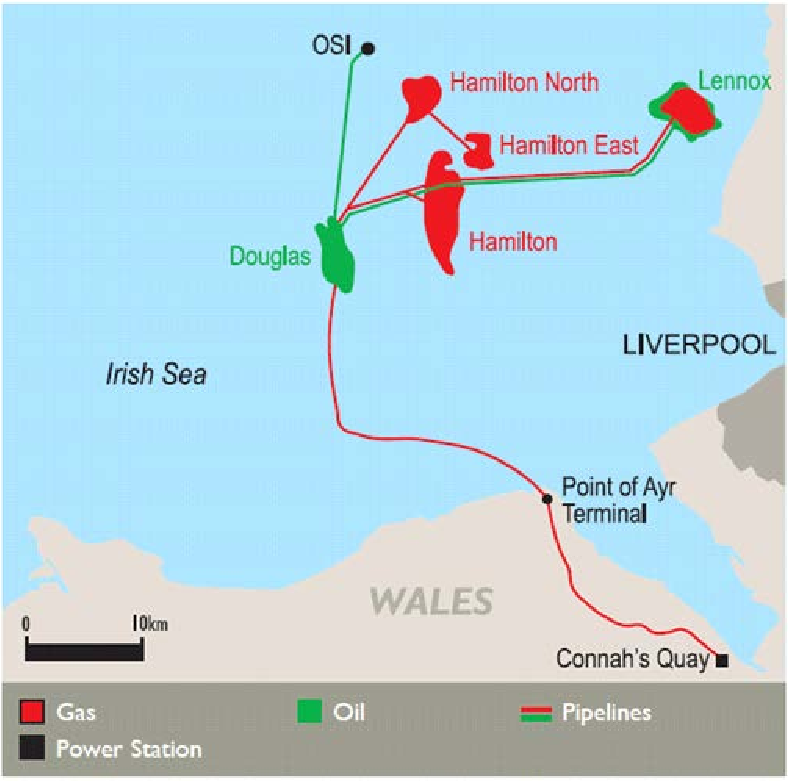
Fig 3.7 Pre Combustion Carbon Capture (Doosan)

There are no CCS projects in the UK. Funding has been withdrawn preventing projects in Peterhead and White Rose at Drax. Six CCS projects have completed Front End Engineering Design (FEED) and two others are proposed. The focus of the six projects with design is power generation with CCS and the two proposed developments are for industrial CCS at Teeside and a gasified coal project at Grangemouth in Scotland.

Pale Blue Dot in conjunction with Costain, Axis and ETI have completed a study[11] looking at five storage locations deep underground and offshore around the UK. For the North West of England storage in the East Irish Sea is a possibility in the depleted Hamilton Gas Fields which have a capacity of around 125 $MtCO_2$. This depleted gas field has a levelised unit cost for offshore transport and storage of £11/tonne storage which is the second lowest of all fields (after Endurance in the North Sea) but has a much lower lifecycle cost. This report demonstrates that Hamilton is a strong economic option for CCS.

Around 40km to the north Morecombe gas fields have a combined capacity of 1,030 $MtCO_2$. This could act as a build out area once Hamilton storage capacity is full.

In 2009 CO_2 emissions from the North West Cluster were around 12.6 $MtCO_2$ per annum. With a 90% capture rate, it would take over 100 years to exhaust the storage capacity. It should however be noted that the best location for CO_2 storage from emissions in Western Scotland, Northern Ireland, North Wales, East Ireland and South Wales may also be the East Irish Sea. With the combined CO_2 emission from these areas being 47 $MtCO_2$ per annum there would be a total of around 27 years storage if 90% of CO_2 was to be captured. Generally, storage capacity around the UK is not considered to be a problem.



Source: BHP Billiton Petroleum Operational and Financial Review 2006

Fig 3.8 Hamilton Oil and Gas Fields Plan

Outside of the UK there are 15 full scale CCS projects that have been in operation for a number of years. A further 7 projects are due to come on line by the end of 2017. Statoil have CCS at the

[11] Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource April 2016.

Sleipner field in the Norwegian North Sea, this plant has been in operation for over 10 years. In the power generation sector SaskPowers Boundary Dam facility in Canada has been in operation since 2014.

Fig 3.9 SaskPower Boundary Dam Power Station with CCS

Boundary Dam is a 115 MW power station, 1.3 million tonnes of CO_2 are captured with CO_2 emissions reduced by 90%.

Hydrogen Storage

There are 4 methods of hydrogen storage to be considered.

- High Pressure (HP) vessel storage
- Salt cavern storage
- Hydrogen Transmission System (HTS) line-pack
- Ammonia storage

High Pressure Vessels

Hydrogen can be stored as a gas in pressurised containers. In small volumes storage can be in a pressure range of 125bar to 800bar.

Transport has inherent pressure vessel storage capacity, in vehicle fuel tanks and filling stations negating the need for extensive centralised hydrogen storage.

Salt cavern storage

Salt caverns are voids created by washing rock salt out in the form of brine. The caverns are then capable of storing large volumes of gas.

Underground Gas Storage (UGS) has been operating worldwide for over 90 years and there are 630 facilities of different types in operation.

The techniques are, however, relatively new in the UK. There are only seven operational UGS facilities in the UK at:

- Rough (offshore Southern North Sea)

- Aldbrough and Hornsea (East Yorkshire)
- Hatfield Moors (Yorkshire)
- Humbly Grove (Weald)
- Holford and Hole House Farm (Cheshire)

Another 20 or so are at various stages in the planning process, but face lengthy delays (see image below)

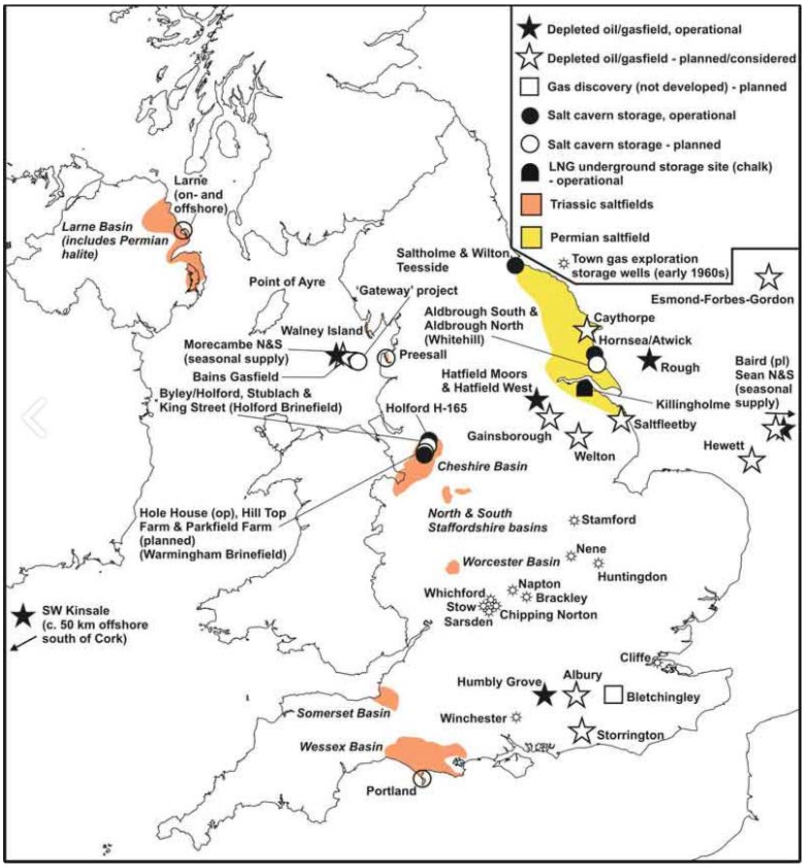


Fig 3.10 Map of Salt Cavern Stores in UK

Line-pack

Line-pack is the pressurised storage of hydrogen in the Hydrogen Transmission Network (HTS). The amount of available line-pack storage will be dictated by the length, diameter and operating pressure of the HTS.

Ammonia Storage

It is possible to store hydrogen as a liquid in ammonia. By storing the hydrogen as a liquid, it is kept at a much greater energy density than when it is stored in a gaseous form. In ammonia, hydrogen makes up 17.6% of the weight. It has a 45% higher energy density than liquid hydrogen and can be 'cracked' over a catalyst to produce hydrogen and nitrogen gas. Ammonia is one of the most widely used chemicals across the world so there is considerable expertise in the production, storage and distribution of ammonia. At publication of this study the economics of this method of storage are not fully known, although studies are currently ongoing to assess the potential for this technology,

3.2 Possible UK locations for Hydrogen Production Hubs

The Cadent Gas report, The Liverpool Manchester Hydrogen Cluster and the Northern Gas Networks, H21 Leeds City Gate report both assess suitable locations around the UK for hydrogen production hubs. The essential components for locating hydrogen production hubs are;

1. Access to a sufficient quantity of methane feedstock for hydrogen production through reforming.
2. Sufficient hydrogen storage capacity to meet demand profiles.
3. Close proximity to CCS infrastructure, with sufficient capacity to meet project CO_2 sequestration quantities.
4. A suitable industrial landscape.
5. Established petrochemical engineering knowledge and expertise.

Each of the areas assessed in the reports noted above have their own unique attributes. The Liverpool – Manchester corridor has all the pre-requisites required to develop a hydrogen production hub. The established petrochemical industry in the region would provide the specialist engineering resources required to develop a successful hydrogen production hub.

The Protos development is ideally situated to provide access to all the hydrogen chain components. The development also has access to shipping, which could be used as a transitional methodology for the storage and sequestration of CO_2 whilst storage facilities and infrastructure are being developed for the East Irish Sea basin.

