

HyMotion

Network-supplied hydrogen unlocks low carbon transport opportunities

A report by Progressive Energy Ltd on behalf of Cadent

June 2019



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Ed Syson A road map for hydrogen transport

This HyMotion report is a practical road map to using hydrogen to decarbonise transport, particularly commercial transport, in the North West and offers a role model for the whole of the UK.



It is also part of a suite of projects that Cadent is leading on which use hydrogen. There is one critical reason we are doing all of this; so that we can help the UK reduce its carbon emissions by 2050 and provide a cleaner and more sustainable way of heating our homes and transporting our goods and ourselves.

The concept of our larger project, HyNet, is to produce hydrogen in the North West and deliver it using our network for use as industrial power and domestic heat. Of course, once you have done this, the hydrogen is easily available for use in other settings such as transport. This HyMotion report specifically details how this network-delivered hydrogen creates substantial opportunities for the UK also to address carbon emissions generated from transport – lorries, trains, buses and cars.

It is now widely accepted that the only way the UK can reach the 2050 targets is by including hydrogen in its future energy choices. Our research shows that an intelligent, co-ordinated repurposing of our gas network – which serves homes, industry and transport - can deliver low carbon benefits much more cost-effectively than many other options.

Many people have been talking about taking steps to reduce carbon emissions for a while now. Cadent is actually making it happen. HyNet will reduce carbon emissions into our atmosphere by over a million tonnes per annum by the mid-2020s. It creates the option of using hydrogen vehicles over long ranges

and refuelling quickly. In other words, hydrogen will allow customers to use vehicles in much the same way as they do now.

At Cadent, we are passionate about making our HyNet concept a reality, but we cannot deliver it alone. We can offer our network infrastructure (the value of which should not be underestimated) and our expertise. But we look to national and regional government as well as leading industrial partners for support, constructive policy changes and of course investment.

We are committed to continuing our work with a wide range of regional and national stakeholders who have the knowledge and drive to help bring the benefits of HyNet to life. We hope that this report will form the basis on which we can continue to work together constructively to achieve real change.

A handwritten signature in black ink, appearing to read 'Ed Syson'.

Edward Syson
Chief Safety and Strategy Officer, Cadent.

Executive Summary

Analysis by the Committee on Climate Change (CCC), shows that the transport (or 'mobility') sector is the largest emitter in the UK economy and accounted for 28% of all Greenhouse Gas (GHG) emissions in 2017.¹ In the same report, the CCC also strongly suggests that current Government policies for decarbonising mobility will contribute to a failure to meet the UK's Fifth Carbon Budget (for 2032) target by at least 25%.

The Government's recently published 'Road to Zero' strategy sets out objectives to electrify cars and reduce emissions from heavy goods vehicles (HGVs) through policies such as ending the sale of diesel and petrol cars and subsidising electric charging infrastructure.² The CCC response to the strategy, however, stated that the proposed measures do not go far enough.³ New Government policies, combined with action from industry, will be required for mobility-related carbon reduction targets to be met.

Hydrogen has been identified by the Government and CCC as one potential solution. The CCC report on a possible future hydrogen economy recognises that, in particular, hydrogen may have an important role to play for long distance journeys and heavy goods transport.⁴ This view was echoed further in the recent CCC 'Net Zero' report.⁵

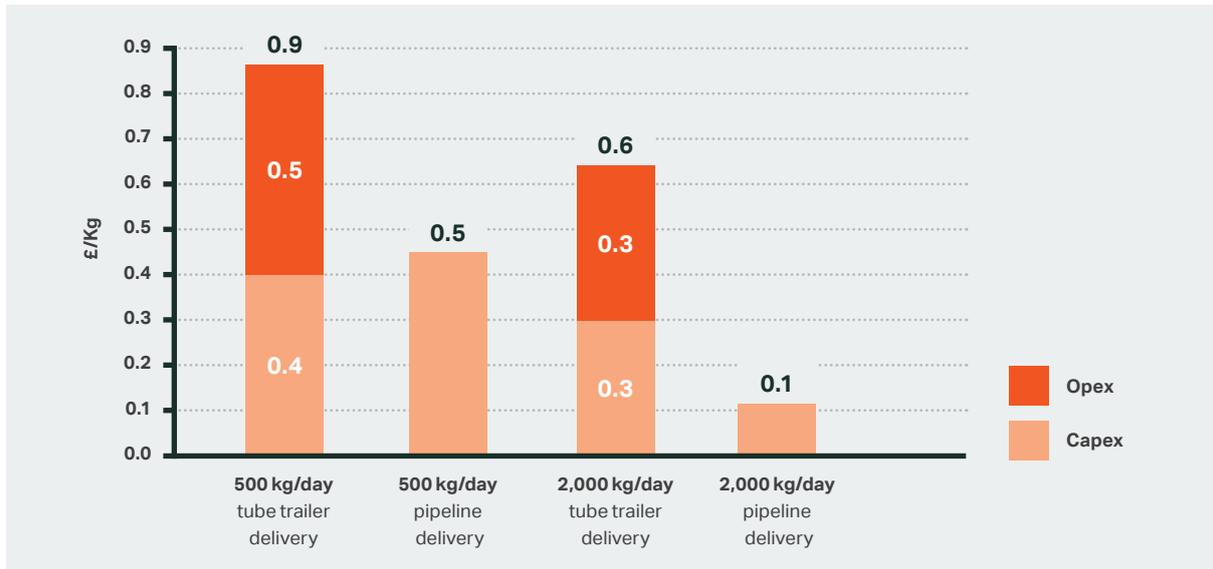
Cadent's HyNet project will produce low carbon hydrogen through reformation of natural gas combined with carbon capture, utilisation and storage (CCUS).⁶ HyNet has primarily been designed to supply low carbon heat to industry and a blend of hydrogen to Cadent's existing natural gas network, but also provides the opportunity to supply low cost hydrogen for mobility. The HyMotion project has considered the relative merits of such an approach, modelled potential demand scenarios and sought to determine technical and commercial solutions to enable deployment.

Hydrogen fuel cell electric vehicles (FCEVs) share powertrain technologies with battery electric vehicles (BEVs), but the roll-out of BEVs is currently ahead of FCEVs. This is largely due to a lack of low cost, low carbon bulk hydrogen production and refuelling infrastructure, both of which HyNet seeks to address.

The key messages from HyMotion can be summarised as follows:

1. Both FCEVs and BEVs are required to meet wider decarbonisation targets. Each will serve distinct sectors of the mobility market, depending upon the required 'duty cycle'. FCEVs are more suited to providing longer ranges and faster refuelling times, while BEVs can better cater for short, 'stop-start' journeys;
2. The likely future gap between low carbon electricity generation and demand is such that BEVs are unlikely to deliver sufficiently deep decarbonisation. Without delay, therefore, the Government must design a suitable policy mechanism by which to support the use of hydrogen in FCEVs (alongside existing support for BEVs);
3. FCEVs are currently relatively expensive. However, manufacturers are planning to increase volumes over the next five years and it is expected that FCEVs will be of similar cost to BEVs when production volumes reach parity;
4. Hydrogen cars, buses, trains and ships are ready for deployment, but more work is required to bring hydrogen HGVs to the UK market, which could make a critical contribution to decarbonisation. This will require the Government to provide innovation support to encourage fleet operators to work with vehicle manufacturers to develop suitable vehicles for the UK;
5. The low energy density of hydrogen means that distributing it by road is expensive. Using the 'trunk' of the HyNet project, and 'spurs' to hydrogen refuelling stations (HRSs), network distribution offers far lower costs under all scenarios. This is illustrated in Figure 0-1.

Figure 0-1: Comparison of hydrogen distribution costs.



6. Network supplied hydrogen via HyNet will deliver low carbon, mobility-grade hydrogen in the North West at a cost that is 40-70% lower than what can be achieved through electrolysis as shown in Figure 0-2. This will allow the fuel costs of FCEVs to match the cost of BEVs and diesel vehicles.

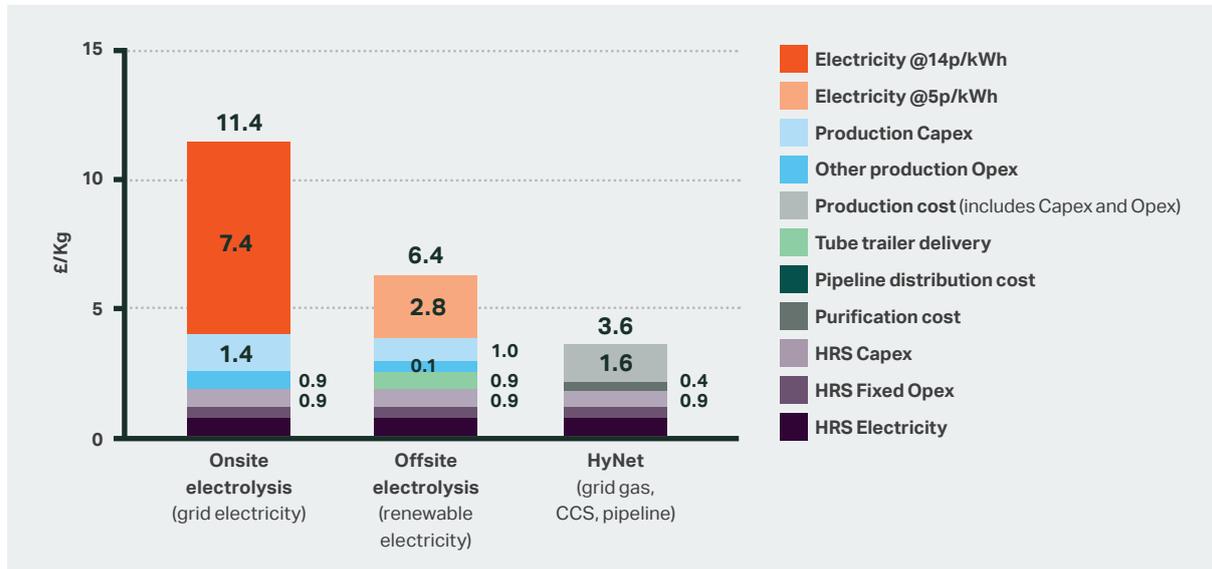
7. Once economies of scale are realised, network delivery of hydrogen from HyNet will mean that the Total Cost of Ownership (TCO) of FCEVs is comparable with both BEVs and diesel vehicles. Consumer choice of vehicle will therefore in future be determined by the required duty cycle;

8. Under the 'medium' demand scenario modelled for hydrogen vehicle take-up, in 2030, FCEVs will use 1.1TWh/annum of hydrogen (around 15% of that supplied by HyNet). This equates to a reduction in mobility-related GHG emissions in the HyNet 'area' by nearly 4% and a reduction in NOx emissions of nearly 10%; and

9. In the near term, technical solutions to enable network delivered hydrogen for mobility must be demonstrated via collaborative working between gas network operators, gas supply companies and the wider mobility sector. Cadent is working on several related initiatives to deliver this vision. Such innovation could represent a major opportunity for technology export, in line with the Government's Clean Growth Strategy.⁷

In summary, HyNet provides the opportunity to provide low cost, transport grade hydrogen across the North West as part of a wider local hydrogen cluster, which will function as an exemplar for the rest of the UK. HyNet will enable the TCO of hydrogen vehicles to at least match diesel vehicles and decarbonise parts of the mobility sector that are unsuitable for electrification.

Figure 0-2: Comparative costs of hydrogen production and distribution.



Acronyms

Acronym	Full Name	Acronym	Full Name
ATR	Auto-thermal Reformer	Mt	Million Tonnes
BEV	Battery Electric Vehicle	MtCO ₂ pa	Million Tonnes of Carbon Dioxide per annum
BioSNG	Bio-Substitute Natural Gas	MWh	Megawatt hour(s)
Capex	Capital Expenditure	MWth	Megawatt hour(s) thermal
CAZ	Clean Air Zone	NOx	Nitrous Oxides
CCC	Committee on Climate Change	OEM	Original Equipment Manufacturer
CCA	Climate Change Agreement	Ofgem	Office for Gas and Electricity Markets
CCUS	Carbon Capture, Utilisation and Storage	OLEV	Office for Low Emission Vehicles
CO ₂	Carbon Dioxide	Opex	Operational Expenditure
DfT	Department for Transport	PSA	Pressure Swing Absorption
FCEV	Fuel Cell Electric Vehicle	RAB	Regulated Asset Base
GHG	Greenhouse Gas	RIIO	Revenue = Innovation + Investment + Outputs
GMCA	Greater Manchester Combined Authority	RTFO	Renewable Transport Fuel Obligation
GWh	Gigawatt-hours	SMR	Steam Methane Reformer
H ₂	Hydrogen	TCO	Total Cost of Ownership
HGV	Heavy Goods Vehicle	Tpa	Tonnes per annum
HRS	Hydrogen Refuelling Station	TWh	Terawatt hour(s)
Ktpa	Thousand tonnes per annum	TWhpa	Terawatt hour(s) per annum
LCRCA	Liverpool City Region Combined Authority	vol.	By volume
LNG	Liquefied Natural Gas		

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1.0 Introduction

Analysis by the Committee on Climate Change (CCC), shows that the transport (or 'mobility') sector is the largest-emitter in the UK economy and accounted for 28% of all Greenhouse Gas (GHG) emissions in 2017.¹ In the same report, the CCC also strongly suggests that new Government policies for decarbonising mobility are required for the UK to meet its Fifth Carbon Budget.

The Government's recently published 'Road to Zero' strategy sets out objectives to electrify cars and reduce emissions from heavy good vehicles (HGVs) through policies such as ending the sale of diesel and petrol cars and subsidising electric charging infrastructure.² The CCC response to the strategy, however, stated that the proposed measures do not go far enough.³ Government and industry must work together for mobility carbon reduction targets to be met.

Hydrogen has been identified by the Government and CCC as one potential solution. The CCC report on the hydrogen economy recognises that, in particular, hydrogen may have an important role to play for long distance journeys and heavy goods transport.⁴ This view was echoed in the recent CCC 'Net Zero' report.⁵ Government has provided £14m of funding for hydrogen vehicles and refuelling infrastructure towards supporting development of the sector, in addition to an earlier £9m awarded in 2018.⁶ This is, however, likely to be a fraction of the level of support required to realise the full potential of hydrogen mobility and help meet the Fifth and further Carbon Budgets.

Cadent's HyNet project will produce low carbon hydrogen through reformation of natural gas combined with carbon capture, utilisation and storage (CCUS). As presented in Figure 1-1, the hydrogen will be sent via a new pipeline to a range of industrial sites and injected into the existing natural gas network to create a blend that can be used to heat homes and business without any changes needed to heating and cooking appliances. The focus of the project is the North West of England and it will supply low carbon hydrogen to more than two million homes. Carbon dioxide (CO₂) from the

natural gas reformation process will be stored safely offshore, using proven technology, in the Liverpool Bay oil and gas fields, which are nearing the end of their economic life. This provides a blueprint which can be replicated at other industrial decarbonisation clusters and incrementally expanded.