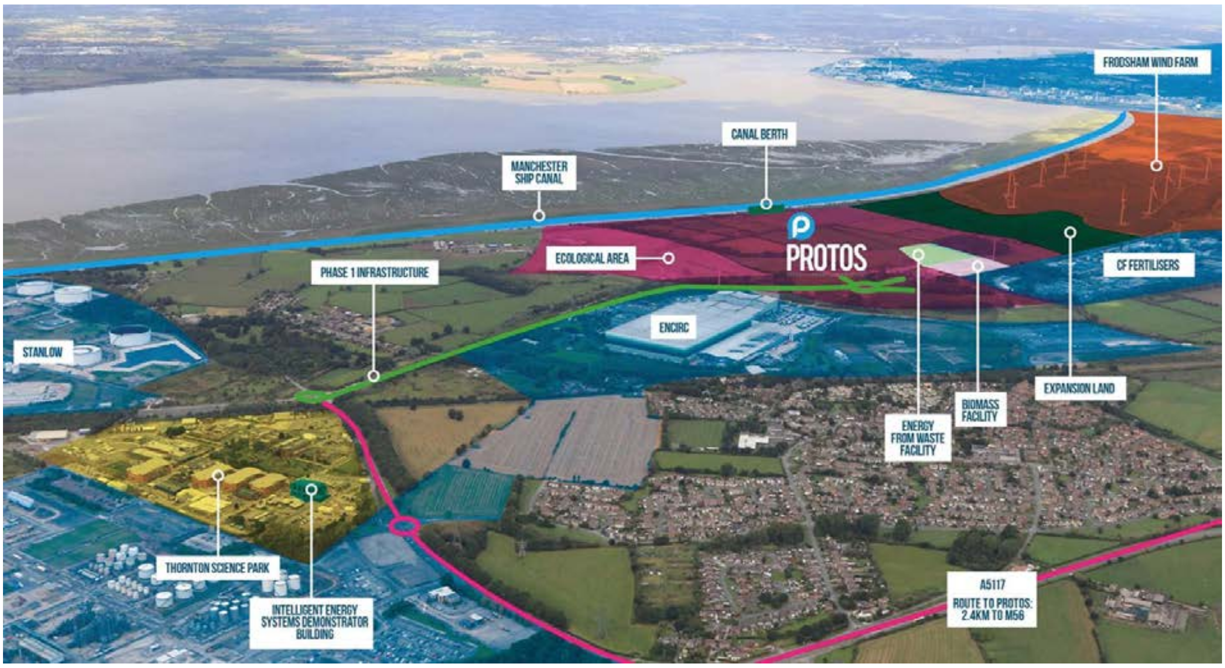
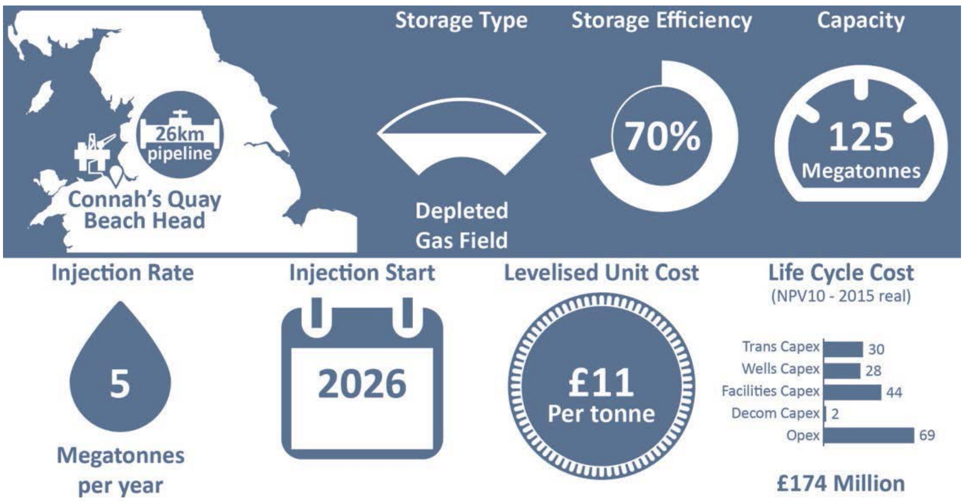


Fig 3.11 Protos Development

Fig 3.12 Thornton Energy Centre

The University of Chester's Thornton energy research centre is located in close proximity to the Protos development. Headed by Professor Joe Howe the research centre is collaborating with skills providers and business to ensure that the regions' workforce have the necessary skills required to realise and connect to the opportunities afforded by a hydrogen economy. This includes mechanisms to encourage employers to engage young people so they understand the skills and training requirements needed to progress their careers in decarbonised economy.

Access to CCS in the East Irish Sea would make the location ideal for the permanent sequestration of CO_2 produced from the methane reforming process. The Pale Blue Dot report, Progressing Development of the UKs Strategic UK CO_2 Storage Resource[12] assesses the storage capacity of the Hamilton field as 125Mt, with a levalised cost of £11 per/t CO_2 stored.



12 https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2016/04/D16-10113ETIS-WP6-Report-Publishable-Summary.pdf

Due to the regions underlying salt geology the area is rich in potential for hydrogen storage in salt cavities. Existing salt cavity storage sites in the Cheshire basin could be repurposed for hydrogen storage, with the opportunity to extend to meet project capacity for all the assessed scenarios.

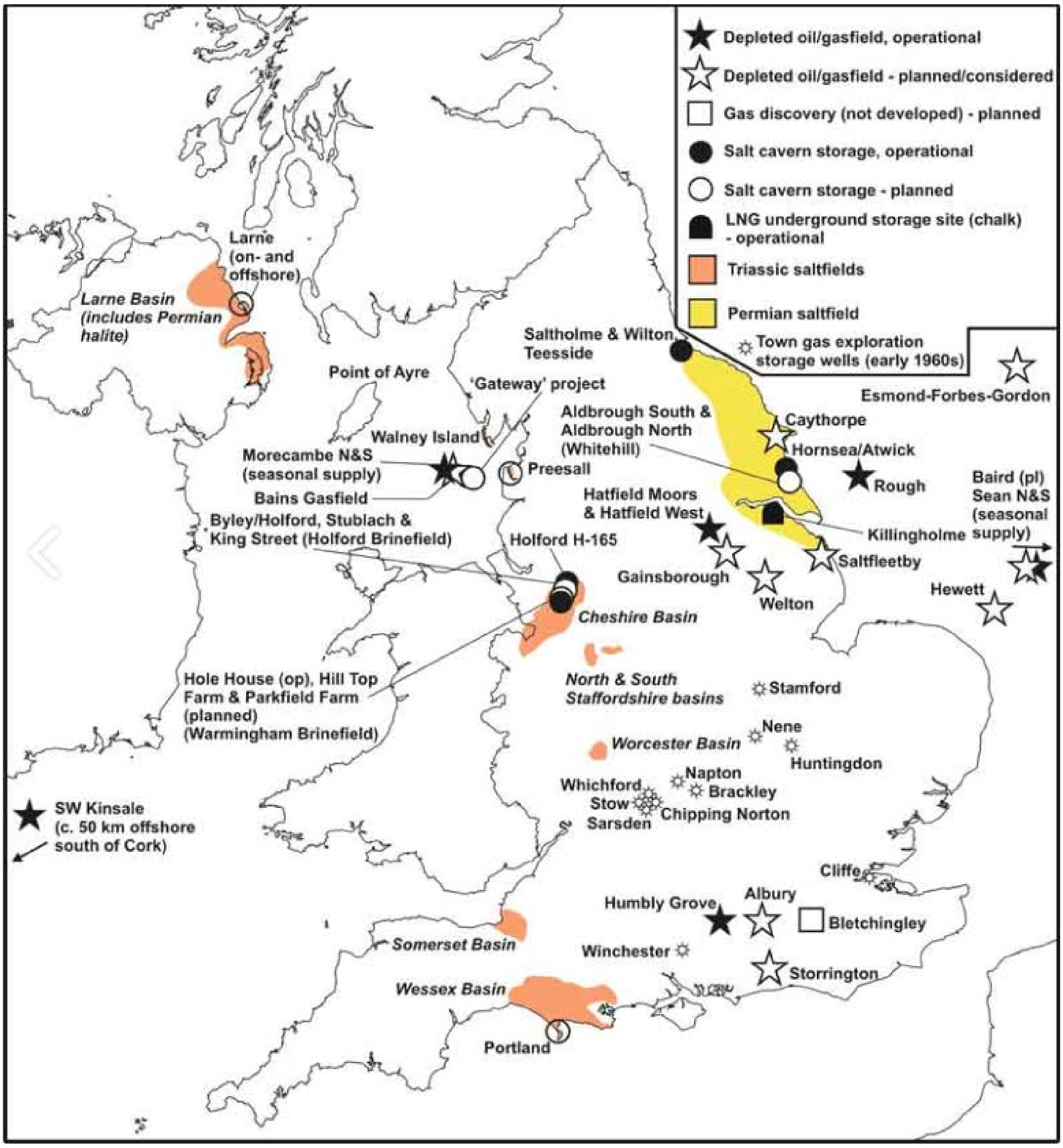


Fig 3.13 UK salt fields and potential storage locations

4 Hydrogen Supply and Demand

4.1 Demand Modelling Methodology

In this section, we have made a high-level assessment of the potential demand for hydrogen in the scenarios described in section 4. We have split the demand into four categories these are industrial, domestic and commercial heating, transport and the existing base demand.

For industrial demand, we have used the Cadent[13] report which gives the gas consumption of the 10 largest users in the L-M area and the 2017 DUKES report[14] which shows the total gas use in the UK and the split between industry and domestic / commercial heating use.

For domestic heat demand, we have also used the Cadent and DUKES reports for our source information.

For transport, we have used the Department for Transport Statistics to establish the baseline for current road transport fuel consumption and associated carbon emissions. In switching of fuel from petrol / diesel we assume that 1 kg of hydrogen is equivalent to 0.83 gallons or 3.77 litres of fuel regardless of vehicle type. In this section, we do not determine which type of vehicle switches to hydrogen rather than battery. This is discussed further in section 7.

We take the existing base demand as the CF Fertilisers site only since in the Cadent project this is connected to the CCS infrastructure to give an additional 350 Kt CO_2 abatement per annum.

For industry, heating and transport we assume that demand remains consistent to 2050. We have found many sources suggesting increased natural gas demand of 16%[15] to 2035 (BAES) whereas other sources suggest a decline of up to 17%[16] Committee on Climate Change (2016). These could be considered as a guide to the likely accuracy of forecasts to 2030.

Transport may alter with the potential for increased efficiency and “MaaS” (Mobility as a Service) where car sharing may reduce the number of vehicles. This may be countered by population growth and increased vehicle ownership. As a result, we also assume that the equivalent amount of fuel used continues at current levels. Cost of vehicles, fuel and the introduction of clean air zones may also have a big impact.

We have used the following dates as reference points for each scenario:

- **2017 – Current situation**
- **2026 – This is the suggested completion date for the Cadent project**
- **2035 – This is an intermediate point between 2026 and 2035 and represents a midpoint on the H21 rollout.**

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[13] Cadent rep – The Liverpool Manchester Hydrogen Cluster, Progressive Energy (Aug 2017)I

[14] Digest of UK Energy Statistics 2017

[15] BAES 2016 Updated Energy & Emissions Projections Reference Scenario

[16] Next steps for UK heat policy – Committee on Climate Change (Oct 2016)

- **2050 – This is the outer limit of our modelling and matches the date in the Paris agreement to reduce emissions by 80%.**

In each scenario, we describe the transition for each category and present tables of hydrogen demand and carbon abatement.

4.2 Slow Progression Pathway

4.2.1 Industrial Demand –

There are a number of industrial hydrogen producers within the L-M cluster some details of these are given in the Cadent report[17] and can be summarised as below:

- **Inovyn, Runcorn –** by product from chlorine production
- **CF Fertilisers, Protos –** used in fertiliser production generated in onsite SMR
- **BOC Chemicals, St Helens –** for glass manufacturing produced in small SMR
- **Essar, Stanlow –** by product from crude oil cracking

On this pathway, it is forecast that there is no large scale new use in industry for hydrogen.

4.2.2 Domestic / Commercial Heating

With no readily available hydrogen distribution network and no financial incentive to switch fuel source there is no uptake of hydrogen as a replacement for natural gas.

4.2.3 Transport Demand

Due to the 2040 ban on sales of new diesel and petrol cars we envisage that there will be some demand for hydrogen fuelled transport within the study area. In this scenario which has limited local or national government backing we believe only limited hydrogen refuelling infrastructure is likely to be available and this will limit the uptake. By 2050 it is expected there will be only a few petrol or diesel vehicles on the road. We expect that by 2035 around 5% of vehicles will be hydrogen fuelled and these will be predominantly vehicles like buses, taxis, refuse collection vehicles and local fleet vans. We would expect this to increase to 10% by 2050.

Year	2016	2026	2035	2050
% of transport*	0	0.0	5%	10%
TWh Hydrogen	0	0.0	0.85	1.69

*Based on fuel consumption – as described in section 6.1

Table 4.1 Scenario 1 Hydrogen Demand Transport Sector

[17] The Liverpool Manchester Hydrogen Cluster 2017 (Progressive Energy for Cadent)

4.2.4 Existing baseload Demand

Details of actual hydrogen use at the four locations covered in section 6.2.1 are not known. The Cadent report does show that if the CF Fertilisers site was connected to CCS infrastructure then 0.35 Mt of CO_2 would be captured annually. This is the equivalent of 2.8 TWh annum annually and this is forecast to remain steady to 2050.

Year	2016	2026	2035	2050
TWh Hydrogen (pa)	2.8	2.8	2.8	2.8

Table 4.2 Scenario 1 Hydrogen Baseload Demand

4.2.5 Hydrogen Supply Chain

In this scenario, the forecast hydrogen demand is given below. This is the sum of the demand from industry, heating, transport and the existing baseload.

Year	2016	2026	2035	2050
(TWh) all sectors (pa)	2.8	2.92	3.65	4.49
(TWh) ex baseload	0	0.0	0.55	1.69

Table 4.3 Scenario 1 Hydrogen Supply Chain

The baseload is produced on site at CF Fertilisers and it is forecast that this will continue to 2050. This leaves the hydrogen required for vehicle fuel. This will be distributed from a small number of filling stations. In this scenario, we expect the fuel to be generated by electrolysis and distributed by tanker as such there is then no requirement for hydrogen storage, hydrogen transmission infrastructure or CCS. There will however be a reduction in the CO_2 emissions associated with transport. The expected reductions in emissions are presented below.

Year	2016	2026	2035	2050
CO_2 emissions reduction (MT CO_2 / annum)	0	0.00	0.22	0.67

Table 4.4 Scenario 1 Carbon Emissions Reduction

4.3 NW Regional Hydrogen Hub

In this scenario, the North West develops a regional hydrogen hub with targeted industry, space heating and transport making a partial transition to hydrogen.

4.3.1 Industrial Demand

This scenario follows the recommended progression set out in the Cadent report[18] with a dedicated hydrogen pipeline running from Protos using the route of the Manchester Ship Canal to the city of Manchester with a spur under the River Mersey to Greater Liverpool. This pipe can then supply the 10 largest industrial users in the L-M area. The Cadent report states that this would require 4.9 TWh of Hydrogen annually (based on 2016 consumption). This is forecast for completion by 2026. Beyond 2026 there is scope for expansion to pick up other large industrial users this is not included within this assessment.

Year	2017	2026	2035	2050
Hydrogen Consumption (TWh/annum)	0	4.2	4.2	4.2

Table 4.5 Scenario 2 Hydrogen Demand Industrial Sector

4.3.2 Domestic / Commercial Heating

As in Section 6.3.1 above the domestic demand is based on providing a blend of up to 10% hydrogen to the domestic and commercial users within the L-M area. This is scheduled to be complete by 2026 but relies on the successful completion of the HyDeploy[19] trial at Keele University where 0.5 MW of Hydrogen will be generated by an electrolyser and blends of up to 20% of hydrogen will be trialled on a full-scale basis. For this scenario, we assume that 10% is the chosen blend but a higher proportion may be feasible up to around 4.8 TWh/annum. As above whilst there is scope to expand and link to a wider area we assume that demand would remain flat post 2026.

Year	2017	2026	2035	2050
Hydrogen Consumption (TWh/annum)	0	2.4	2.4	2.4

Table 4.6 Scenario 2 Hydrogen Demand Heating Sector

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[18] Cadent report – Liverpool Manchester Hydrogen Cluster, Progressive Energy (2017)

[19] https://cadentgas.com/About-us/Innovation/Projects

4.3.3 Transport Demand

With the 2040 ban on sales of new petrol and diesel vehicles and hydrogen generation available locally this scenario is likely to see a higher uptake rate for hydrogen transport. The current base is 0% of vehicles but this could be expected to increase from around 2026 reaching around 1/3rd of all vehicles by 2050. The uptake rate is expected to be much faster in this scenario post 2026 with the roll out of the Cadent project providing local hydrogen generation, transmission infrastructure and CCS. We would expect this to act as a catalyst for the growth of hydrogen fuelled transport within the region.

Year	2016	2026	2035	2050
% of transport*	0	0.7%	10%	32%
TWh Hydrogen	0	0.12	1.69	5.4

*On a fuel consumption basis.

Table 4.7 Scenario 2 Hydrogen Demand Transport Sector

4.3.4 Existing baseload Demand

The existing baseload demand is expected to remain flat in this scenario at 2.8 TWh annum.

4.3.5 Hydrogen Supply Chain

In this scenario, the forecast hydrogen demand is given below. This is the sum of the demand from industry, heating, transport and the existing baseload.

Year	2016	2026	2035	2050
(TWh) all sectors	2.8	9.52	11.1	14.8
(TWh) ex baseload	0	6.72	9.3	12
Generation Capacity GW	0	1	1.3	1.6

Table 4.8 Scenario 2 Hydrogen Supply Chain

The vast majority of the hydrogen is expected to be supplied by SMRs located in the Protos area. An initial generation capacity of around 1 GW would be required to meet the 2026 demand including transport elements and allowing for standby capacity of approx. 250 MW. There is also likely to be some hydrogen provided by electrolysis from constrained renewable power with this hydrogen incorporated into the distribution system or used for transport.

In the Cadent scenario, no hydrogen storage is required with buffering via “line pack” within the transmission network and management of the proportion of hydrogen going to space heating. We have added some transport to this mix that will also have a fairly steady demand with filling stations expected to hold around 3 days of hydrogen on site.

This option has CCS in the depleted East Irish Sea cluster initially in the Liverpool Bay oil and gas fields at Hamilton and Hamilton North. To enable this, a pipeline will be constructed running from the SMRs located at Protos and running via Connah’s Quay to Point of Ayr where it would join the existing natural gas pipe that runs to the oil and gas fields. This pipe could then also capture the emissions from the SMR at CF Fertilisers located at Ince. There is an estimated total capacity across the Liverpool and Morecombe Bay Fields of 1,148 Mt expected to be available by 2030.

There will be a reduction in the CO_2 emissions associated with all sectors the expected reductions in emissions are presented below.

Whilst emissions reduction associated with industry and space heating are flat, post 2026 there is a large increase in emissions reduction associated with transport. This is due to the assumption that the uptake of hydrogen based transport follows the same pattern across the UK and the L-M hub area provides 33% of all hydrogen produced in the UK (assume 30% imported).

Year	2016	2026	2035	2050
CO_2 emissions reduction ($MtCO_2$ / annum)	0	1.4	4.0	10.2

Table 4.9 Scenario 2 Carbon emissions reduction

At the 2050 rate there is in excess of 100 years carbon storage available in the Irish Sea Fields.

4.4 UK Wide Hydrogen Demand

In this scenario, the UK makes a transition to a full hydrogen economy. We assume that all natural gas users in industry and space heating convert to hydrogen and we also assume that hydrogen becomes the main fuel for road transport.

4.4.1 Industrial Demand

The industrial demand is assumed to match the total demand for 1/3rd of the UKs production. It should be noted that 30% of total UK demand is expected to be imported and 5% provided by electrolysis so overall 23% of UK hydrogen is expected to be produced in the L-M area by SMR or ATR.