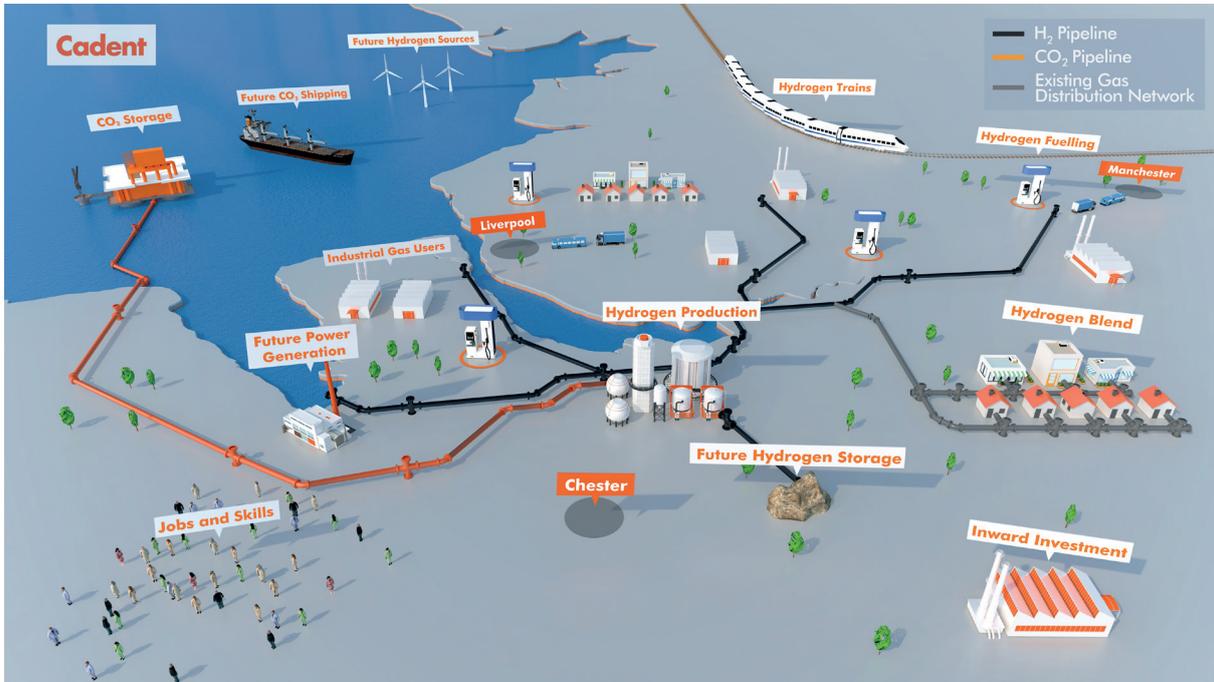
The availability of affordable, network-delivered, low carbon hydrogen has important implications for the mobility sector. It provides an opportunity for hydrogen to be delivered to vehicles at a price that is comparable to petrol and diesel and which is significantly lower than is possible using other low carbon hydrogen production technologies. HyNet also offers the opportunity for widespread adoption of hydrogen as a vehicle fuel, which will reduce CO₂ emissions, improve air quality and encourage economic growth, as described in a recent report relating to HyNet.⁷

The goals of the HyMotion project can be summarised as follows:

1. Build upon the existing cost and emissions evidence base;
2. Model scenarios for future deployment of vehicles and hydrogen refuelling stations (HRSs);
3. Highlight market opportunities and pathways to mass deployment of different vehicle types; and
4. Identify and support projects to enable network-delivered hydrogen for mobility.

This report is a summary of the evidence developed as part of the HyMotion project. It provides a non-technical summary of the project to date and is complemented by a detailed Technical Appendix.

Figure 1-1: Overview of the wider HyNet project.



The HyNet project produces low cost, low carbon hydrogen that is distributed via a new pipeline network to decarbonise heat, power and transport.



2.0 Hydrogen mobility in context

2.1 UK Mobility Sector: The essential facts.

The mobility sector uses 42% of the total energy in the UK, while just 19% of the total energy used is for electricity generation.⁸ Data from the Department for Transport (DfT) suggests that total energy consumption by the UK mobility sector is around 650TWh per annum.⁹ The same dataset shows that cars and vans (>350TWh/annum) are the primary energy consumer but that aviation (c.150TWh/annum) and HGVs (c.80TWh/annum) are also important.

'Consumption' of most forms of mobility has increased significantly since 1990 but any potential resulting increase in CO₂ emissions has been largely offset by improvements in vehicle efficiency and use of biofuels. The DfT data shows that since 2000:

- Car and van travel has grown by 5% but emissions have been offset by a 10% improvement in fuel efficiency for new vehicles and increased use of biofuels;
- Freight transport has declined by around 20%, but the impact on emissions is relatively small. This is because overall fuel efficiency of freight has declined due to reductions in levels of domestic shipping, which is more fuel efficient than road freight.

The mobility sector also has a significant impact on air quality. Improved emission control systems have reduced the level of nitrous oxides (NO_x) from new vehicles by over 50% since 2000, while the level of particulates from new vehicles has reduced by around 25% during the same period. However, these improvements have been offset by an increase in vehicles numbers, which means that the level of air pollution in many UK cities is still too high. Consequently, in 2018, Liverpool City Council, alongside 32 other local authorities, was directed by Government to produce studies on the steps it would take to comply with roadside NO_x limits in the shortest amount of time. Subsequently, Liverpool City Council has also been directed to submit a local plan to the Joint Air Quality Unit (JAQU) by 31st October 2019. To combat air pollution, it is

also worth noting that both Greater Manchester Combined Authority (GMCA) and Liverpool City Region Combined Authority (LCR CA) are currently assessing the viability of Clean Air Zones (CAZ) for parts of the city regions.

2.2 Will current policy deliver?

Data published by the CCC shows that transport emissions, including international aviation, have increased by 14% since 1990 and that the sector is significantly off-track from delivering the reductions required to meet the UK's Fifth Carbon Budget.¹⁰

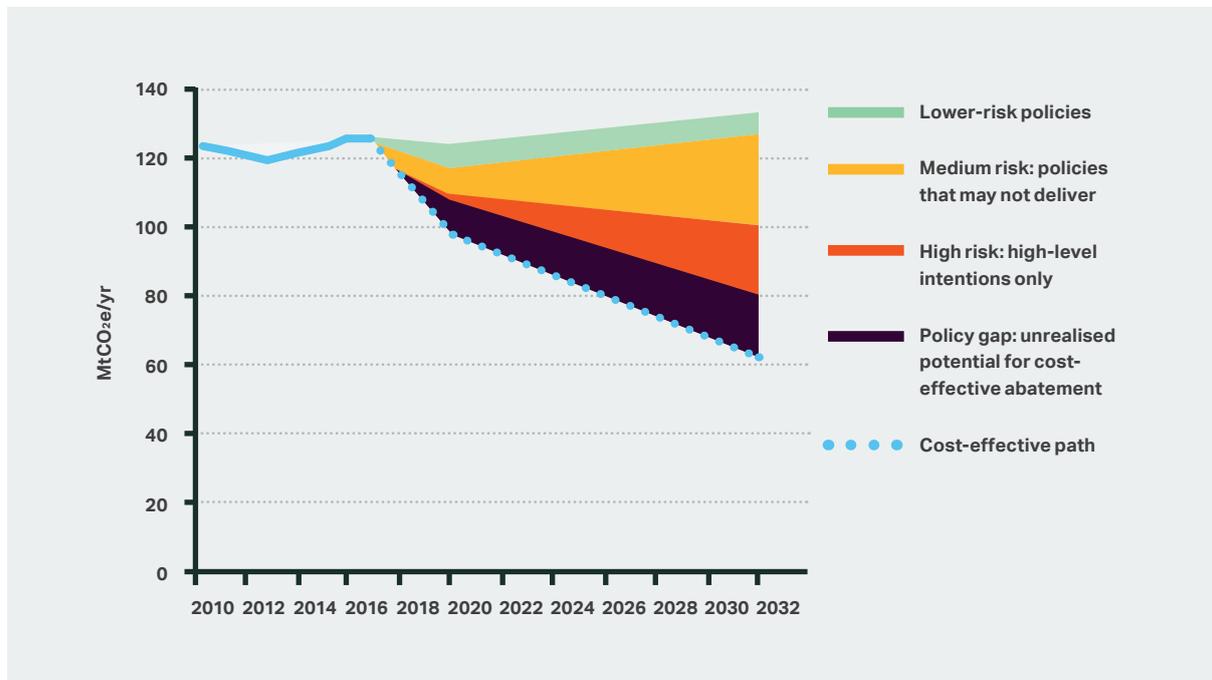
The broad current plans for decarbonising the mobility sector, as set out in the Government's Road to Zero strategy, can be summarised as follows:

- Improving petrol and diesel vehicle efficiency through standards and tax incentives;
- Electrification of transport through a commitment to end the sale of conventional vehicles by 2040 and financial support for electric vehicles and charging infrastructure;
- Increasing the proportion of renewable fuels used in transport through an obligation on fuel suppliers to sell low carbon fuels; and
- Modal shift of transport to walking or cycling for people or from HGVs to rail or water for freight.

The CCC views these policies as insufficient to deliver the reductions in emissions required to meet the UK's 2050 commitments under the 2008 Climate Change Act. The 'gap' between what might be achieved by these policies, and the level of reduction required is presented in Figure 2-1. This shows that even if all current 'high-level' policy intentions (considered as 'high risk') are successful, the level of emissions reduction in 2030 will still be nearly 10 MtCO₂/annum short of what is required.

Biofuels are a further alternative to hydrogen and electrification as a route to decarbonising mobility and currently make up around 3% of fuels sold in the UK. Liquid and gaseous biofuels, including

Figure 2-1: Gap between Government mobility policy and required CO₂ reductions by 2030.



Even under the most optimistic scenario, whereby all current 'high-level' policy intentions (considered as 'high risk') are successful, the level of mobility-related emissions reduction in 2030 will still be nearly 10 MtCO₂/annum short of what is required.

biomethane and Bio-substitute natural gas (BioSNG) have an important role to play, but this is likely to be constrained by the limited availability of low-cost, sustainable biomass feedstocks, for which there is also competition from the heat and power generation sectors.

2.3 Why choose hydrogen?

The key Government policy for achieving high-levels of emission savings is electrification of mobility. There is no doubt that battery electric vehicles (BEVs) reduce transport emissions and air pollution. However, they suffer from the following challenges:

- The 'range' (i.e. distance they can travel on one charge) of BEVs is lower than petrol or diesel;
- Charging times for BEVs are considerably higher than for petrol or diesel;

- Excluding fuel duty and VAT, electricity is more than three times the cost of diesel, which means that the transition to BEVs will increase overall energy system costs, even allowing for the higher efficiencies of BEVs;

- The electricity network will require significant reinforcement to charge BEVs, further increasing costs to wider electricity customers;

- Electrification only delivers deep reductions in GHG emissions if BEVs are charged using renewable (or nuclear) electricity. As discussed further below, further growth in deployment of BEVs will therefore require considerable additional Government spending to support new renewable generation.

The likely pathways for the production of low carbon hydrogen in the UK are water electrolysis, gasification of sustainable biomass and reformation

of natural gas combined with CCUS, as is proposed under the HyNet project. The key advantages of hydrogen compared to other mobility fuels can be summarised as follows:

- It has no CO₂ emissions at the point of use;
- It can be produced at sufficient volumes to meet the UK's total mobility (and heat and power) demand;
- Large volumes can be stored for long periods and cost effectively in salt caverns, as currently takes place for large scale natural gas storage;
- It can be transported efficiently using existing gas networks;
- It can be converted into electricity (to meet both power and mobility requirements) efficiently using fuel cells;
- Hydrogen fuel cell electric vehicles (FCEVs) have an extended range comparable to that of diesel vehicles (hydrogen vehicles share powertrain technologies with BEVs and so are referred to as FCEVs); and
- FCEVs can be refuelled very quickly, again consistent with existing petrol and diesel vehicles.

A number of these issues are explored in further detail below.

It is also possible to use hydrogen in internal combustion engines, either alone or in dual-fuel vehicles, such as those which have been deployed by ULEMCo in the UK.¹¹ Such an approach represents a low cost option, which is likely to be attractive to some mobility sub-sectors, particularly in the short-term. In the medium to longer term, however, the falling costs and greater efficiency of FCEVs is such that they form the main focus of this report.

2.3.1 Energy density, range and charge duration.

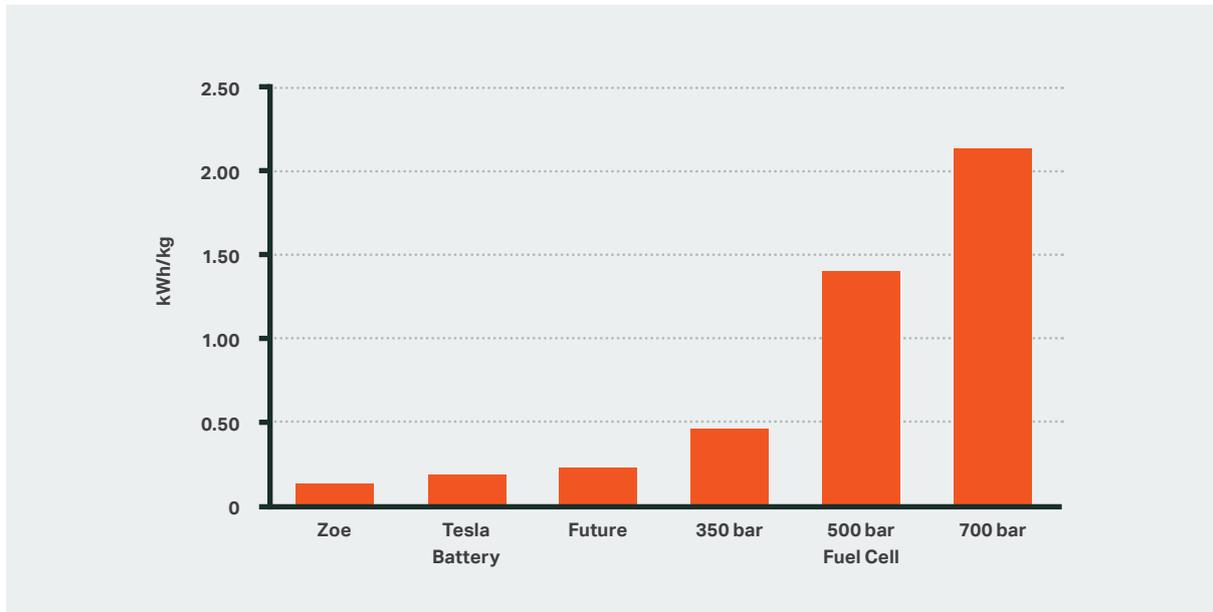
There have been impressive advances in the energy density of batteries over the last decade. Hydrogen has a very high energy density by mass but its energy density by volume is low and so it must be stored at high pressures for use in vehicles, which requires high strength tanks to store the hydrogen safely. Taking this into consideration, however, as presented in Figure 2-2, hydrogen still achieves far higher energy densities than batteries. This analysis takes into consideration the mass of the tanks required to store hydrogen safely in fuel cells and the mass of the wider packs used to house cells in batteries. This facilitates far greater range of FCEVs over BEVs.

There are two internationally agreed pressure levels for on-board hydrogen storage; 350 bar and 700 bar. Most major global automotive OEMs have adopted 700 bar for cars (which have restrictive packaging constraints), while 350 bar has generally been used in Europe for larger vehicles such as buses and trucks. However, in both cases there are examples which deviate from these 'norms'.

Battery mass and cost increase linearly as range or vehicle size increases. This is because batteries are made up of a number of cells which increase linearly with battery size. The mass and cost of fuel cells and hydrogen storage generally increases more gradually with scale because it involves larger rather than additional units. As a result, FCEVs should be more suitable than BEVs for large, heavy vehicles which require high ranges.

As highlighted above, the charging time for all BEVs can be a major issue for owners. Standard home chargers operate at 7kW to 22kW and will charge a car in 6-15 hours. There is also a growing network of public 50-120kW chargers that can recharge compatible BEVs in 1-2 hours. These charging times, combined with restricted range, require a significant change in how vehicles are used that will increase journey times. In comparison, hydrogen vehicles can refuel in 5 minutes, a similar time to existing cars.

Figure 2-2: Energy storage density of BEVs and FCEVs.