Year	2017	2026	2035	2050
Hydrogen Consumption (TWh/annum)	0	4.2	23.9*	38.2

**Assumes 58% of conversion to hydrogen is complete by 2035 as per H21 roll out, Manchester area by 2035 then Liverpool by 2038.*

Table 4.10 Scenario 3 Hydrogen Demand Industrial Sector

4.4.2 Domestic / Commercial Heating

As with the industrial section above we assume that there is a transition from 2026 to 2050 going from 10% of the L-M area demand to 1/3rd of the UK demand.

Year	2017	2026	2035	2050
Hydrogen Consumption (TWh/annum)	0	2.4	55.7*	93.9

**Assumes 58% of conversion to hydrogen is complete by 2035 as per H21 roll out, Manchester area by 2035 then Liverpool by 2038.*

Table 4.11 Scenario 3 Hydrogen Demand Heating Sector

4.4.3 Transport Demand

In this scenario with national government policy driving a transition to a hydrogen economy uptake of hydrogen vehicles is rapid beyond 2026 when the basic infrastructure to produce hydrogen with CCS is in place. By 2050 it is envisaged that hydrogen fuel accounts for 62% of all road transport.

Year	2016	2026	2035	2050
% of transport*	0%	1%	17%	62%
TWh Hydrogen	0	0.71	12.1	43.9

**On a fuel consumption basis*

Table 4.12 Scenario 3 Hydrogen Demand Transport Sector

4.4.4 Existing baseload Demand

The existing baseload demand is expected to remain flat in this scenario at 2.8 TWh annum.

4.4.5 Hydrogen Supply Chain

In this scenario, the forecast hydrogen demand is given below. This is the sum of the demand from industry, heating, transport and the existing baseload.

Year	2016	2026	2035	2050
(TWh) all sectors	2.8	10.1	94.5	178.8
(TWh) ex baseload	0	7.3	91.7	176
Generation Capacity* GW	0	1.2	13	25

**Assumes standby capacity of 300 MW in 2026, 2.5 GW by 2035 and 5 GW by 2050.*

Table 4.13 Scenario 3 Hydrogen Supply Chain

In this scenario, some large-scale hydrogen storage will be required to account for the seasonal variation in heating demand. In the H21 city gate report[20] 40 days intra seasonal storage is required for the space heating element. In this instance, we cannot quantify the required volume but as the scope of this rollout is wide and demand is many times higher there will be much more flexibility in generation. There is currently around 4% storage of national demand in the UK which is approximately 2 weeks storage. It should be noted that some natural gas storage will still be required for the SMR / ATR units.

The Stublach caverns owned and operated by storengy near Northwich have a total potential capacity of around 450,000,000 Nm^3 if all are developed[21]. There are a number of other potential sites in this area with potential for large scale storage. A pipeline of around 25 km would be required from the production site near Protos to storage location close to Northwich.

The Cheshire area geology has Triassic salt fields with extensive salt caverns some of which have already been converted for natural gas storage. We would expect these storage facilities to play a key role in a national hydrogen rollout.

[20] H21 City Gate report

[21] Storengy https://www.storengy.com/countries/unitedkingdom/en/our-site.html

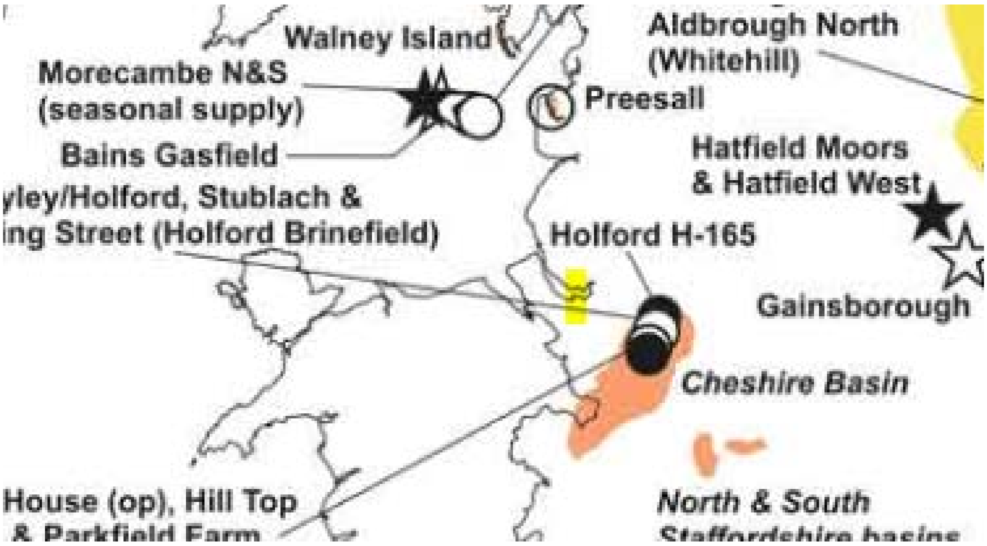

Fig 4.1 Section of map showing underground gas storage facilities and salt fields in NW region (BGS)

This scenario has the potential to decarbonise industry, heating and transport and as a result substantial CCS capacity would be required. This is demonstrated in the table below.

Year	2016	2026	2035	2050
CO_2 emissions reduction ($MtCO_2$ / annum)	0	1.47	14.8	34.5

Table 4.14 Scenario 3 Carbon Emissions Reduction

5 Transport

5.1 Transport Sector Overview

36% of energy used in the UK is for transport, of domestic transport fuel use 92% is road transport, this is equivalent to 35.8 million tonnes of fuel per year. Table 5.1 below gives a breakdown of fuel use by sector.

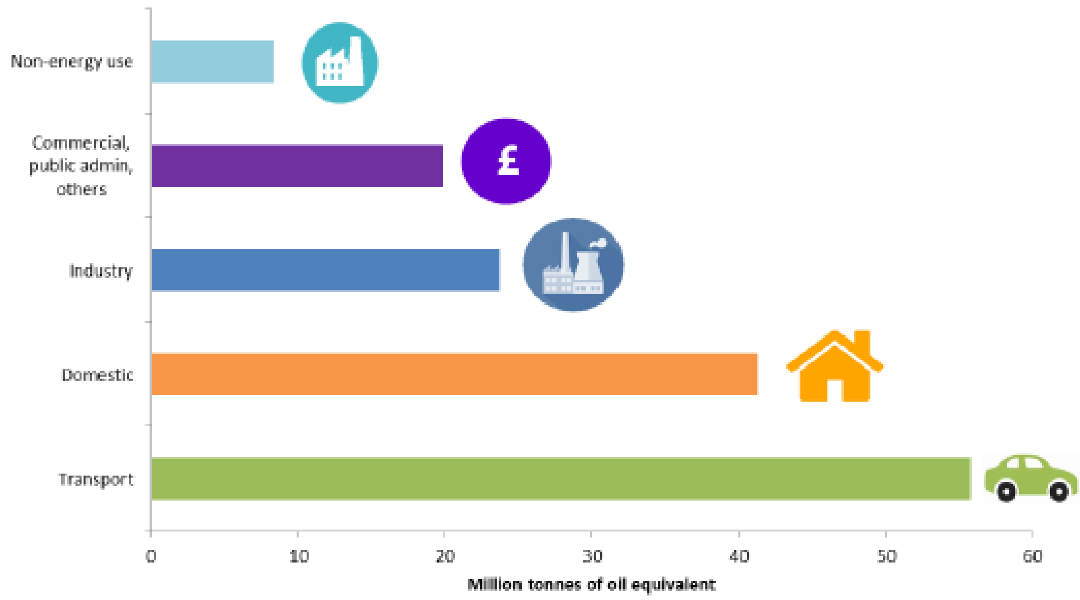

Fig 5.1 Final Energy Consumption 2016 (Source DUKES 2017)

Type	% of fuel used
Cars	63%
LGV (Vans)	16%
HGV	17%
Buses	3%
Motorbikes	0.5%

Table 5.1 Road Transport Fuel Consumption by Vehicle Type

The road transport sector was responsible for 117 million Tonnes of CO_2 emissions in 2012[22]

Type	% CO_2 emissions	Mt CO_2 emissions / annum
Cars	59%	69
LGV (Vans)	14%	16.4
HGV	22%	25.7
Buses	4%	4.7
Motorbikes	1%	1.2

Table 5.2 Road Transport Carbon Emissions by Vehicle Type

NOx and PM_{10} are commonly measured air pollutants. Road transport contributes significantly to the emissions of both NOx and PM_{10}. The proportion of NO_X and PM_{10} by different transport types differs to CO_2 and is shown in the table below (Source Emissions inventory for Greater Manchester 2010).

Type	NO_x	PM_{10}
Cars	37%	66%
LGV (Vans)	14%	15%
HGV	38%	15%
Buses	11%	3%
Motorbikes	Neg	Neg

Table 5.3 Road Transport NOx and $PM1_0$ Emissions by Vehicle Type

The table above shows that HGVs and Buses generate a high proportion of NOx relative to CO_2 and PM_{10} emissions.

In order to meet future CO_2 abatement targets, emissions from transport will need to be significantly reduced. In recent weeks, the UK government has announced that the sale of all petrol and diesel cars (including hybrids) is to end by 2040. Local government will also be given the power to charge levies on diesel drivers on the most polluted roads by 2020.

[22] Department for Transport Table ENV0201

Meeting CO_2 abatement targets and banning the sale of new petrol and diesel cars will have a major impact on NO_X and PM_{10} emissions. This will dramatically improve air quality in the regions towns and cities which will in turn provide health benefits.

To achieve the above there needs to be a movement away from diesel and petrol. Hydrogen can be utilised as an alternative and should be considered as a serious alternative to battery powered electric vehicles. As a fuel, hydrogen would be provided in filling stations in a similar manner to petrol and diesel. Refuelling a FCEV takes around 5 minutes, compared to a much longer charging period for battery powered electric vehicles. The range of a FCEV range between refuelling is around 300 miles, similar to today's user experience. In both fuel cell electric vehicles and plug in electric vehicles the vehicle is electric powered it is just that the hydrogen powered vehicle is using a fuel cell to generate the electricity rather than supplying the electricity from a battery. In the 3 scenarios modelled in section 6 we have assumed the following mix of vehicle types by 2050.

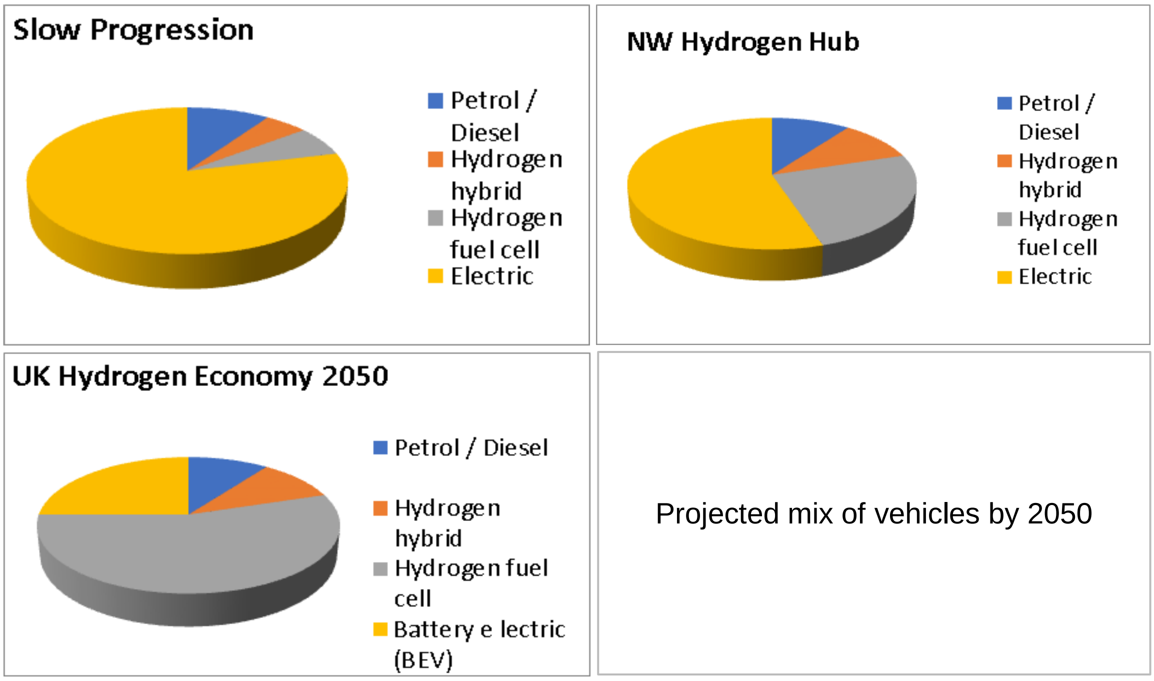

Fig 5.1-5.3 Predicted Road Transport Blend in 2050 by Scenario

The key factors that will determine uptake of hydrogen vehicles are:

- **Cost of vehicle relative to alternatives**
- **Cost of fuel relative to alternatives**
- **Cost of taxes relative to alternatives**
- **Availability and convenience of refuelling network**

5.2 Hydrogen Vehicle Technologies

Globally there is significant interest in the use of hydrogen as a vehicle fuel. By the end of 2017 there will be three fuel cell electric vehicles (FCEVs) commercially available in the UK. These are the Toyota Mirai, Hyundai iX35 and Honda Clarity. One of the major drawbacks is the current lack of refuelling infrastructure with less than 10 currently available in the UK. Across the world California seems to lead the way with around 50 hydrogen filling stations to be available by the end of 2017.

Fig 5.4 Toyota Mirai

Current costs for a Toyota Mirai are around £66,000 or Toyota have a 4yr £750/month contract which includes fuel, tyres and all maintenance. Whilst these costs are at least twice that of a comparable petrol or diesel car the projected cost of both hydrogen and electric vehicles is expected to reduce rapidly. The UK H_2 mobility report [23] forecasts parity in total cost of ownership between a FCEV and a similar diesel by 2030. A sharp fall in purchase cost is predicted within 5 years.

Beyond cars there are also hydrogen buses and trucks available. These have significant advantages over electric vehicles due to the weight of batteries that would be required.

Hydrogen buses have been successfully introduced in Aberdeen with a fleet of 10 buses and a dedicated filling station. A 1MW Electrolysis unit generates the hydrogen required to fuel the buses. The buses were manufactured by Van Hool. Toyota plans to have over 100 hydrogen buses operating in Tokyo in time for the 2020 Olympic Games.

Fig 5.5 Aberdeen Hydrogen Powered Buses (Aberdeen City Council)

[23] UK H_2 Mobility, Phase 1 Results (2013)

Fig 5.6 Aberdeen Hydrogen Bus Filling Station (Aberdeen City Council)

Toyota are also trialling a Hydrogen Fuel Cell powered truck in the Port of Los Angeles with a range of 200 miles which is to be used for short distance heavy load journeys.

It is also possible to retrofit hydrogen technology to existing diesel vehicles. ULEMCo offer a system that will typically run on hydrogen 70% of the time reducing CO_2 emissions from 250 g/km to 75 g/km. A Ford Transit conversion would be able to run over 200 miles on hydrogen.

Battery powered electric vehicles will also have a substantial role to play in the decarbonisation of transport and there are already thousands of electric vehicles and hybrids on the road throughout the UK. The main drawback in terms of decarbonisation with the ever increasing take up of these vehicles is that the power generation used to recharge the batteries needs to be renewable otherwise there are still significant CO_2 emissions. Provision of sufficient vehicle recharging points will also be a major infrastructure challenge.

NOx and particulate emissions will be reduced with either battery or hydrogen fuelled transport with zero emissions at the exhaust for either FCEV or BEV vehicles.

Fuel cell company AFC energy is working with Peel Environmental to assess the techno-feasibility of a hydrogen fuel cell precinct, which is consistent with the government's Northern Powerhouse initiative. This work is ongoing and is based at Protos.

5.3 Air Quality

5.3.1 Pollution from the Transport Sector

Poor outdoor air quality is responsible for 40,000 deaths per year in the UK and costs the NHS around £20 billion annually[24]. Air Quality in Urban Areas is the main problem with 8% of deaths due to poor air quality[25]. In the North West of the UK high levels of fine particulates ($PM_{2.5}$) is thought to contribute around 3,200 deaths per year[26]. Clearly improved air quality would have a significant impact on the long-term health of urban populations for generations going forward. Transport is a significant contributory sector. Whilst emissions are falling there are still many areas of the UK where levels of NO_X and Particulates are over EU guideline values. The EU Nitrogen Dioxide limit is 40µg/m^3.

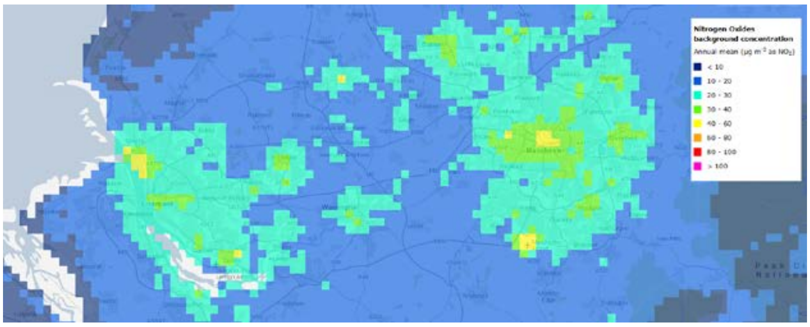

Fig 5.7 Annual Mean NO_X concentration in Liverpool and Manchester areas. Taken from Defra Interactive Air Quality Maps

The map below shows that areas of Liverpool and Manchester exceed that limit. The annual average limits for PM10 an PM 2.5 are 40µg/m3 and 25µg/m3 respectively. There is however 3-year limits on PM2.5 to reduce the average to 20µg/m3. There is however no real safe limit for PM2.5, all exposure is problematic. The map shows that the L-M region is meeting the EU standard for PM2.5.

Fig 5.8 Annual Mean $PM_{2.5}$ concentration in Liverpool and Manchester areas. Taken from Defra Interactive Air Quality Maps

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[24] Royal College of Physicians: Every Breath We Take The lifelong impact of air pollution 2016.

[25] Defra Technical Note - Air Quality: Public Health Impacts

and Local Actions

[26] Public Health England – Estimating Local Mortality Burdens associated with Particulate Air Pollution.

NO_X and PM_{10} concentrations tend to be particularly high at roadside areas in busy urban areas where poorer communities often live. Reducing emissions in these areas would give substantial health benefits.

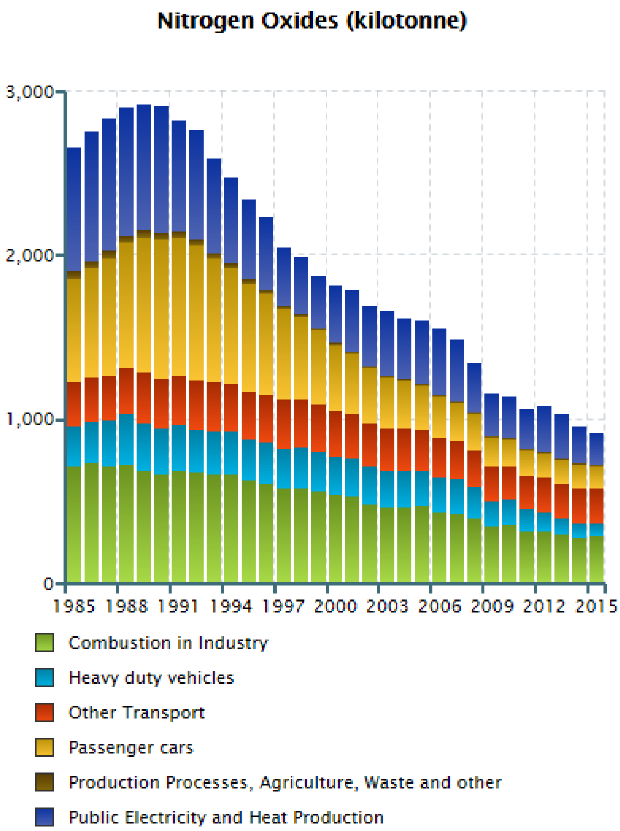

Fig 5.9 Annual NOx emissions by Source (National Environment Emissions Agency)

The chart above shows that nationally overall NO_X emissions have reduced considerably since a peak around 1990. Transport (HGV, Others and Passenger Cars) makes up 47% of total NOx emissions, 19% of PM_{10} and 22% of $PM_{1.0}$ emissions. [27]

Local information has been more difficult to source the charts below are from the Transport for Greater Manchester report from 2013 although the data is only up to 2010. Nationally there have been significant improvements in NO_X and PM_{10} emissions since this point in time. For Greater Manchester as a whole 75% of NO_X emissions and 81% of PM_{10} emissions are related to road transport.[28] A transition away from petrol and diesel based transport can therefore have a considerable positive impact on air quality in the Liverpool and Manchester areas.