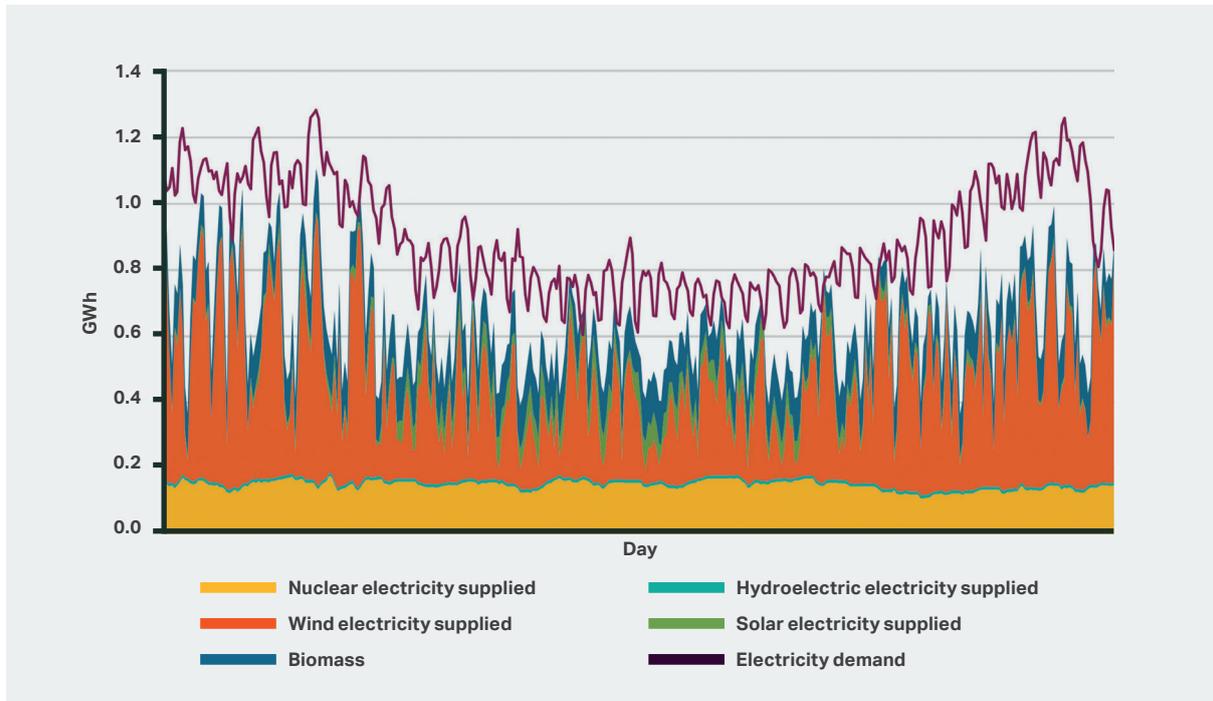


Hydrogen achieves far higher energy densities than batteries even when the mass of the storage cylinders is considered. This gives FCEVs a major range advantage over current BEVs.

“Alstom carried out a detailed study to optimise the design of low carbon trains for UK routes where electrification is not cost effective. We compared an all-battery system to a hydrogen fuel cell and battery hybrid system and it was clear that the fuel cell hybrid offered better economic and environmental performance in addition to higher reliability. Alstom has already deployed its Coradia iLint hydrogen hybrid trains in Germany and is currently working with Eversholt Rail to deploy its Breeze trains in the UK.”

Mike Muldoon, Head of Business Development & Marketing, Alstom UK&I.

Figure 2-3: Renewable electricity supply vs total power demand.



This graph shows that in 2030, according to Government forecasts, the supply of low carbon electricity will meet 68% of demand from homes and business. Any incremental additional demand from BEVs will therefore have to be met by generation from fossil fuels, likely natural gas.

2.3.2 Lack of availability of low carbon electricity.

The availability of low carbon electricity is constrained by several factors, primarily the availability of Government support under the current 'Contract for Difference' regime and planning restrictions for onshore wind in England. This means that it is very unlikely that low carbon generation will match demand for the foreseeable future.

The forecast supply of renewable electricity compared to total power demand across 2030 is shown in Figure 2-3. This is based on Government forecasts of future renewable power production, and similar data on current power consumption adjusted to reflect population growth and a 10% improvement in the efficiency of electrical appliances¹² and shown for a representative annual profile through the year.

The analysis shows that total demand of 328TWh is matched with 223TWh of low carbon electricity leaving a 105TWh gap. This analysis is consistent with National Grid's 'Future Energy Scenarios' work.¹³

Part of this gap could be met by imports of low carbon power from Europe, albeit wind patterns between the UK and mainland Europe are not entirely inconsistent and therefore availability of imports is likely to be limited. Until bulk low carbon hydrogen is available for power generation, however, as is being explored by the HyNet project, the majority of additional power will be generated from fossil fuels. At some point in the future, batteries from BEVs may be employed as 'virtual power plants', supplying power to the grid as well as

drawing out power, thus helping balance supply and demand. Should this take place at scale, it could have small impact in reducing the gap between low carbon supply and demand at certain times of the day, but this is by no means guaranteed.

The above analysis does not consider the following additional challenges associated with the transmission and distribution of renewable electricity to vehicles:

- The ongoing switch of generation from large centralised fossil fuel stations to offshore wind and other renewables requires substantial changes to the transmission and distribution networks;
- Home charging of BEVs requires significant reinforcement of local distribution networks to meet the additional demand. For example, current guidelines allow 2kW per household in local electricity distribution networks. Domestic BEV chargers typically operate at 7kW, which means local networks need to be upgraded after only a few have been installed. On average, an electric car will increase home power consumption by 60%.
- Rapid charging will require new network capacity to deliver power to strategic charging points.

All of these issues will take time to resolve and increase the cost of electricity to customers. Vivid Economics, in a study on behalf of the CCC, estimate that the cost of reinforcing the electricity distribution network to accommodate BEVs and heats pumps is more than £40 billion.¹⁴



2.4 Why hydrogen from natural gas?

As mentioned above, there are three main methods of producing low carbon hydrogen at scale that are likely to be deployed in the UK:

- Electrolysis using low carbon electricity;
- Gasification of biomass with or without carbon sequestration; and
- Reforming of natural gas, oil or coal into hydrogen with CCUS, as proposed in the HyNet project.

The key advantages to reforming of natural gas with CCUS are:

- The UK has access to large reserves of natural gas, both in domestic waters and overseas, via existing pipelines and liquified natural gas (LNG) imports. This enables bulk production to deliver meaningful volumes of hydrogen in the context of meeting the UK's 2050 carbon target;
- As discussed in Section 5.2, high levels of CO₂ capture can be achieved resulting in GHG savings of more than 75% compared with diesel or petrol;
- Offshore oil and gas fields within UK waters are reaching the end of economic life and have been shown to be suitable for CO₂ storage;¹⁵
- Costs of hydrogen production are far lower than alternatives, as explored in Section 4.2.

In summary, reforming of natural gas is an important source of hydrogen that is able to deliver sufficient quantities in the medium term to meet the mobility (and heat) elements of the UK's carbon targets cost effectively. It is also currently the only way to establish hydrogen (and CCUS) infrastructure and so provide for other sources of energy, such as domestic offshore wind or overseas solar power, to feed the hydrogen network in the future.

3.0 Availability and potential for cost reduction

3.1 Deployment status.

FCEV technology is well understood. Cars have been available to purchase in the UK since 2014, and other forms of vehicle are also now commercially available. In each case, however, both the current lack of availability of bulk, low carbon hydrogen and lack of refuelling infrastructure have held back large-scale production. The expected development of hydrogen vehicles in each segment of the market is summarised in Figure 3-1.

The UK is one of the leading countries in respect of hydrogen vehicle deployment for cars, buses, trains and ferries. The truck or HGV market is more challenging because the UK market is relatively small and has a different regulatory approach and design requirements to the rest of the world, including Europe. This means that manufacturers have not yet demonstrated fuel cell electric HGVs in the UK. As discussed below, this is of critical importance to meeting the UK's carbon objectives, as the long range and fast-refuelling requirements are such that it is a market less suited to BEVs.

Global and UK FCEV availability in each market segment is summarised in Table 3-1.

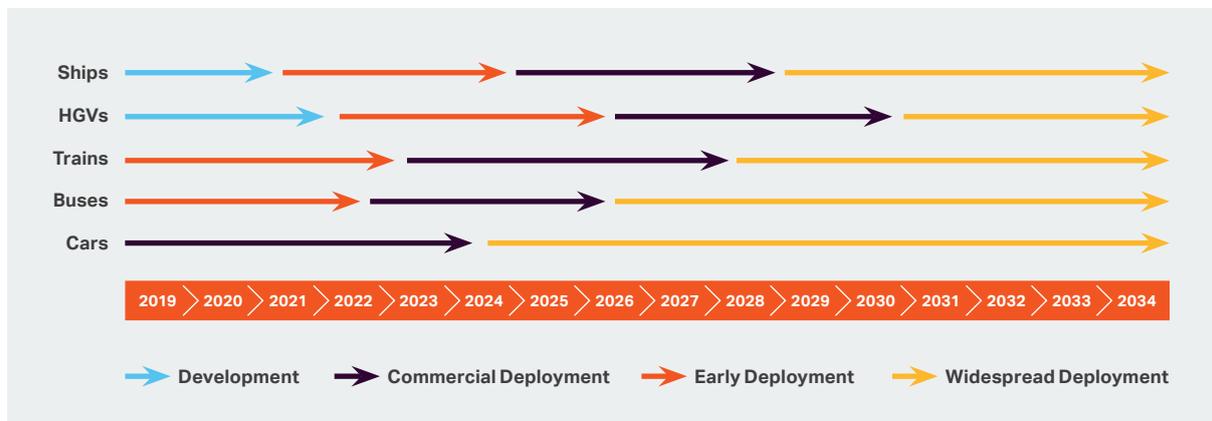
3.2 Potential for cost reduction.

As mentioned above, most of the components used in FCEVs are common to BEVs and so, in the sense of technology evolution, the FCEV industry has the potential to 'piggyback' on the early success of BEVs. However, there are two key technologies that are specific to FCEVs:

- The fuel cell converts the hydrogen into electricity. There are several competing designs which are largely based on proton exchange membrane technology, although solid oxide fuel cells have been deployed in buses.
- The hydrogen tank that stores the fuel at high pressures. These high-pressure tanks are made from complex materials that are light but strong enough to contain the fuel safely.

It is the production of these components that constrains FCEV production. Producing the fuel cells and tanks in small quantities is expensive. FCEVs are therefore currently more costly than both BEVs and conventional petrol and diesel vehicles. Toyota is currently producing 3,000 FCEV 'Mirai' vehicles per year, each of which cost around \$65,000. However, in fuel cell production, most costs are in the production

Figure 3-1: Deployment status of FCEV types in the UK.



In the majority of sectors, FCEVs are ready for deployment, but large-scale production has been held back by the current lack of availability of bulk, low carbon hydrogen and a lack of refuelling infrastructure.

Table 3-1: Summary of FCEV availability in different market sectors.

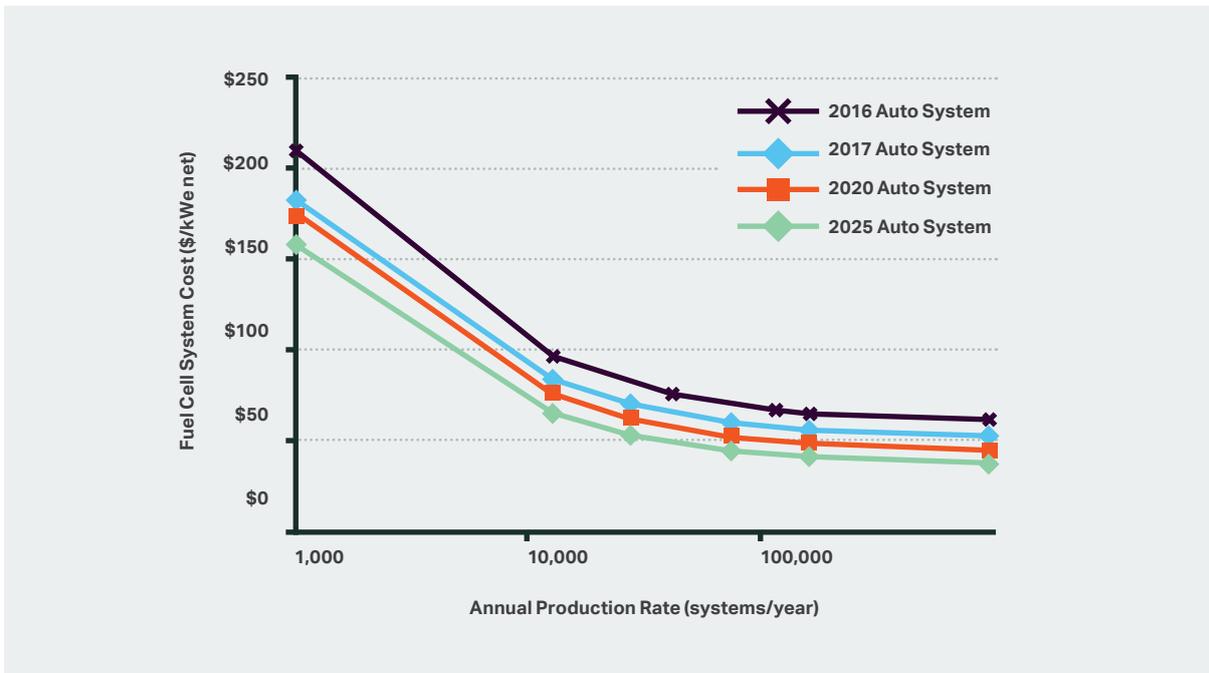
Market Segment	Current Manufacturers	Total Number of Vehicles Currently Operating	Commercially available in the UK	Planned Deployments
Cars	Toyota Mirai. Hyundai Nexa. Honda Clarity. Mercedes. Riversimple. Microcab.	c. 10,000	Yes	Audi, Daimler (Germany) and Kia to launch vehicles in 2020. Toyota and Hyundai ramping up production in 2020's to 30,000 units per year.
Buses	ADL. Van Hool. Daimler. Allenbus. Wrightbus.	c. 1,000	Yes	More models coming to market across 2019 and 2020, including those developed by Alexander Dennis for deployment in Liverpool. EU funding to deliver further 350 buses over the next five years.
HGVs	None commercially available.	c. 5	No	Hyundai to deploy 1,000 trucks in Switzerland by 2023. Nikola to launch vehicles in Norway and USA in 2021. Ballard/Re-fire to supply 500 vehicles in Shanghai.
Trains	Alstom Coradia. iLint.	2	No	Alstom working with Eversholt Rail on UK trains.
Maritime	HySeas III. Zemships.	None	No	Early deployment projects being developed in Orkney (UK), Finland, Norway and Sweden.

line and so there are significant economies of scale yet to be delivered. Consequently, a report from the US Department of Environment suggests that costs will reduce significantly with volume as shown in Figure 3-2.¹⁶ As a result, Toyota is targeting the production of 30,000 fuel cell vehicles early by the 2020s and Hyundai has recently announced a \$6.8 billion investment in fuel cell technology.^{17 18}

Section 4.0 shows that low cost, low carbon hydrogen produced by HyNet has the potential to transform hydrogen mobility by making the total cost of ownership (TCO) of hydrogen vehicles comparable to diesel and battery electric vehicles. However, this will only be possible if vehicles are available and produced in sufficient numbers for them to be cost effective. Section 6.0, therefore, suggests the steps that should be taken to ensure FCEVs are brought to market.



Figure 3-2: Projected future reduction in fuel cell system costs.



In fuel cell production, most costs are in the production line and so costs will reduce significantly as volumes increase.

4.0 FCEVs as a cost competitive solution

4.1 Regulatory drivers and UK deployment of FCEVs.

The UK Climate Change Act and Air Quality Plan have led to the following interventions in the UK transport market:

- Capital grants have been made available for hydrogen vehicles and associated refuelling infrastructure from the Office for Low Emission Vehicles (OLEV), the European Union and a limited number of local authorities;
- Lower rates of car tax are offered for FCEVs (and BEVs) and the capital allowances and 'benefits in kind' regime for business encourages their adoption;
- No duty is charged on the hydrogen or electricity used in FCEVs and BEVs, while duty equivalent to £55/MWh is charged on diesel. Generally, buses can recover most of this cost, while trains are wholly exempt from duty.
- The Renewable Transport Fuel Obligation (RTFO) currently provides an incentive for the production of bioethanol, biodiesel or electrolytic hydrogen produced using renewable electricity. The DfT is currently considering amending the RTFO to include low carbon hydrogen produced from natural gas with CCUS;

- The Low Carbon Emission Bus incentive and Bus Service Operator Guarantee provides support to some bus operators for using low carbon buses including BEVs and FCEVs; and
- Local authorities in cities such as Manchester, Liverpool, London and Oxford are considering implementing zero emission zones that would only permit free entry for FCEVs and BEVs.

These measures have achieved a modicum of success. There are currently more than 15 public HRSs in the UK, around 100 hydrogen cars and 20 hydrogen buses. Demand is constrained by the low number of filling stations, current high cost of hydrogen and the commercial availability of some vehicles. As explored in Section 6.0, industry and Government will need to work together to address these constraints before hydrogen can be widely adopted.

4.2 Hydrogen production and distribution costs.

Hydrogen has a very low energy density by volume which makes it expensive to transport it by road. Comparisons with other fuels, as presented in Table 4-1 suggest that pipelines should be the primary method of transporting hydrogen when it becomes a mainstream fuel.

Table 4-1: Energy density of Hydrogen compared with other fuels.

Fuel	Energy Density (MJ/m ³) at 350 bar for gases	Primary Transport Mode
Diesel	38,600	Road tanker
LPG	25,300	Road tanker
LNG	22,200	Road tanker
CNG	12,740	Pipelines
Liquid hydrogen	10,044	Road tanker
Hydrogen	4,158	Currently cylinders

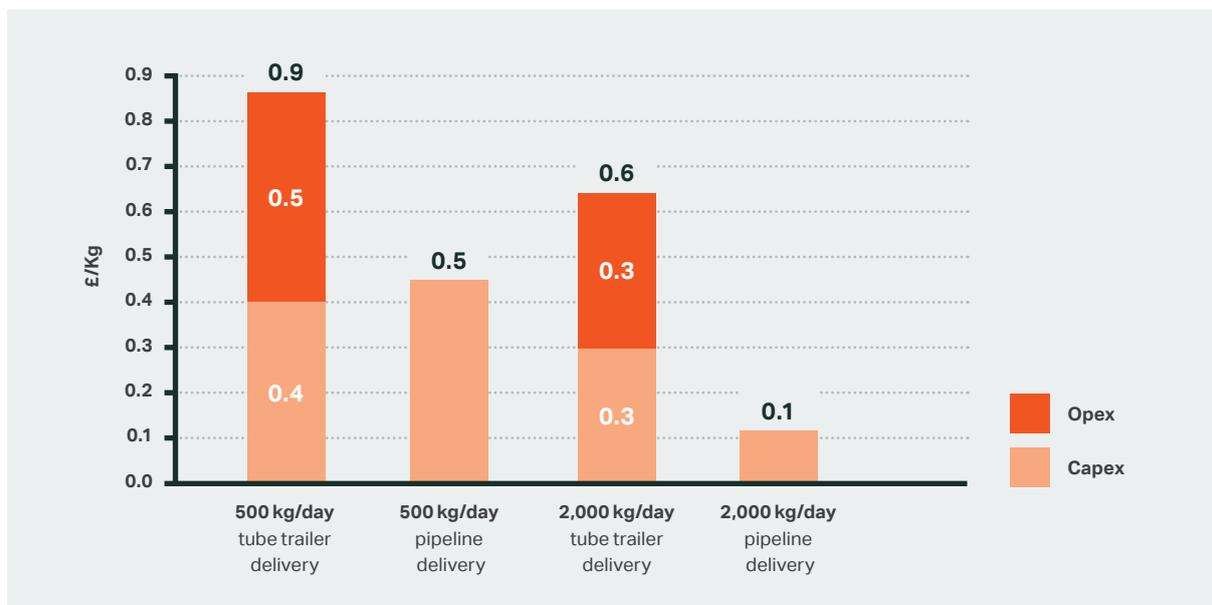
The costs for distributing hydrogen to HRSs in the HyNet region via either road (in a tube trailer) or via pipeline are compared in Table 4-2 for a 500kg/day station, which would support 40 buses and a 2,000 kg/day station, which would support 200 buses. The cost estimates are based on the delivery of hydrogen within the HyNet region, as defined in previous HyNet reports.¹⁹ Under this scenario, trailers carry the hydrogen from a central production point to an HRS as part of an average 60 km round trip. For pipeline delivery, the refuelling stations are assumed to be an average of 1km from the HyNet pipeline network.

The main costs for the tube trailer scenarios relate to driver salaries, fuel and the capital cost of the vehicles. The only cost for the pipeline is the capital cost of construction of the 'spur' from the trunk HyNet hydrogen distribution pipeline, which is assumed to already exist as a result of the wider HyNet project. Operation and maintenance of the pipeline is included in the cost of the gas as a result.

Delivery of hydrogen via an underground pipeline is also inherently safer than delivery by tube trailer. At present, natural gas is delivered safely to millions of homes and businesses and the gas industry is working hard with Government and regulators to ensure that similar levels of safety will be achieved for hydrogen networks. Furthermore, pipeline delivery will avoid the need for above ground storage and therefore any need to meet related safety requirements.

Currently, transport hydrogen is produced by electrolysis of water at HRSs, which provides very high purity hydrogen. Some developers and HRS operators are exploring the production of hydrogen at sites directly linked to offshore wind farms, where electricity costs are lower, combined with road transport of the hydrogen in tube trailers, to see if this can reduce costs. This model relies upon support under the RTFO, which requires connections to new wind farms only.

Table 4-2: Comparison of hydrogen distribution costs.



Pipeline delivery is by far more cost effective in the HyNet area than road delivery. The advantages are greatest for large refuelling stations that are located close to the core HyNet pipeline network.

Most fossil hydrogen used in industry is currently produced via steam methane reforming (SMR) of natural gas. At present, this hydrogen is transported by road to some HRSs in the UK, but offers very little, if any GHG abatement versus diesel.

HyNet is different in that it will use a more efficient reforming process known as Auto Thermal Reforming (ATR), and it will capture the resulting CO₂ for transportation and storage safely offshore. This provides a low carbon hydrogen to be injected into a pipeline network for distribution to customers. More details can be found in the HyNet report.²⁰

Hydrogen from both SMR and ATR is less pure than hydrogen produced by electrolysis because it contains contaminants from the natural gas feedstock. These can largely be removed using technology at the ATR or SMR plant called pressure swing adsorption (PSA) to produce hydrogen that can be used in FCEVs. There are some uncertainties, however, around the costs of such purification, not only because the standard for grid hydrogen has not yet been determined, but because additional clean-up may also be required at the HRS. Standards for grid hydrogen purity are being explored as part of the Government's current Hy4Heat project, which should provide some clarity towards the end of 2019.²¹ In addition, this issue is being explored further as part of HyMotion, as discussed in Section 7.1.

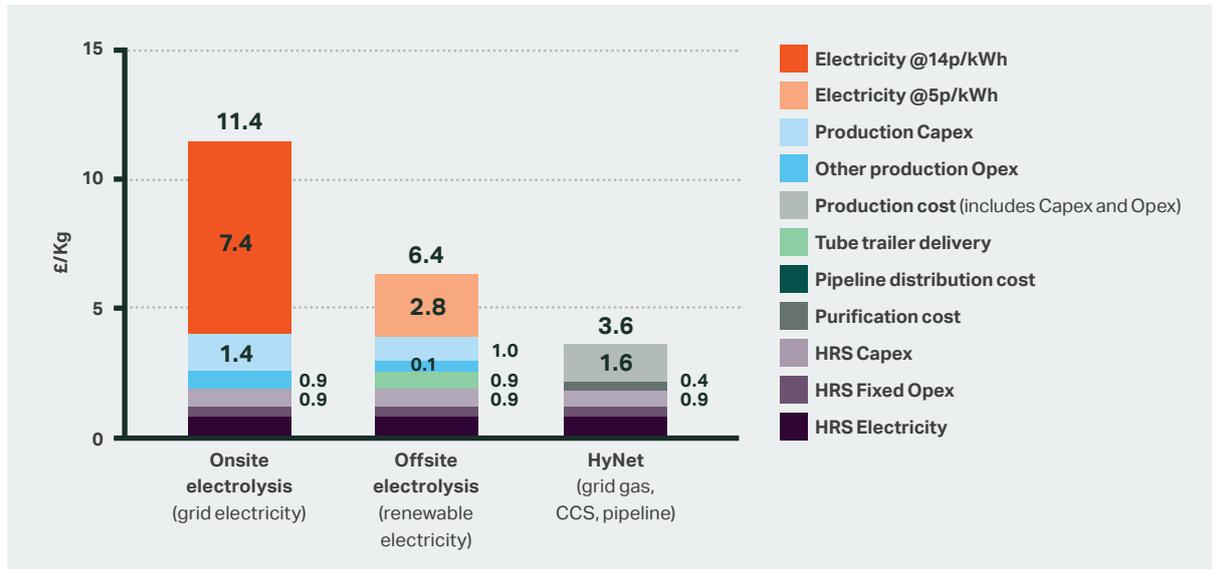
The costs of each low carbon production and distribution option are presented in Figure 4-1. For the ATR option, this modelling is based upon the 'worst case' cost for purifying hydrogen from the network, with additional clean-up required at the HRS. Even with these potential additional costs, the modelling suggests that HyNet will be able to deliver hydrogen to FCEVs at prices that are 70% lower than are being achieved by electrolysis at HRSs today. These prices will transform the economics of hydrogen vehicles and means they can be competitive with diesel and BEVs, as explored in Section 4.3.

As mentioned above, HyNet benefits from substantial economies of scale because hydrogen is primarily being produced for heat and the costs of the trunk pipeline are spread across a very large number of users. It should be noted, however, that the cost estimates for the HyNet project are currently evolving via significant further ongoing project design work and will change prior to financial close. Furthermore, in respect of Opex, the key cost input for the HyNet hydrogen is natural gas. Government forecasts suggest that this could vary between 1.04p/kWh and 2.18p/kWh compared to the 1.62p/kWh used in the forecast.²² Historically, there has been a high degree of correlation between natural gas, power and diesel prices. High natural gas prices will therefore increase the cost of HyNet hydrogen, but it will remain competitive because the cost of electricity, electrolytic hydrogen and diesel will also be correspondingly higher.

Onsite electrolytic production of hydrogen is well understood, and stations are currently selling hydrogen at around £10-15/kg. Production volumes for a single station will be lower than centralised production and so there are also high capital and operating costs. Production at the HRS involves a high cost of electricity because power must be purchased from the grid and includes the charges for transmission, distribution and supply. The key uncertainty, however, is the price of electricity. The Government forecast a range of prices between 13.0p/kWh and 15.2p/kWh for electricity in 2022, compared to the price of 14.0p/kWh used in this model.

Centralised or 'offsite' electrolysis benefits from economies of scale because one site will serve several HRSs. The cost of electricity is also lower because off-peak power is assumed to be taken directly from a renewable source (likely offshore wind due to higher load factors), thus avoiding grid charges. These savings are partially offset, however, by the cost of transporting the hydrogen to the HRSs.

Figure 4-1: Comparative costs of Hydrogen production and distribution.



Low cost hydrogen from HyNet has the potential to transform the economics of FCEVs, such that they can be competitive with existing diesel and BEVs.

4.3 Total cost of ownership.

Fuel costs are only one component of running a vehicle. For private cars, capital cost, maintenance and insurance are important factors. For commercial vehicles, salary costs, performance and availability are equally important. For example, many HGVs will be run for 16 hours per day and if an alternative technology cannot achieve similar performance it will increase costs for the vehicle owner.

An analysis of the TCO of a vehicle is very complex because it depends on how the vehicle is used. This varies significantly for different vehicle types and the purpose of those vehicles. For example, for the same model of car, the TCO is very different if this is used as a private car used for a 10-mile daily commute rather than if it is used as a taxi. For HGVs, the vehicles that have the lowest costs for short distance deliveries in an urban setting will not be competitive for long-haul motorway transport. Broad comparisons of the cost of ownership for average use are provided below, but it is important to understand the factors behind each cost and the niche that FCEVs will fill in each case.

4.3.1 Capital costs.

The capital cost of vehicles is driven by the cost of raw materials, manufacture and marketing. The end-of-life (or 'residual') value of the vehicle allows owners to recover some of the capital cost. Generally, BEVs and FCEVs are mechanically simpler and raw material use is lower for FCEVs than for diesel vehicles. A qualitative comparison of these parameters for diesel, BEVs and FCEVs is presented in Table 4-3.

Currently, BEVs are around 50% more expensive than diesel equivalents but Morgan Stanley see BEVs reaching cost parity with diesel cars in 2025.²³ The key risk to achieving this is the cost and availability of sustainable rare metals used in batteries. Large scale production of low cost BEVs relies on new sources of these metals coming to market or alternatives being found.

A key additional uncertainty for BEVs is the life of the battery, which is the most expensive component in a BEV. Informal analysis of batteries in a Nissan Leaf BEV suggest that the battery degrades by 20% over five years.²⁴ However, user data for Tesla cars

Table 4-3: Capital Cost Comparison of Vehicle Types.

Parameter	Diesel	BEV	FCEV
Manufacturing Cost	Very low due to 100 years of experience and economies of scale – around 6m vehicles sold per year in Europe in 2018.	High because only 10 years of experience and overall sales small – 0.2m sold in Europe in 2018.	Very high because little experience and very low volumes – 6,000 cars sold in total (similar to BEVs in 2010).
Powertrain	Mechanically complex internal combustion engine, gearbox and differentials.	Simple electric engines with no need for gearbox or differentials.	Simple electric engines with no need for gearbox or differentials.
Battery	N/A	Large battery with high material costs for lithium, cobalt, graphite.	May use small battery for regenerative braking.
Fuel cell	N/A	N/A	Majority of cost is in manufacturing with relatively low material costs.
End of life value	Most components can be recycled or reused easily.	Significant challenges in reuse or recycling of battery.	Most components can be recycled or reused easily.

suggests that degradation is only 5% after ten years, perhaps reflecting a better thermal design.²⁵ These results are consistent with manufacturer guarantees but more formal, peer reviewed studies are necessary to provide greater certainty.

The analysis presented in this report assumes that batteries have the same life as the vehicle – 10 years or more. However, if further research shows that the useful lifetime of a battery is only five years it will significantly increase both the cost and GHG impact of BEVs.

The cost of FCEVs is currently at least double that of diesel vehicles. As described in Section 3.2, however, these premiums have the potential to fall significantly in the future. Toyota sees FCEVs reaching cost parity with hybrids in 2025.²⁶ Furthermore, the company believes that FCEVs are cheaper to produce than BEVs and once volumes are increased should be highly competitive.

4.3.2 Operating costs.

This report considers ‘total’ fuel costs and maintenance. Other operating costs such as driver salaries are assumed to be similar for diesel vehicles, BEVs and FCEVs.