[27] National Environment Emissions Agency

[28] The Greater Manchester Emissions Inventory 2010 Update - HFAS Report 1750 June 2013

5.3.2 Scenario Comparisons in Air Quality Improvements

In the UK H2 Mobility report it suggests a network of 65 Hydrogen Refuelling Sites would be sufficient to kick start the uptake of Hydrogen fuelled transport. The aim is to achieve this by 2020 and to then expand this to 1,150 by 2030. The initial 65 sites would include sites in both Liverpool and Manchester. We have assumed that 10 would be required to support a local network for buses, taxis, refuse collection vehicles and some fleet vans.

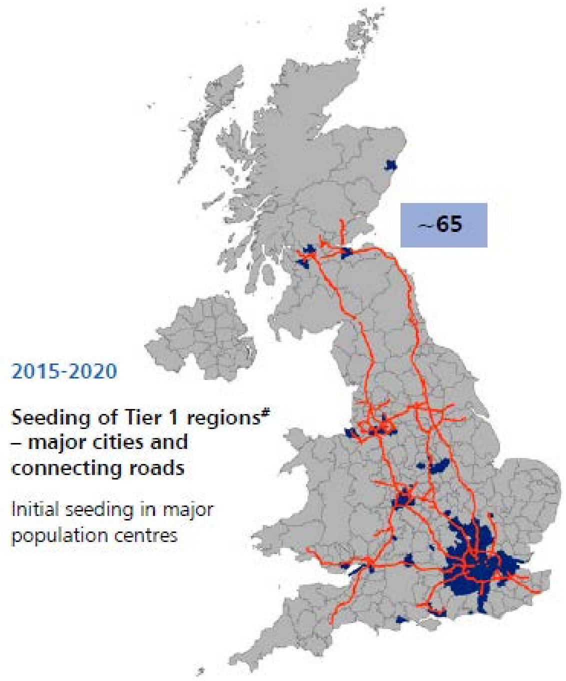

Fig 5.10 Initial Hydrogen Refuelling Network (Source UK H2 Mobility report)

The graphs below demonstrate the possible displacement of fossil fuels in the road transport sector within each of the developed scenarios.

5.3.3 Slow Progression - Road Transport Fuel Mix

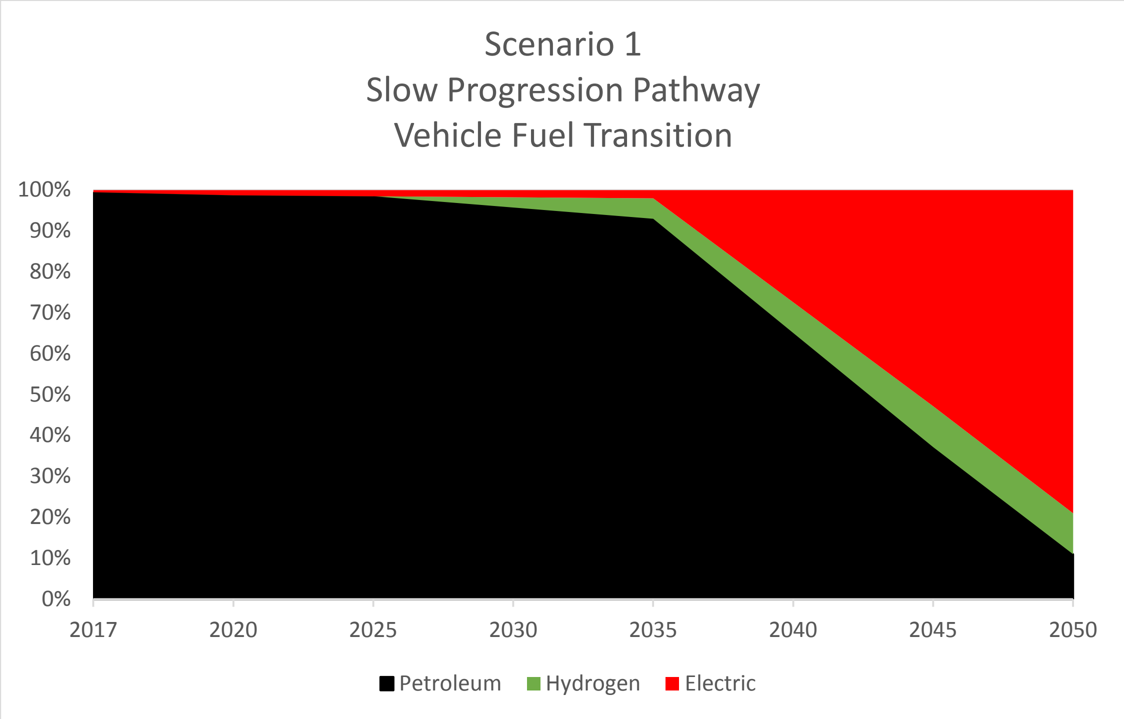

Fig 5.11 Scenario 1 Transport Sector Fuel Consumption

In this scenario, there is only a small take up in hydrogen transport with this beginning post 2026. With the majority of transport BEV based there is still a large reduction in transport related NO_X and PM_{10} emissions by 2050.

Year	2017	2020	2025	2030	2035	2040	2045	2050
NOx kT annum	-	0.20	0.30	0.49	0.69	3.31	5.92	8.61
PM_{10} kT annum	-	0.02	0.04	0.06	0.08	0.40	0.71	1.03

Table 5.5 Scenario 1 NO_X and PM_{10} transport emissions reduction

5.3.4 NW Hydrogen Hub – Road Transport Fuel Mix

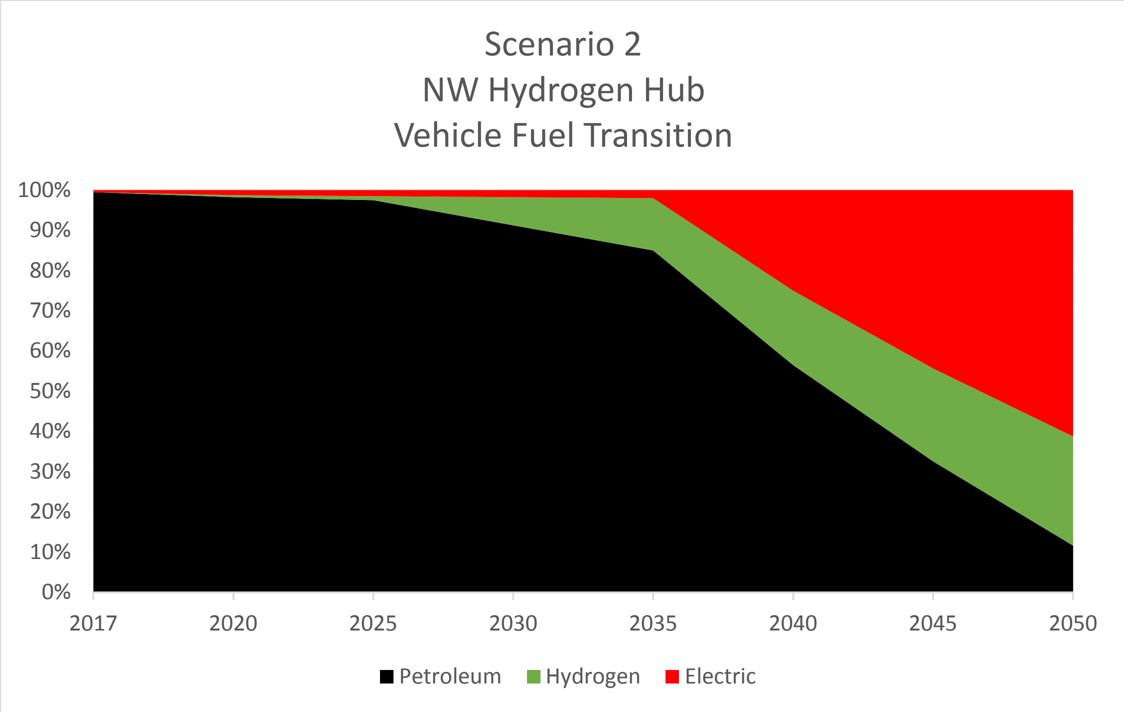

Fig 5.13 Scenario 2 Transport Sector Fuel Consumption

In this scenario, there is local hydrogen infrastructure available by 2026 so we expect that there will be a gradual increase in hydrogen transport starting with local fleet, buses, taxis and refuse collection and then expanding into private cars, LGVs and HGVs between 2035 and 2050. BEV vehicles are still expected to be dominant by 2050.

	2017	2020	2025	2030	2035	2040	2045	2050
NOx kT annum	-	0.20	0.30	0.54	0.79	2.98	5.17	7.42
PM_{10} kT annum	-	0.02	0.04	0.06	0.08	0.40	0.71	1.03

Table 5.6 Scenario 2 NO_X and PM_{10} transport emissions reduction

5.3.5 UK Hydrogen Economy - Road Transport Fuel Mix

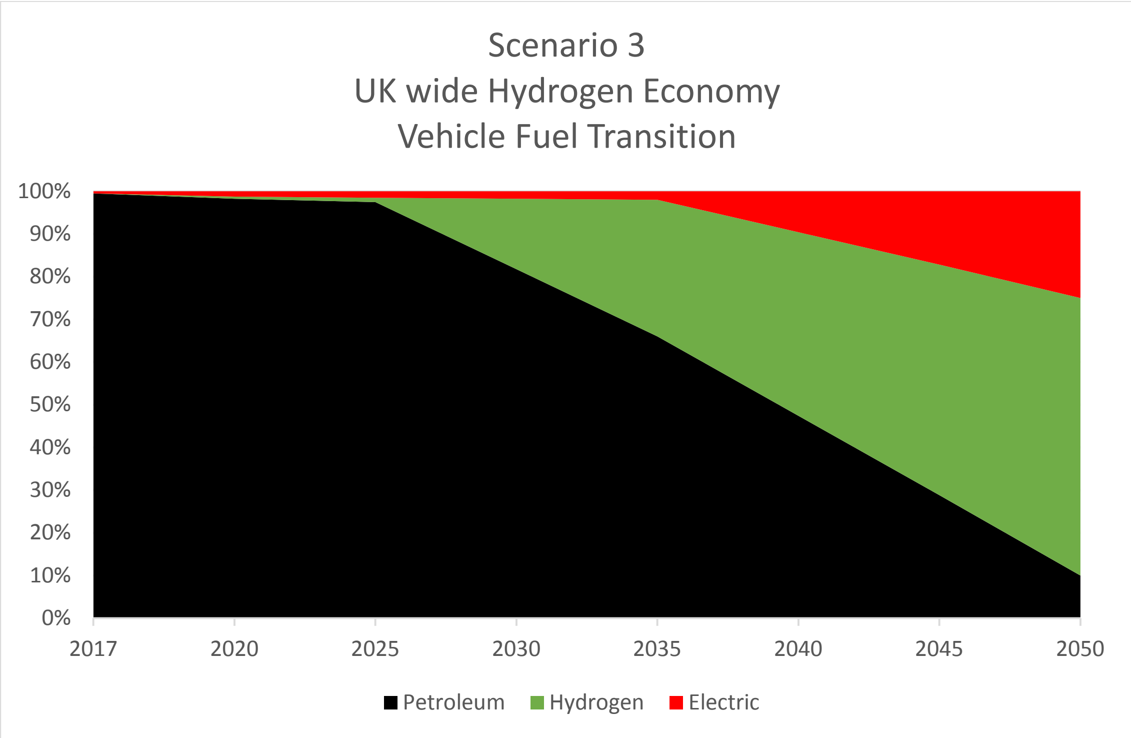

Fig 5.15 Scenario 3 Transport Sector Fuel Consumption

With this scenario, a national network of hydrogen refuelling stations would be established and by 2050 hydrogen is the dominant fuel source. NOx and PM_{10} emission improvements occur earlier than in the other scenarios as the 2040 ban on petrol and diesel car sales is not the only driver with the early provision of hydrogen refuelling infrastructure and reduction in cost of ownership meaning progress is made earlier.

	2017	2020	2025	2030	2035	2040	2045	2050
NOx kT annum	-	0.17	0.30	0.89	1.48	3.61	5.73	7.92
PM_{10} kT annum	-	0.02	0.04	0.11	0.18	0.43	0.69	0.95

Table 5.7 Scenario 3 NO_X and PM_{10} transport emissions reduction

As previously discussed emissions are at their highest where busy roads such as Motorways and the main arterial routes into towns and cities coincide with residential areas. These can be seen on the image below of the Greater Manchester Air Quality Management Area (AQMA).

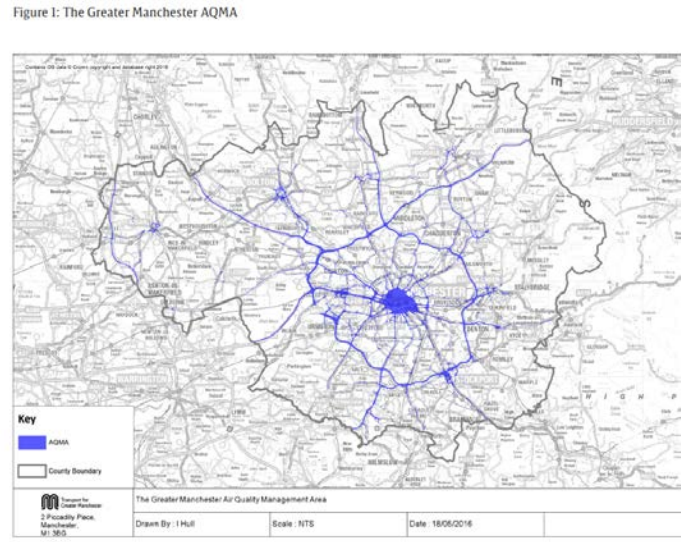

Fig 5.17 Greater Manchester Air Quality Management Area

In terms of reductions buses make a disproportionately large contribution to NOx emissions on major roads for example they make up only 1% of traffic but emit 11% of NOx. This will be higher on the main city centre routes. Targeting buses for an early transition to hydrogen (or battery) would have a significant impact on NOx. The impact on PM_{10} would however be lower at up to 3% of emissions on major roads.

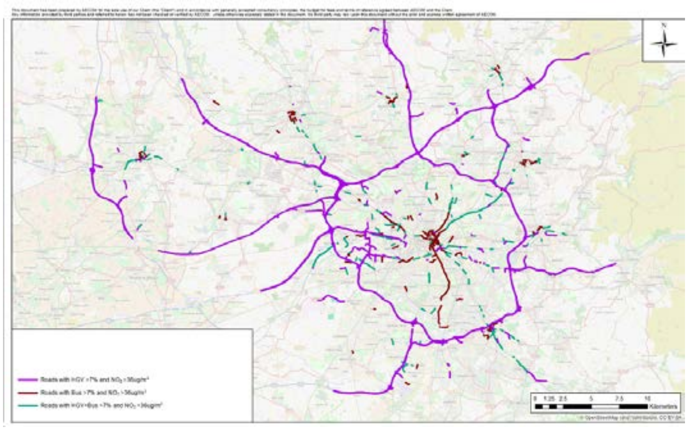

Fig 5.18 Greater Manchester Roads with high bus and HGV proportions and high NO_x

This image shows roads with high proportions of HGV and Buses and NO_X levels close to the 40 ug/m^3 annual average. It clear shows that the problems caused by buses are close to each population centre and the major commuter roads into the centre of Manchester. HGVs dominate the NO_X emissions along the motorways. Emissions from HGVs are likely to fall significantly in the next few years as older vehicles are replaced with vehicles meeting the higher Euro standards. A transport for Greater Manchester emissions summary[29] forecasts a drop in fleet weighted emission factors for HGV (Artic) from 1.51 in 2015 to 0.35 by 2020 this is an 80% reduction. This will have a substantial impact on the regions motorways.

[29] www.tfgm.com/gmles/Documents/03 Emissions in Greater Manchester.pdf · PDF file

We have estimated the amount of emissions from a number of sources in the L-M area where local authorities or large locally based businesses have control over the type of vehicle utilised.

Type	NO_x tonnes per year	PM_{10} tonnes per year
Buses	1845	144
Taxis (Non private hire)	81	9.8
Waste Collection	225	3
United Utilities Fleet*	61	3.8
All of above	**2,212**	**188**

*Chosen as an example of a large local fleet.

Table 5.8 NO_X and PM_{10} emissions in study area by transport type

If efforts were made to get the above vehicles converted to Hydrogen or BEV as a matter of priority then over 15% of the region's NO_X and PM_{10} emissions would be removed. This would also have a significant impact on the areas of Liverpool and Manchester that are close to EU air quality limits and would give health benefits to some of the most densely populated areas of the region.

5.4 Measuring Health Benefit

HM Treasury use values for air quality damage of £25,252 per tonne of NOx from transport[30]. In the section below we have calculated the financial benefit of the air quality improvement associated with Hydrogen Transport only for each scenario, this benefit covers the study area only. If Electric transport was also considered then the values below would increase. This simple measure clearly shows that there is a substantial value to be gained in a transition to "cleaner" transport.

NOx reduction benefit £M/annum	2020	2025	2030	2035	2040	2045	2050
Scenario 1	-	-	8	17	25	34	34
Scenario 2	2	3	24	44	68	93	118
Scenario 3	2	3	56	108	145	182	219

Table 5.9 Indicative Health Benefit of NOx reduction by Scenario

30 https://www.gov.uk/guidance/air-quality-economic-analysis

6 Gross Value Added (GVA)

6.1 GVA Calculation Methodology

Regional Gross Value Added or GVA is the value generated by any unit engaged in the production of goods and services. GVA is typically estimated using either production GVA (P) or income GVA (I) approaches.

The income approach to estimating GVA measures the incomes earned by individuals (gross wages and salaries) and corporations (for example, profits) in the production of goods and services.

The production approach to estimating GVA measures the value of outputs produced (goods or services) less the value of the inputs consumed in producing those outputs.

KPMG have produced a comprehensive report titled Energising the North – An evaluation of the economic contribution of the energy sector to the North of England[31]. This report identifies the GVA associated with a variety of energy scenarios to 2050. One of the scenarios is titled the "Evolution of gas" where over time the use of methane gas for heating reduces over time and is replaced by hydrogen. In the transport sector, it assumes that hydrogen fuel cell vehicles cover the majority of transport demand. This is essentially the same as Scenario 3 so the GVA calculated is the same.

In the North West region in 2015 the provisional GVA of the electricity, gas, steam and air conditioning supply sector was £2 billion. This has increased from £1.4 billion since 2010. The GVA for the UK as a whole is £24.8 million so the North West provides 8% of UK GVA.

In the KPMG report the GVA is broken down into components based on the BEIS/Ofgem analysis of the fuel bill breakdown.

A dual fuel bill is broken down as follows:

- Wholesale cost – 46%
- Network cost – 21%
- Environmental and social obligation costs – 7%
- Other supply costs and margins – 21%
- VAT – 5%

These sections are then broken down further to give the following for the North as a whole. The GVA statistics by sector are available for the sub regions so we have then used the previously calculated split to breakdown GVA for Greater Manchester and Merseyside.