The range of maintenance activities for electric vehicles is far less than internal combustion engine vehicles because the number of moving parts is lower. Electric vehicles do not have a gearbox, clutch, timing belt or spark plugs. As a result, maintenance costs for BEVs and FCEVs are expected to be less than diesel vehicles once there are sufficient vehicle numbers to support a greater number of qualified mechanics and supply chains mature, which will lead to lower cost spare parts.

Total fuel costs are a function of fuel efficiency and the price paid for fuel. Current fuel efficiencies are presented in Figure 4-2. These figures reflect the following factors:

- Electric motors (in BEVs and FCEVs) are more efficient than internal combustion engines particularly in stop-start operation;



- Electric vehicles benefit from regenerative braking; and
- Hydrogen fuel cells operate at efficiencies of 40-60%.

It is helpful to consider the fuel costs per 100 kilometres to understand how this influences vehicle choices. At current prices, the efficiency for diesel results in a fuel cost for a bus of around £37/100km including fuel duty, which means that a hydrogen price of £4.60/kg would result in fuel cost parity between a fuel cell and diesel bus. FCEV costs will fall as the efficiency of hydrogen vehicles improves, whilst the cost of diesel may also rise as a result of Government policy in line with the Road to Zero strategy.

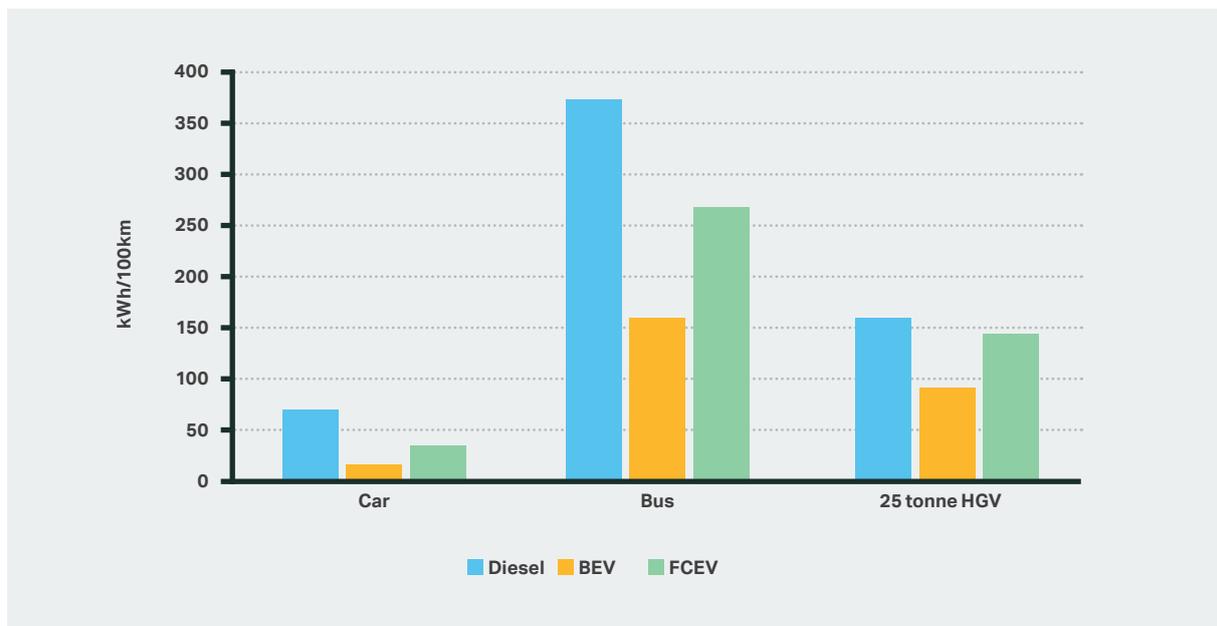
At present, the £4.60/kg target price for hydrogen to achieve 'diesel parity' is significantly lower than can be achieved by electrolysis, either on or offsite from the HRS. The £3.60/kg cost that can be achieved by HyNet, however, is highly competitive with diesel.

Government forecasts a range of prices for domestic customers in 2025 between 17.5p/kWh and 19.7p/kWh for electricity.²⁵ At such prices, fuel costs for battery electric cars will be £3.15 to £3.54 per 100 km, which is around 60% of the current average cost of £5.70 per 100km for diesel cars. However, this saving is entirely due to the fuel duty charged on diesel and so if this were taken into account, the fuel cost of battery electric cars would be higher than for diesel cars. Fuel cell cars achieve fuel cost parity with battery electric cars if the hydrogen price is £4.20/kg, which is higher than the expected cost of HyNet hydrogen set out in Figure 4-1. There are also likely to be additional improvements in FCEV efficiency, which will reduce costs further.

4.3.3 Whole TCO analysis.

Estimates of the capital and operating costs of vehicles discussed above have been combined to produce estimates of the TCO of diesel vehicles, BEVs and FCEVs, as presented in Figure 4-3. In respect of these results, it should be noted that:

Figure 4-2: Comparison of fuel efficiency between vehicle types.



BEVs are the most efficient vehicles, with FCEVs also far more efficient than diesel. Fuel efficiency is, however, just one element in the TCO of vehicles.

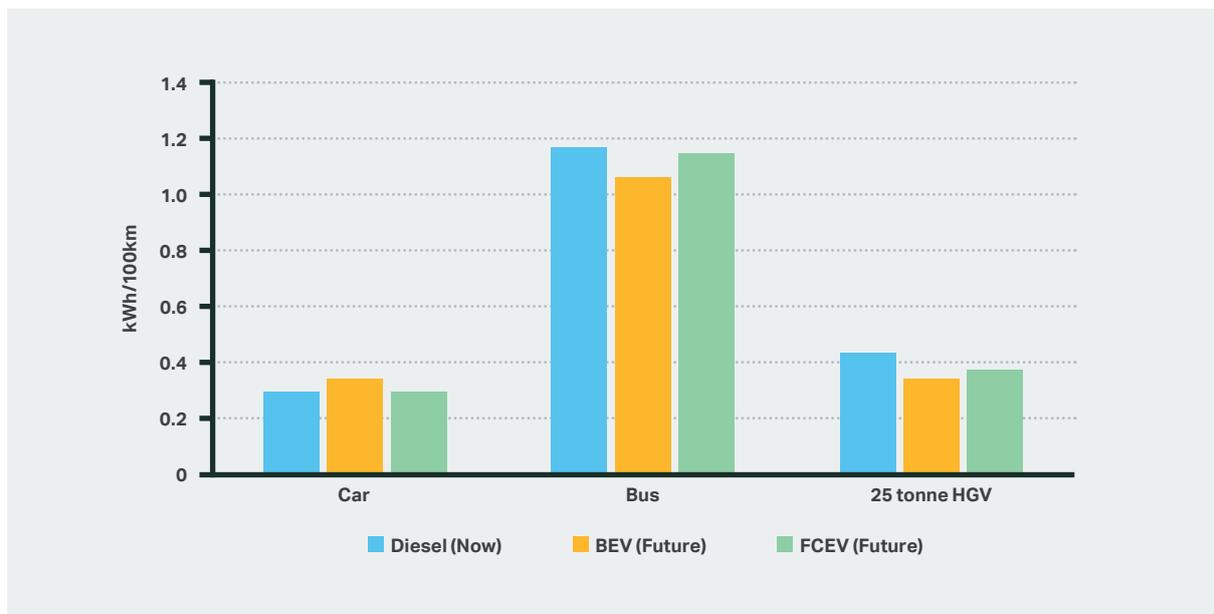
- This is only a high-level analysis based on an 'average' duty cycle and does not consider detailed, potentially highly variable duty cycles of vehicles;
- The analysis below assumes a delivered electricity price of £140/MWh and a diesel price of £1.10/litre (including Fuel Duty). Both of these are in line with Government Green Book estimates;²⁷ and
- The maritime and rail sectors have both been excluded from this analysis, as current data for FCEVs (and BEVs in the case of the former) is not sufficiently meaningful to merit inclusion.

Broadly, the higher expected capital cost of BEVs and FCEVs is offset by lower operating costs because of the higher efficiencies of electric vehicles. Fuel duty plays a significant role in the analysis, particularly for buses and HGVs. If fuel duty were charged on electricity or hydrogen used in BEVs and FCEVs then their costs would increase.

It is challenging to predict when the expected 'future' costs for BEVs and FCEVs will be achieved. The potential for reductions in capital costs described in Section 3.2, will only be achieved when large numbers of vehicles are produced. This can only be driven by Government and local authorities (supported by Government) either via the setting of emission standards that exclude diesel vehicles from the market and from local geographies, or policies that incentivise the take up of FCEVs and BEVs.

The BEV and FCEV costs shown in Figure 4-3 should be achieved by 2030 if Government policy develops in ways consistent with the aspirations set out in the 'Road to Zero' strategy.²⁸ Under current policies it is possible that BEVs will achieve cost parity in the next five years in some segments. However, new Government action will be required to bring significant numbers of FCEVs to market, as discussed in Section 6.0.

Figure 4-3: Total cost of ownership for different vehicle types.



At some point in the future, very much dependent on Government policy, BEVs and FCEVs will have similar TCOs to diesel. Depending upon the particular vehicle and duty cycle, under some scenarios BEVs will have a lower TCO and for others, FCEVs will be more attractive.

“Toyota places great importance on the environment and a key issue for sustainable transport is reducing the material input, increasing product life and reducing end of life waste through reuse and recycling. Batteries have a finite life and it is challenging to reuse, refurbish or recycle a degraded battery. A key advantage of fuel cell, which is often overlooked, is that they have lower material input, much longer lifetimes and can easily be reused in multiple applications and when no longer required have virtually 100% recyclability. As a result, FCEVs are likely to deliver far greater environmental benefits than BEVs and lower costs to customers.”

Jon Hunt, Alternative Fuels Manager, Toyota.



5.0 Meeting climate and clean air goals

5.1 Deployment of Hydrogen vehicles.

Figure 5-1 and Figure 5-2 present estimates of the total potential demand for hydrogen and related deployment of FCEV vehicles in the North West region in 2030. This estimate is based on several key assumptions, which vary across 'low', 'medium' and 'high scenarios', including:

- The TCO of FCEVs in comparison to other options;
- Potential Government and local regulation and policy incentives;
- The availability of FCEVs.

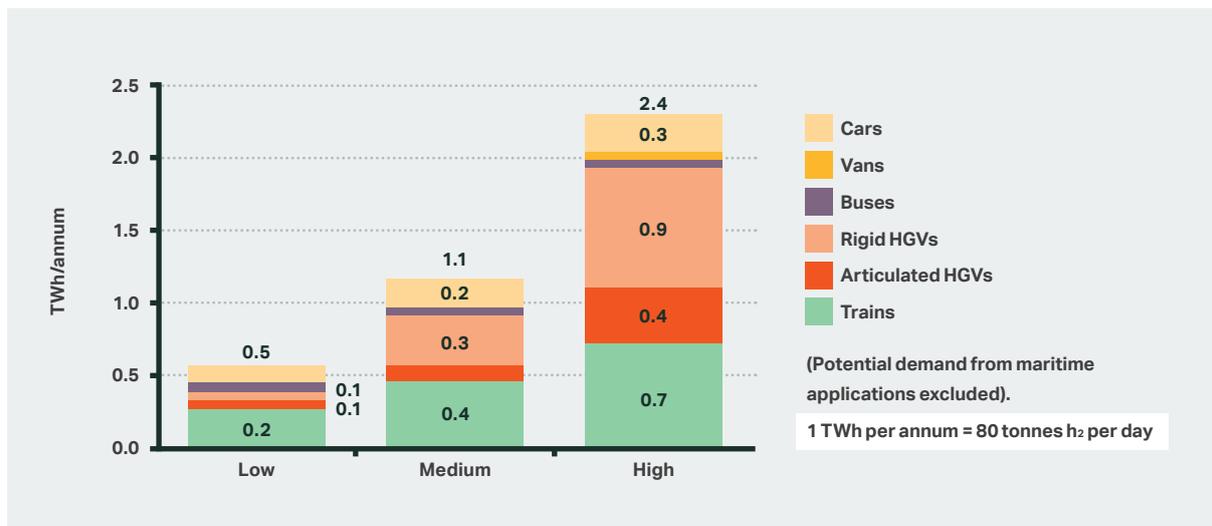
The medium and high scenarios also both assume that the North West benefits from low cost and available low cost hydrogen from the HyNet project.

The expected hydrogen demand in 2030 ranges between 0.5TWh and 2.4TWh, compared to total expected HyNet hydrogen production in 2030 of 6-9TWh for heat. In the medium scenario this equates to around 19,000 vehicles, a small proportion of the overall fleet, as shown in Figure 5-2.

The greatest potential is in trains and HGVs, where FCEVs have clear advantages over BEVs. The take-up in buses is relatively high at over 9%, but the overall bus energy consumption is low and so the impact of buses in respect of CO₂ abatement is likely to be small. Car and van take-up is likely to be low (in percentage terms) because FCEV cars are only preferable to BEVs in a limited number of (long-range) segments, for example, taxis.

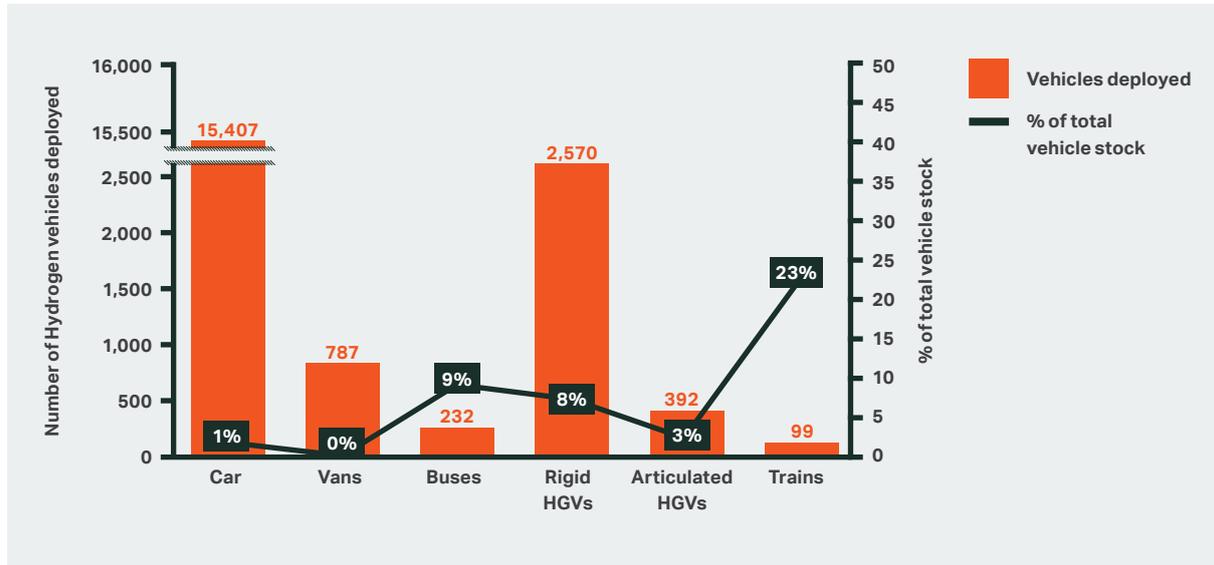
The medium scenario appears to be broadly in line with other published forecasts. A recent study from the Hydrogen Council forecasts FCEV market share of 8% for passenger vehicles and 7% for HGVs by 2030.²⁹ At the same time, Frost and Sullivan forecast that 240,000 FCEVs will be deployed across Europe in 2030.³⁰

Figure 5-1: Estimates of Hydrogen demand from FCEVs in the North West in 2030.



The medium and high scenarios both assume that the North West benefits from low cost and available low cost hydrogen from the HyNet project.

Figure 5-2: Estimates of FCEV deployment in the North West in 2030.



Percentage take-up of buses is relatively high, but HGVs and trains have far higher fuel demand and therefore offer greatest potential for CO₂ reductions.

The following factors are likely to lead to high deployment of FCEVs:

- The successful delivery of the HyNet project to provide low cost, low carbon hydrogen to vehicles across the North West;
- Ongoing Government commitment to the targets enshrined in law by the Climate Change Act, such that there are new, long-term support mechanisms for all forms of FCEVs;
- The introduction of zero emission zones in areas of poor air quality where only BEVs and FCEVs may operate;
- Good availability of FCEVs in the UK market for cars, trains and HGVs; and
- Improvements in battery performance, costs and sustainability are modest.

The key risk that is likely to prevent high deployment is the failure of vehicles to come to market. Some car manufacturers in Japan, Korea and China are investing heavily in FCEVs, driven by Government support for hydrogen. If this investment is withdrawn for commercial or political reasons, then the development of vehicles will be delayed.

Another aspect of this risk is the introduction of vehicles specifically into the UK market. The cost of adapting cars from the Japanese market is relatively small and understood. As described above, however, this is a significant challenge in the HGV market, because UK standards are very different to those in the USA and Asia and Far Eastern manufacturers with fuel cell expertise have very little presence. Fuel cell HGVs will only enter the UK market if Government and industry work together to introduce them.

5.2 Climate change benefits.

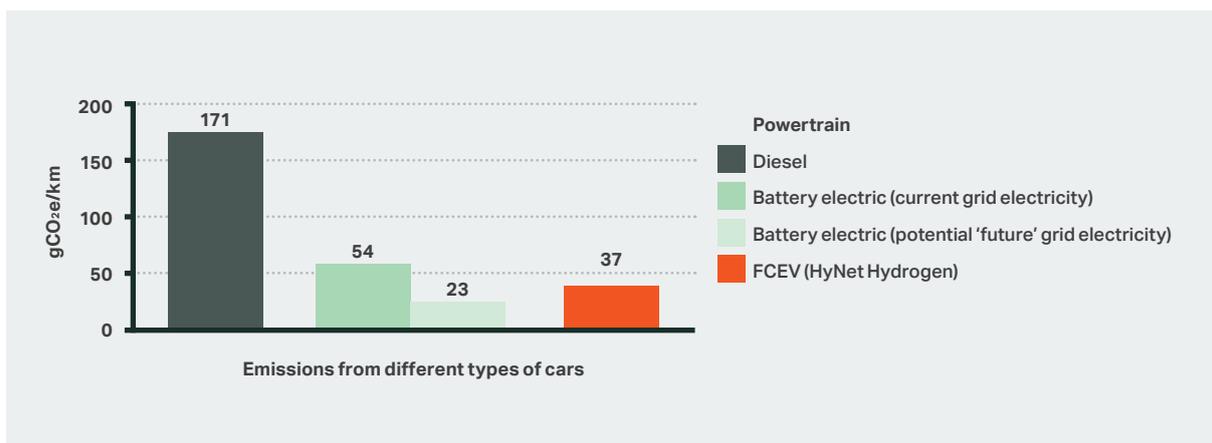
The GHG emissions for a fuel cell car are compared to those from diesel and battery electric cars in Figure 5-3. This shows that BEVs offer significant savings compared to diesel vehicles (either now or in the future) because of their higher efficiencies and the lower 'carbon intensity' of electricity generation compared with combustion of diesel in engines. This would be the case even if the electricity sourced for BEVs was generated from natural gas. Deeper CO₂ reductions can be achieved if wholly renewable electricity is used to recharge the batteries but, as discussed in Section 1.3, it is highly uncertain as to when (in time) incremental demand created by BEVs will be met by low carbon power.

The basis for the assumed carbon intensity of hydrogen from the HyNet project is described in detail in the related project reports and results in savings of nearly 80% compared to diesel cars.³¹ This is better than the savings delivered by BEVs unless they are fuelled by renewable electricity.

The above analysis deliberately ignores the emissions associated with the production and manufacture of batteries, fuel cells and hydrogen storage. These could increase emissions by around 37gCO₂/km for both batteries and fuel cells, but can be addressed using low carbon energy in the manufacturing process and increased scale of production.^{32,33} If battery life is at the lower end of expectations, however, as discussed in Section 4.3.2, then this could become material.

Figure 5-4 presents the overall benefit of the medium deployment scenario on CO₂ emissions in the North West. The forecast reduction of over 0.3m tpa in 2030 is around 4% of the current transport emissions in the region and is especially significant because it primarily addresses vehicle types that aren't suited to BEVs.

Figure 5-3: Comparison of CO₂ emissions from cars.



Hydrogen cars will deliver the deepest CO₂ emissions reduction unless power for BEVs can be sourced entirely or largely from renewables, which appears unlikely based on the forecast gap between renewable demand and generation.

5.3 Cost of carbon abatement.

The TCO analysis presented in Section 4.3.3, and detailed in the Technical Appendices, showed that, for cars, BEVs are expected to cost 5p/km more than diesel vehicles if fuel duty is ignored. FCEVs are expected to cost 2p/km more. These costs can be combined with the GHG savings shown in Figure 5-3 to produce an estimated cost of carbon abatement as shown in Figure 5-5. This metric can be useful for Government when comparing different policy options.

The results presented in Figure 5-5 represent an ‘average’ scenario for cars only, and will vary across vehicle types and duty cycles. The BEV figures would also improve significantly if BEVs were charged using low carbon electricity; but as mentioned above, this appears very unlikely even if Government aspirations for offshore wind deployment are wholly fulfilled.

The £150/ tCO₂ cost of abatement for a HyNet FCEV compares very well to other decarbonisation options for the mobility sector. According to analysis by the DfT, efficiency improvement in vans is expected to cost £120/ tCO₂, greater car fuel efficiency will cost £200/tCO₂ and greater HGV fuel efficiency £220/ tCO₂. It is also worth noting that these other ‘efficiency’ measures, which are also likely to merit Government

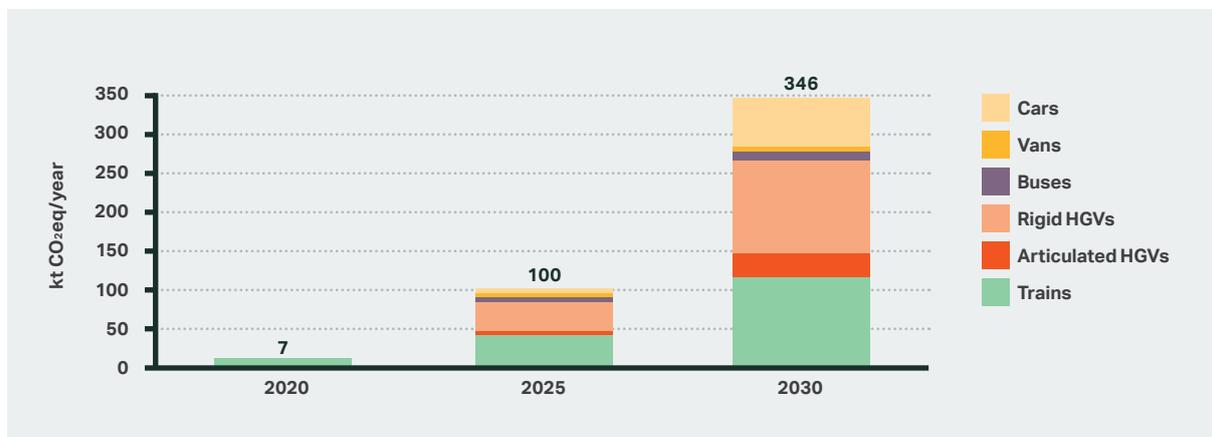
support alongside alternative fuels, could only deliver limited amounts of abatement. So, while apparently cost competitive, additional measures are required to deliver upon the Government’s Road to Zero Strategy and to meet future Carbon Budgets.

5.4 Air quality benefits.

Figure 5-6 presents the overall benefit of the medium deployment scenario on NO_x emissions in the North West. The forecast reduction of over 3,000 tpa in 2030 represents around 10% of the current NO_x emissions in the region and is based on FCEVs replacing current diesel vehicles only. There would be similar savings in particulate emissions. Again, such potential benefits are especially significant because they primarily address vehicle types that aren’t suited to BEVs.

NO_x can also be reduced by improving the design of diesel vehicles. However, FCEVs are intrinsically clean – the only emission from the tail pipe is water. This means that the reduction in NO_x (and particulates) from FCEVs is very likely to be achieved in practical terms. In contrast, there are concerns that improved pollution abatement via catalytic converters and user measures will be frustrated by either poor

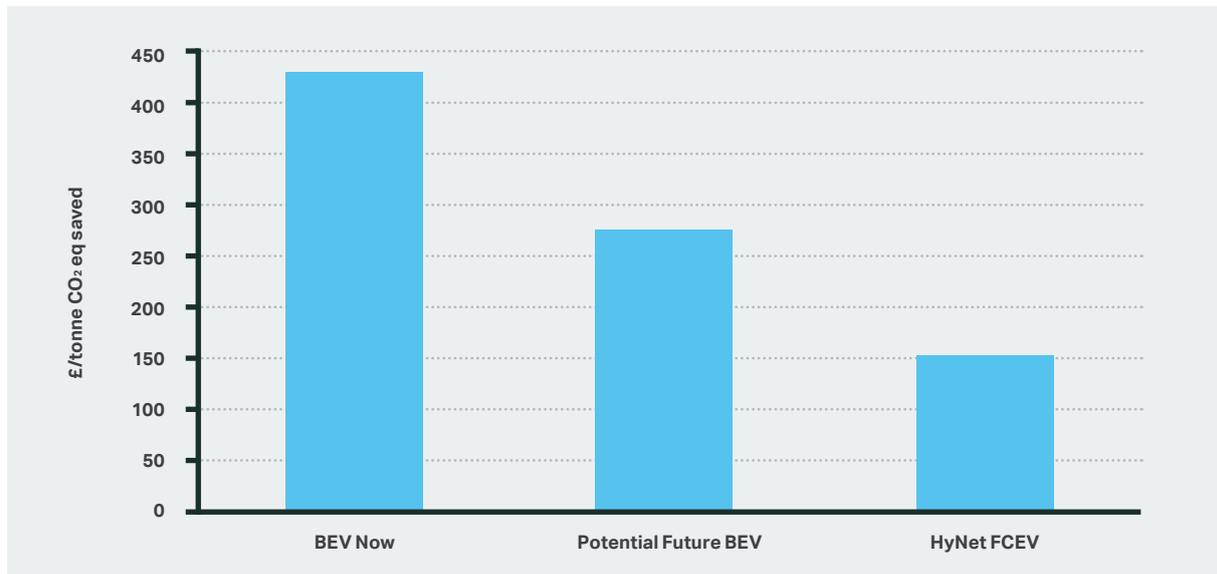
Figure 5-4: Potential total CO₂ reduction from FCEVs in North West (medium scenario).



FCEVs in the North West could deliver a meaningful volume of CO₂ reduction by primarily addressing the mobility sectors which are not suitable for BEVs.

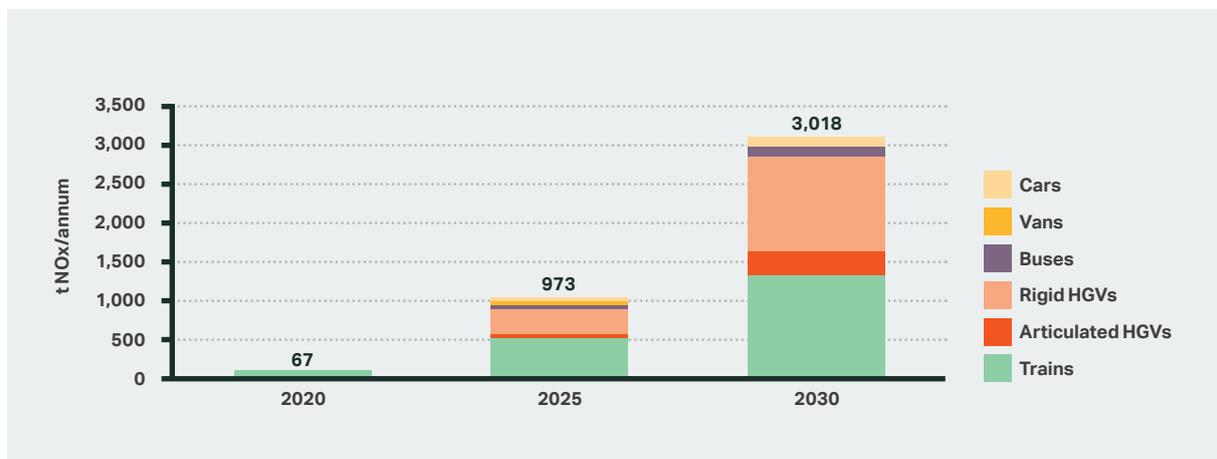
maintenance of systems or fraud, such as 'Ad Blue cheating', whereby operators have purchased the vehicle technology to reduce NOx, but install software to avoid Ad Blue checks and so reduce costs.

Figure 5-5: Comparative cost of carbon abatement (cars).



Deployment of FCEVs fuelled by HyNet hydrogen provides a highly cost-effective form of CO₂ abatement. Alongside other low carbon vehicles, FCEVs will enable the Government to meet its policy goals at lowest cost.

Figure 5-6: Potential total NOx reduction from FCEVs in North West (medium scenario).



FCEVs in the North West could deliver a meaningful volume of NOx reduction by primarily addressing the mobility sectors which are not suitable for BEVs.

6.0 Roadmap to deployment

6.1 A Hydrogen mobility plan for the North West.

As described above, the primary objective of HyNet is to deliver a hydrogen infrastructure for the supply of low carbon heat in the North West. This infrastructure can also be used to decarbonise mobility and power. This supply of low cost, low carbon hydrogen will not, however, result in the adoption of FCEVs unless good quality vehicles are available together with a network of HRSs. Industry and Government need to work together to deliver the full potential benefits of a transition of the mobility sector, in part, to hydrogen. In respect of each mobility sub-sector, a set of targeted industry and Government actions are described in Table 6-1 to deliver this transition.

Not only will a collaborative approach between Government and industry result in reductions in CO₂ emissions and better air quality, but this is an opportunity for the creation of an FCEV industry in the UK, both in terms of vehicle manufacture and also in respect of equipment to distribute and purify network-delivered hydrogen at HRSs. This will result in additional gross value added (GVA) to the UK economy, as described in a recent report relating to the wider

HyNet project.³⁴ In addition, there will be employment opportunities resulting from infrastructure deployment and the opportunity to export services and expertise overseas, consistent with Government's Clean Growth Strategy.³⁵

Fuel cell innovation is primarily taking place in the Far East but there are several UK companies that are active in developing the technology including Arcola, Alstom UK, Toyota UK, Johnson Matthey and Intelligent Energy. These will all benefit from Government support for the deployment of FCEVs.

Assuming Government and industry take such appropriate action to promote FCEVs, a potential roadmap to deployment is presented in Figure 6-1.

6.2 Bringing vehicles to market.

As described above, Toyota and Hyundai have both committed to bringing hydrogen cars to the market in large volumes by the mid-2020s, while Audi is planning to launch FCEVs in the early 2020s. These manufacturers are likely to offer fuel cell cars in the UK provided that the Government continues to offer

Table 6-1: Industry and Government actions required to deliver FCEVs.