The combined GVA for Greater Manchester, Merseyside and Cheshire for 2015 was £1.470 billion with GDP growth at 2.8% this is adjusted to £1.5 billion.

[31] KPMG Energising the North An evaluation of the economic contribution of the energy sector to the North of England (2017)

Component	BEIS bill breakdown	Adjusted % of breakdown of Northern GVA	Greater Manchester, Merseyside and Cheshire GVA 2016 £ Million*
Wholesale Costs	46%	32%	£480 mil
Upstream gas	23%	4%	£ 60 mil
Electricity generation	23%	28%	£420 mil
Network costs	21%	26%	£390 mil
Gas transmission	2%	2%	£ 30 mil
Electricity transmission	4%	5%	£75 mil
Gas distribution	6%	7%	£105 mil
Electricity distribution	9%	11%	£165 mil
Hydrogen networks	NA	0%	0
Heat networks	NA	~0%	0
Other Supply costs and margins	21%	26%	£390 mil
Environmental and social obligation costs	7% subsidies not in GVA	0%	0
Domestic appliances	NA	7%	£105 mil
Non-domestic appliances	NA	8%	
Transport	NA	1%	£15 mil

VAT	5% (not in GVA)	0%	NA
Total	100%	100%	£1,500 mil

*2015 GVA for "North" split down to Greater Manchester, Merseyside and Cheshire and then given uplift (2.8%) to 2016

Table 6.1 Breakdown of baseline GVA

This figure is effectively the baseline value for the rest of the assessment. Whilst there would be change in other sectors associated with this we look solely at the impact on transport, hydrogen networks and construction.

Much of the specific GVA associated with the hydrogen economy would be centred on the Stanlow, Runcorn and Protos area but the GVA data by industry doesn't breakdown to a local authority area with granularity down to county level only. It should be noted that the overall GVA per head for Cheshire is higher than Greater Manchester and Merseyside. It is also well above the UK and England average values. This reflects the high value industry already located in this area.

Area	GVA (Income Approach per Head) Indexed
UK	100
England	102
Greater Manchester	85.3
Merseyside	76.2
Cheshire	118.7

Table 6.2 Indexed GVA by study sub area

In transport, we assume as per the KPMG report[32] that the cost of FCEV would fall into line with a typical diesel / petrol car and have a typical sale price of £17,500. Of this 62% is the cost of the inputs (excluding employee costs). Of the remainder of £6460 per vehicle sold a localisation factor of 40% is applied meaning the local GVA is £2,584 per vehicle unit sold.

32 KPMG – Energising the North (2017)

If the average vehicle cost is higher than £17.5k then the GVA will increase. HGVs, Buses and Refuse Collection Vehicles would be far more expensive but they have far higher emissions and the vehicle blend is split by emissions so this will to a certain extent, level things out. This is a simple methodology to give a high level indicative figure only.

There would be considerable construction work associated with the development of hydrogen infrastructure. Using UK wide statistics, the UK construction sector value for 2015 was £144 billion across all construction sectors. The UK wide construction GVA for the same period is £102 billion meaning each £1 spent on a construction project yields £0.72 of GVA. To regionalise this, we have then applied the 40% localisation factor so for each £1 spent there is £0.29 local GVA.

Total construction costs for delivery of a hydrogen network are taken from the H21 Leeds City Gate report, Cadent report on Liverpool Manchester Hydrogen cluster and for hydrogen refuelling stations £2m per site is assumed.

6.1.1 GVA Assessment – Slow Progression Pathway

This scenario is similar to the “No progression” scenario assessed by KPMG for heating. In this scenario GVA year on year growth is 0%.

For transport, it is envisaged that there is some uptake of hydrogen based transport as the 2040 ban on sales of new petrol / diesel vehicles approaches but this is limited to 10% of total vehicles.

For construction, there is only a limited time period where around 5-6 Hydrogen Refuelling Stations would be constructed at a cost of around £2million per site we have captured 1/5th of the GVA in the 2026 scenario to represent this. As by 2030 we are assuming transport related GVA and the construction phase must precede this point.

		2026	2035	2050	2055
GVA £ Million	Heating (pa)	0	0	0	0
	Transport (pa)	0	1.5	3	3
	Construction (pa)	0.7	0	0	0
	Combined (pa)	0.7	1.5	3	3
	Cumulative (to date)	2.2	10.4	48.6	

Table 6.3 Scenario 1 GVA

6.1.2 GVA Assessment – NW Regional Hydrogen Hub

Under this scenario, by 2026 hydrogen will be produced by SMR plants located in the Protos development. A hydrogen pipeline will be constructed from Protos, extending to the outskirts of Manchester complete with a branch to St Helens. We expect the availability of hydrogen to be the catalyst for a network of hydrogen filling stations, allowing the uptake of hydrogen fuel cell vehicles and hydrogen hybrid vehicles.

In construction, the Cadent project would see 3 years of construction generating £58 million pound each year of GVA. A further £1 million GVA is added for the construction of Hydrogen Filling Stations.

Beyond 2026 construction is limited to further hydrogen filling stations and by 2050 we assume this has ceased.

		2026	2035	2050	2055
GVA £ Million	Heating (pa)	45.0	45.0	45.0	45.0
	Transport (pa)	0.3	6.2	29.3	29.3
	Construction (pa)	58.0	1.4	0.0	0.0
	Combined (p/a)	45.0	51.0	74.0	74.0
	Cumulative (to date)	220	670	1,619	

Table 6.4 Scenario 2 GVA

6.1.3 GVA Assessment – UK Wide Hydrogen Economy

In this scenario, central government energy policy has dictated that the UK gas grid is converted to hydrogen to meet the 2050 Climate Change act targets. GVA for construction in 2026 is associated with the delivery of the Cadent project beyond this we see a total spend on hydrogen conversion of around £122 billion between 2026 and 2050. This is the upper end of the costs given in KPMG report 2050 Energy Scenarios.[33] Of this £73 billion is construction related (the remainder is appliance conversion). This would deliver a local GVA of £291 million annually over the 24 year roll out period. Appliance conversion would deliver further jobs and GVA but it is outside the scope of this assessment.

		2026	2035	2050	2055
GVA £ Million	Heating (pa)	45.0	191.0	294.0	294.0
	Transport (pa)	0.3	26.0	61.0	61.0
	Construction (pa)	58.0	291.9	291.9	0
	Combined (p/a)	103.3	508.9	646.9	355
	Cumulative (to date)	220	3,529	12,777	

Table 6.5 Scenario 3 GVA

33 KPMG, 2050 Energy Scenarios, The UK Gas Networks role in a 2050 whole energy system. 2016.

6.2 Job Creation

A transition to a hydrogen economy would generate temporary and permanent jobs in construction, hydrogen production, CCS, H2 storage, transmission and also in the transport sector. We have made a high-level assessment of jobs created in each sector in the same time periods as the GVA assessment. We have made the following assumptions.

For heating the KPMG report 'Energising the North' [34] does not make an assessment of hydrogen infrastructure jobs linked to GVA, as there is no equivalent to make comparison. For the purposes of this assessment we have used an average of the GVA to job across electricity generation, gas networks and energy supply sectors of £71,000. For transport the KPMG report gives an equivalent of 1 job per £45k GVA. We have used this relationship to generate the data below.

For the construction sector, we have used the used the UK average GVA for construction (£101B) against construction job numbers in 2015 (1.2 million). This gives an average of one job per £84,000 GVA on a national basis. In the above sections, we have discounted GVA using a 40% localisation factor which we therefore need to ignore in this calculation. Job numbers are for new jobs in the appropriate sector compared to a 2016 baseline.

6.2.1 Slow progression pathway

		2026	2035	2050	2055
Jobs by Sector	Heating	0	0	0	0
	Transport	0	33	67	67
	Construction	21	0	0	0
	Combined	**21**	**33**	**67**	**67**

Table 6.6 Scenario 1 Jobs Growth

6.2.2 NW Regional Hydrogen Hub

		2026	2035	2050	2055
Jobs by Sector	Heating	634	634	634	634
	Transport	7	137	653	653
	Construction	1723	43	0	0
	Combined	**2363**	**814**	**1287**	**1287**

Table 6.7 Scenario 2 Jobs Growth

[34] KPMG Energising the North 2017

Note - The transition to a NW hydrogen hub will impact the GVA, job creation and retention in other service categories identified in the KPMG report. As this is a high level assessment we have only considered GVA and job creation in the hydrogen, transport and hydrogen related infrastructure categories

6.2.3 UK Wide Hydrogen Economy

The table below indicates the potential scale of job creation in the study area is the whole UK was to transition towards Hydrogen for both heating and transport.

		2026	2035	2050	2055
Jobs by Sector	Heating	634	2689	4139	4139
	Transport	7	581	1362	1362
	Construction (temp)	1723	8670	8670	0
	Combined	2363	11940	14171	5,501

Table 6.8 Scenario 3 Jobs Growth

Note - The transition to a UK wide hydrogen economy will impact the GVA, job creation and retention in other service categories identified in the KPMG report. As this is a high level assessment we have only considered GVA and job creation in the hydrogen, transport and hydrogen related infrastructure categories.

7 Conclusions

This report, in conjunction with the Cadent and H21 studies defines an opportunity for a major NW regional decarbonised energy project delivering a low cost solution to The 2008 Climate Change Act objectives. By utilising the industrial landscape of the Liverpool to Manchester corridor and by engaging key infrastructure assets, this project can be the first of its kind, and an exemplar to other industrial hubs. The L-M corridor answers most if not all of the Industrial Strategy key areas, leveraging the nearby Thornton Science Park for skills and R&D whilst developing industrial hydrogen supply in an innovative and value added way. Further benefits will accrue form the provision of infrastructure for hydrogen as a transport energy vector thereby improving air quality in the key industrial cities of Liverpool, Manchester and the wider region.

Local, regional and national Government support and funding is a logical next step to further define the project which will be crucial to the provision of decarbonised energy for the Northern Powerhouse.

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