Sub-sector	Industry Action	Government Action
Cars	Manufacturers to continue development of FCEVs and supply them to UK market.	Continue commitment to zero emission vehicles and continue to incentivise FCEVs after BEVs no longer require subsidy. Local Government to introduce zero emissions zones.
HGVs	Development of industry consortium to promote introduction of vehicles to UK market.	Set standards to decarbonise HGVs and to introduce subsidy for zero emission vehicles.
Trains	Cross sector co-operation to generate viable fleet operation business cases supported by train operators.	Drive introduction of first fleets through appropriate funding and residual value mechanisms to support investment.
HRSs	Continue build-out of 350 and 700 bar refuelling networks. Encourage open access to reduce costs for all users.	Continue funding of HRSs in strategic locations.
Supply & Distribution of hydrogen	Continue to develop HyNet North West and proposed North East and Scottish hydrogen networks.	Introduce support for low carbon hydrogen networks for both heat and transport. Ofgem to enable construction of hydrogen networks under RAB.

support for low emission vehicles. This will provide fuel cell options to car buyers.

Hydrogen buses are already on the market with support provided through the Government’s ‘Hydrogen for Transport’ programme.³⁶ In addition, some of the buses in JIVE and JIVE 2 Programmes have received match funding from the Low Emission Bus Scheme and Ultra Low Emission Bus Scheme.³⁷ The success of these bus schemes is likely to lead to demand for more fuel cell buses, but in the short to medium term the realisation of this demand will continue to rely on support from Government to bridge the gap between the cost of hydrogen and diesel buses. Support for hydrogen buses is also available in some areas via the Bus Service Operators Grant (BSOG) and Low Carbon Emission Bus subsidy.

Bringing fuel cell HGVs to the UK market is a major challenge. The following issues should therefore be taken into consideration as part of any related Government policy development:

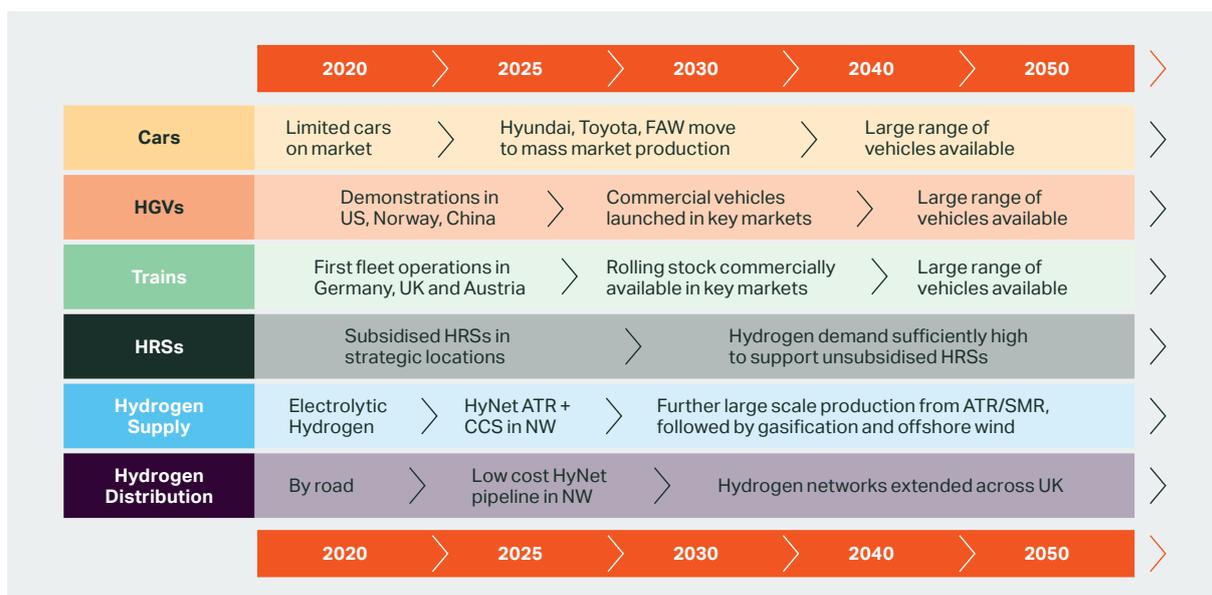
- Fuel cell HGVs are being rolled out in the US, Norway, Switzerland and China where there are supportive tax or support regimes. There are no such incentives for HGVs (or other ‘commercial’ FCEVs) in the UK at

present and therefore neither manufacturers nor fleet operators have shown much interest in working together towards deployment;

- The UK commercial vehicle market is different from the rest of the world because of national regulations in respect of vehicle weight. The overall UK market is small, and manufacturers are unlikely to develop vehicles for a small market.
- The commercial vehicle industry is relatively conservative and prefers vehicles from established manufacturers. This is such that DAF, Mercedes, Scania, Volvo, MAN, Iveco and Renault accounted for 94% of the UK market in 2015.³⁸ Large scale deployment of hydrogen HGVs in the UK will therefore be extremely challenging without the collaborative support of one of these companies.

There is interest from UK fleet operators in FCEVs, but this needs to be matched with technology providers and vehicle manufacturers to build a consortium that will bring vehicles to market. As part of this exercise, it may be necessary to develop new UK standards to enable longer vehicles to provide additional physical space for hydrogen fuel.

Figure 6-1: Potential sub-sector roadmaps to widespread commercial deployment.



Fuel cell trains have been deployed in Germany and Alstom is working with Eversholt Rail Group to deploy its Breeze trains in the UK. Alstom's analysis shows that there are many routes in the UK that cannot easily be electrified and are suitable for the use of hydrogen. The UK rail industry is heavily regulated with a very complex commercial structure. To navigate this structure, Government needs to incentivise the deployment of fuel cell trains via new contractual mechanisms focused on innovation. Furthermore, Government should sponsor the development of full system business cases for UK specification trains to deploy as fleets.

Hydrogen is a good candidate fuel for ships, where space is less constrained than in road vehicles, and hydrogen fuel cell ships are ready for deployment. Ferry companies are keen to adopt low carbon technologies, but economics have thus far driven them to the lowest cost solutions. To encourage the adoption of hydrogen fuel cell vessels, Government will need to provide related support until production reaches sufficient scale to match the cost of fossil fuelled ships.

The impact of providing capital grants for low carbon vehicles has been demonstrated by the 'plug-in' grant scheme.³⁹ Initially, this provided a subsidy of up to £5,000 per electric car and resulted in sales of 15,000 units in the UK in 2018. The subsidy was recently reduced by Government to £3,500 per vehicle and will fall further over time until it is no longer necessary.

6.3 Hydrogen production and distribution.

As discussed above, the cost of HyNet hydrogen is substantially lower than low carbon hydrogen produced by electrolysis but is still more expensive than fossil diesel or petrol. Part of this premium is because the scale of hydrogen production is currently far smaller than diesel production and so doesn't benefit from the same economies of scale. In addition, the efficiency of making hydrogen is lower than refining diesel and there are additional costs for capturing and storing the related CO₂.

Consumers and businesses will not switch to hydrogen if it increases the cost of running their vehicles. It is

likely that the greater efficiency of FCEVs compared to internal combustion engines will eventually reduce the cost of running hydrogen vehicles until they are close to diesel. However, it will take several years for this to be achieved.

Fuel duty provides a partial solution to this issue. Currently, no duty is charged on hydrogen used in transport while diesel is taxed heavily. This duty differential should be maintained to allow hydrogen to compete with diesel. However, further support will be required to bridge the cost gap.

The RTFO provides support for low carbon biofuels. The Government is considering extending the scheme to include 'low carbon' fossil fuels. This extension should include hydrogen produced from reformation of natural gas with CCUS, provided that it can be clearly demonstrated that the resulting hydrogen meets the RTFO GHG reduction target.

The construction of a network, such as that proposed by the HyNet project, to distribute hydrogen to consumers will require a large initial capital investment. It is proposed that this network is funded in the same manner as existing natural gas networks and therefore built by gas distribution companies which then recharge the costs to gas consumers over a relatively long period. This would require agreement between Government, Ofgem and the gas distribution companies. It is a proposition discussed in detail in a HyNet report in relation to heat, but which is equally applicable to mobility.⁴⁰

6.4 Refuelling infrastructure.

A HRS requires filling pumps, compressors, grid connections and potentially, depending on how hydrogen is delivered, hydrogen storage capacity. There are several established suppliers of HRS equipment, such as Linde and NEL. A typical HRS will cost £2-3m depending on the number of vehicles served and distance from the grid, if onsite electrolysis is used to generate hydrogen. The main operating costs include hydrogen (if supplied by tube trailer), labour and power costs for compression together with property costs such as rent and rates.

There are a number of companies, such as Shell and BOC (Linde) that are willing to develop HRSs to serve their own vehicles or on a merchant basis. OLEV and EU funding has been available to subsidise the refuelling infrastructure. To enable mass deployment of FCEV's this support must continue, but the future of such funding support is currently uncertain. The design of related support mechanisms should also take into consideration the need to link capital funding to a requirement for ongoing maintenance of the

HRS. Lessons must be learned from the funding and development of the BEV charging infrastructure, which has been plagued, particularly in the early years, by charging points not being properly maintained.

Revenues for HRSs are driven by the number of vehicles using them. Hydrogen sales of 500kg per day (equivalent to around 50 buses) are usually required for a HRS to meet investor's hurdle rates of return. Even with capital grant support, smaller stations are unlikely to be economically viable.



“Shell is seeking investment opportunities for hydrogen in transport. For example, we have invested in the German H2 Mobility joint venture alongside Air Liquide, Daimler, Linde, OMV and Total, which aims to build, own and operate 400 hydrogen refuelling stations by 2023. We believe that hydrogen has a key role to play in transport in territories where Governments are willing to co-invest with the private sector.”

Mike Copson, Global Business Development, Shell.

6.5 Spatial distribution of infrastructure.

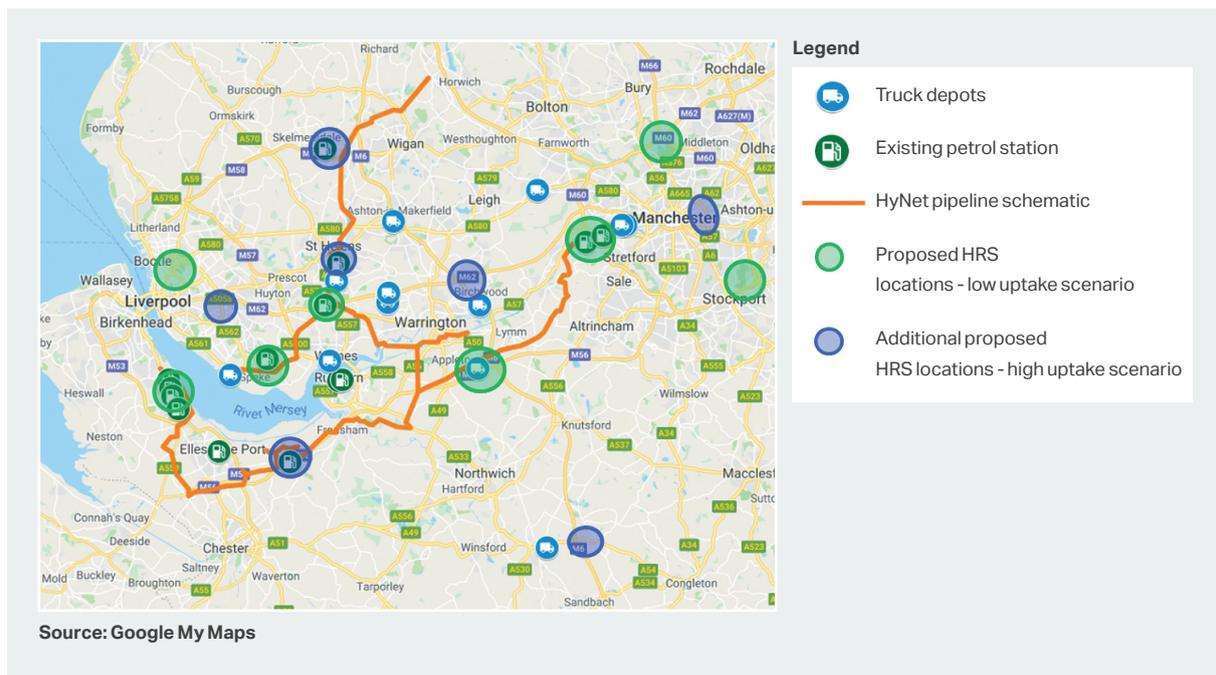
The refuelling infrastructure required to support FCEV deployment in the North West has been assessed with reference to the scenarios set out in Section 5.1. In 2030, the low scenario would require 15 HRSs, each selling 800kg/day, whilst the high forecast would require 30 HRSs selling 1,500kg/day. These volumes will likely require many of the HRSs to be ‘agnostic’ in respect of the type of FCEV that they serve. Overall, such a network of HRSs across the HyNet region would have a capital cost of £40-80m. Selling at those volumes, such a network should be able to operate without public support.

Spatial modelling has also been undertaken to determine appropriate locations for HRSs. This is based on an assessment of the locations of existing petrol and diesel filling stations in the HyNet region together with the current locations of HGV (particularly back-to-base fleets) and local bus depots, along with known existing locations for train maintenance and refuelling. These locations have been modelled against the expected HyNet hydrogen pipeline network routes

to identify locations that minimise network connection costs while optimising the likely number of vehicles that will use the HRS. The results of this analysis are presented in Figure 6-2.

In many cases, there is a natural conflict between locating an HRS as close as possible to the network and locating it at an existing depot. While the former minimises costs, the latter is likely to encourage fleet operators to adopt FCEVs, as it minimises disruption. This analysis suggests that the majority of HRSs can be located relatively close to the HyNet network. To supply some existing major fleet depots, however, several would need to be located around 5km from the network and so may require road delivery of hydrogen, as a dedicated spur pipeline would likely be too costly. An alternative possibility may be to ‘de-blend’ hydrogen from the 20% blend that will be injected into the existing natural distribution network as part of the HyNet project. The potential for this is discussed in Section 7.2.

Figure 6-2: Likely locations of HRSs in the North West.



7.0 Technical solutions to enable deployment

The HyNet project will not deliver low cost, low carbon hydrogen until the mid-2020s. This will provide fuel that will enable the widespread deployment of FCEVs. To enable fast deployment as soon as the network is in place, however, it is essential to take action in the shorter-term to overcome potential technical and commercial barriers to deployment.

The key mobility specific objectives during the development phase of HyNet can be summarised as follows:

- To promote joint working between manufacturers and fleet operators, funded by Government, to catalyse work on UK-focused solutions to enable the deployment of fuel cell HGVs;
- To clearly demonstrate that hydrogen produced by SMR and ATR can be purified sufficiently to meet manufacturers' warranty requirements in relation to FCEVs, as described further in Section 7.1;
- To explore the de-blending of vehicle quality hydrogen from natural gas hydrogen blends, which are likely to be present in the gas network as a result of the HyNet project, as described in Section 7.2.

These objectives will be achieved via:

1. Ongoing engagement with relevant stakeholders to socialise the findings of this HyMotion study with regard to the costs and benefits of hydrogen mobility relative to the fossil fuel status quo and to alternative mobility decarbonisation options;
2. Network-linked infrastructure demonstration projects to prove that network-supplied hydrogen from the HyNet project is suitable for fuelling FCEVs; and
3. The promotion of other projects that seek to deploy hydrogen for mobility in the North West.

7.1 A deliverable Hydrogen refuelling station.

Hydrogen is currently being produced in the HyNet region (and elsewhere in the UK) for industrial uses by SMR without CCUS. This is a carbon intense method of hydrogen production, but the specification of such hydrogen is very close to that which will be produced by HyNet. Consequently, it can potentially be used as a proxy to demonstrate the technical compatibility of HyNet hydrogen with FCEVs.

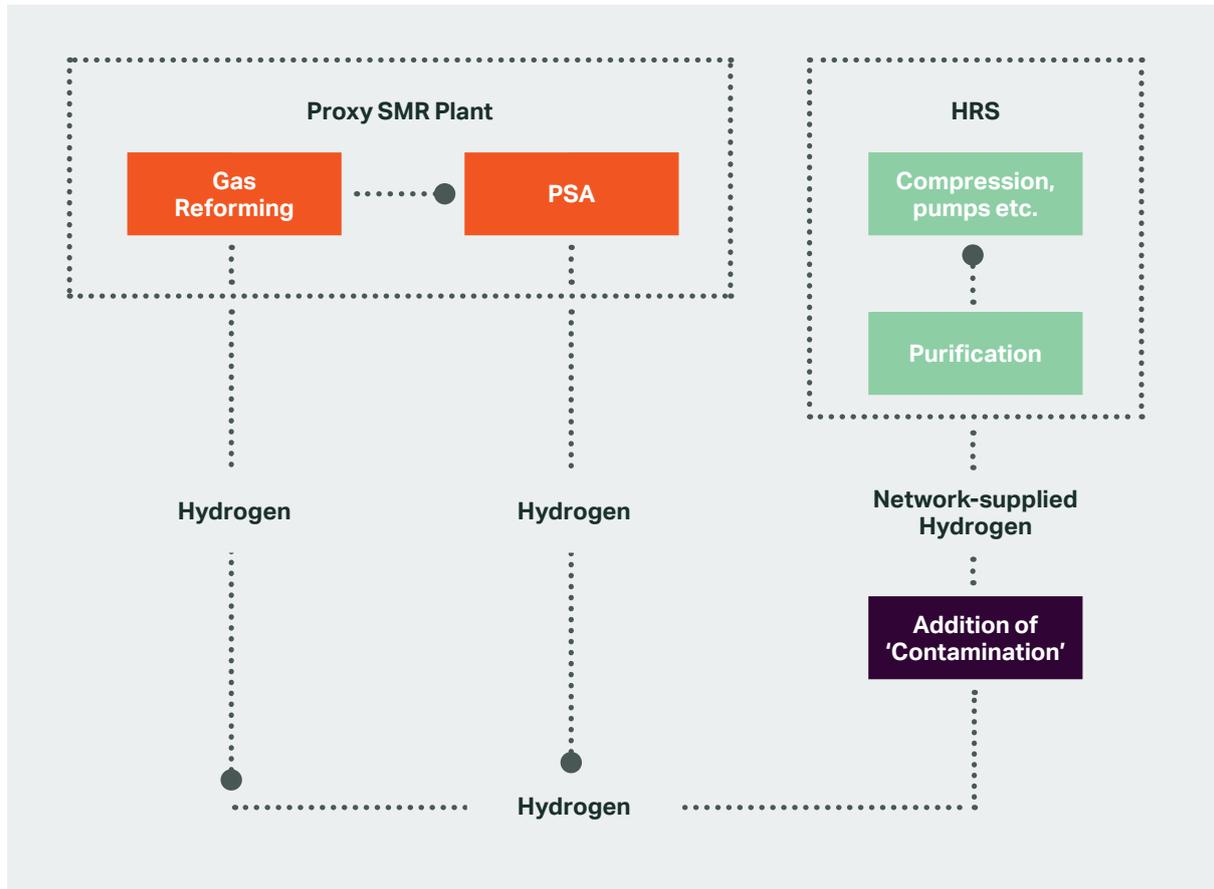
Cadent is therefore considering the development of demonstration projects that would use hydrogen of existing SMR facilities and:

- Add relevant contaminants to replicate the potential impact of network supply on SMR-produced hydrogen;
- Purify the resulting hydrogen to produce a mobility grade product; and
- Deliver that hydrogen to FCEVs and monitor their performance and any impacts on the fuel cells; and
- Demonstrate that such an approach could be permitted in a non-industrial setting, i.e. in petrol station forecourts and bus depots.

At high level, this approach is presented in Figure 7-1. It should be noted that more widely in the HyNet project, Cadent and partners are currently considering the need to employ pressure swing absorption (PSA) to purify hydrogen at the site of the ATR, and hence optionality must remain in respect of the quality of the hydrogen to be used in this potential demonstration project.

Cadent is currently seeking further partners for this project with the intent to develop the concept further during 2019 and then commence deployment in early 2020.

Figure 7-1: Potential project design to demonstrate a network-supplied HRS.



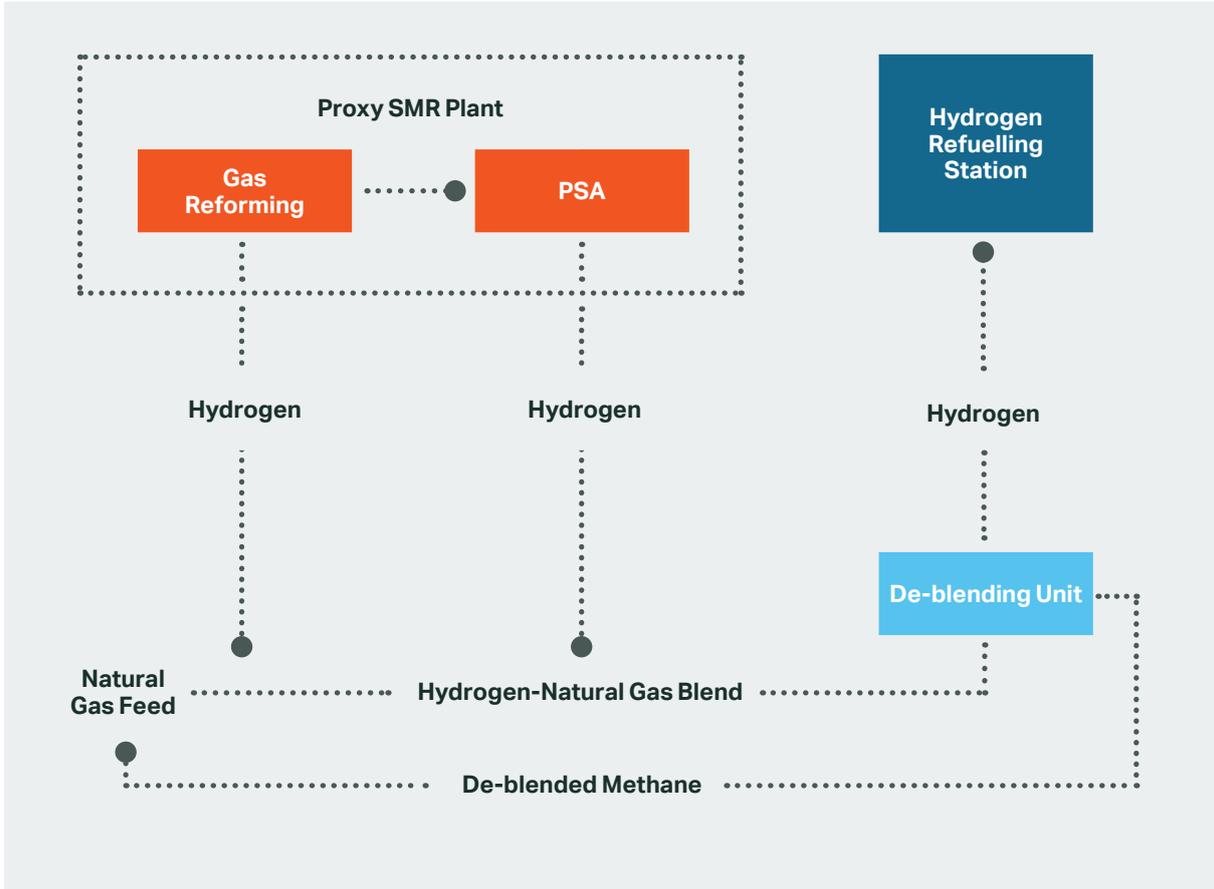
7.2 Unlocking blended Hydrogen from the network.

If hydrogen could be extracted from the blend that is injected into the network as part of the wider HyNet project, supply of hydrogen for mobility at a range of locations would be enabled without the additional cost of new pipelines. Such an approach would facilitate placing of HRSs at a range of locations not previously accessible by the new pipeline, and at potentially very low relative cost.

Cadent's ongoing HG2V project is exploring the impact of impurities in the gas network (upon both a blend and on 100% hydrogen) and will potentially include some lab-scale tests to explore the impact of the resulting hydrogen on fuel cells.⁴¹ Consequently, Cadent is seeking to build upon the findings of this work to develop a relevant project which:

- Identifies and demonstrates an appropriate 'de-blending' technology to strip hydrogen from the blend;
- Determines and demonstrates an appropriate use for the separated (largely natural) gas stream which, for example, might be either injected back into the network or used for onsite generation; and
- Demonstrates that such an approach could be permitted in a non-industrial setting, i.e. in petrol station forecourts and bus depots.

Figure 7-2: Potential project design to demonstrate de-blending to supply an HRS.



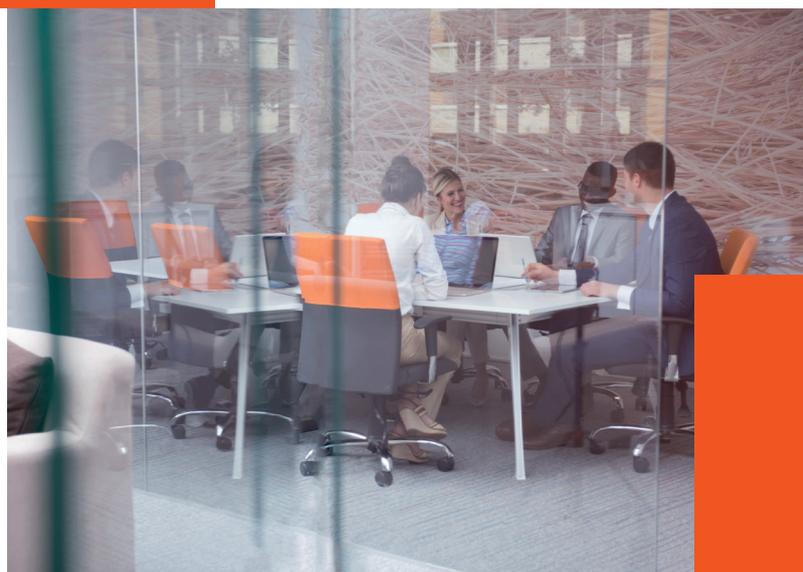
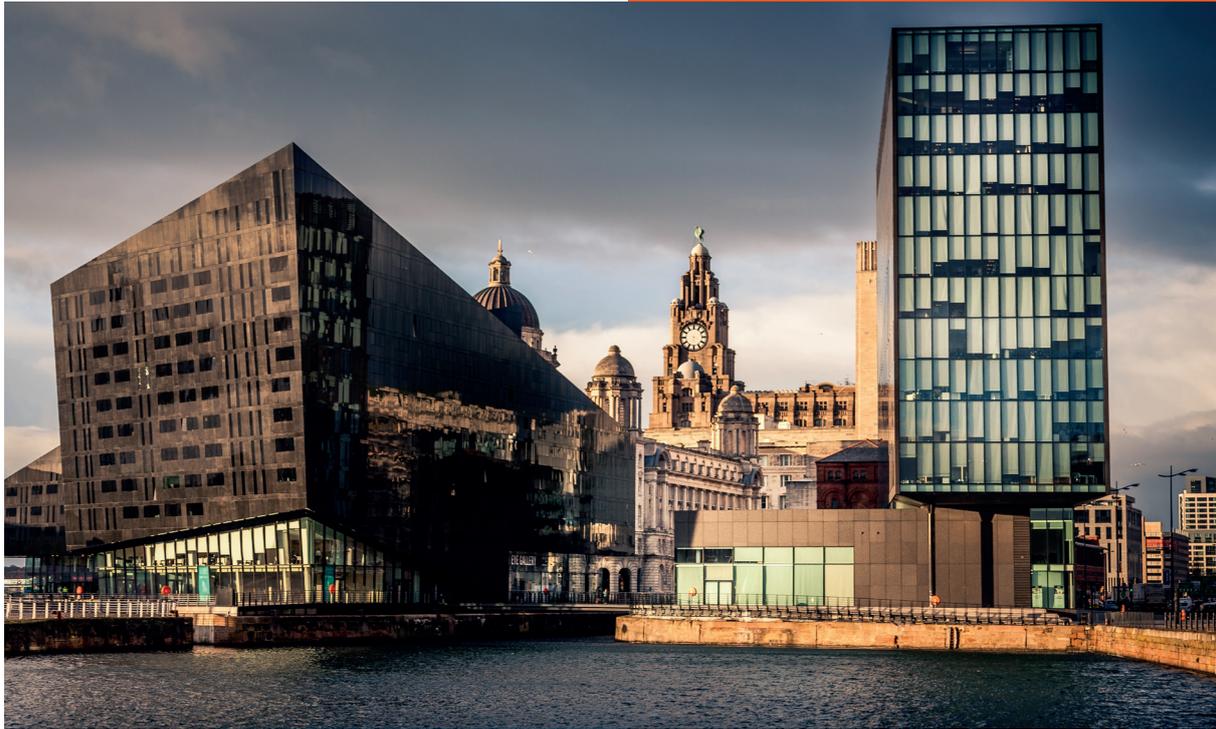
A schematic relating to the potential project is presented in Figure 7-2. Again, it has yet to be determined whether a PSA will be included in the design of the ATR as part of HyNet, and hence optionality must remain in respect of this proposed demonstration project.

Similarly, as per the network-supplied HRS described above, Cadent is currently seeking further partners for this project with the intent to develop the concept further during 2019 and then commence deployment in early 2020.

8.0 Key messages

The key messages from the work can be summarised as follows:

1. Both FCEVs and BEVs are required to meet wider decarbonisation targets. Each will serve distinct sectors of the mobility market, depending upon the required 'duty cycle'. FCEVs are more suited to providing longer 'ranges' and faster refuelling times, while BEVs can better cater for short, 'stop-start' journeys;
2. A likely future gap between low carbon electricity generation and demand is such that BEVs are unlikely to deliver sufficiently deep decarbonisation. Without delay, therefore, Government must design a suitable policy mechanism by which to support the use of hydrogen in FCEVs (alongside existing support for BEVs);
3. FCEVs are currently relatively expensive. However, manufacturers are planning to increase volumes over the next five years and it is expected that FCEVs will be of similar cost to BEVs when production volumes reach parity;
4. Hydrogen cars, buses, trains and ships are ready for deployment, but more work is required to bring hydrogen HGVs to the UK market, which could make a critical contribution to decarbonisation. This will require Government to provide innovation support to encourage fleet operators to work with vehicle manufacturers to develop suitable vehicles for the UK;
5. The low energy density of hydrogen means that distributing it by road is expensive. Using the 'trunk' of the HyNet project, and 'spurs' to hydrogen refuelling stations (HRSs), network distribution offers far lower costs under all scenarios.
6. Network-supplied hydrogen via HyNet will deliver low carbon, mobility-grade hydrogen in the North West at a cost that is 40-70% lower than can be achieved through electrolysis. This will allow the fuel costs of FCEVs to match the cost of BEVs and diesel vehicles.
7. Once economies of scale are realised, network delivery of hydrogen from HyNet will mean that the Total Cost of Ownership (TCO) of FCEVs is comparable with both BEVs and diesel vehicles. Consumer choice of vehicle will therefore in future be determined by the required duty cycle;
8. Under the 'medium' demand scenario modelled for hydrogen vehicle take-up, in 2030, FCEVs will use 1.1TWh/annum of hydrogen (around 15% of that supplied by HyNet). This equates to a reduction in mobility-related GHG emissions in the HyNet 'area' by nearly 4% and a reduction in NOx emissions of nearly 10%; and
9. In the immediate term, technical solutions to enable network-delivered hydrogen for mobility must be determined and demonstrated via collaborative working between gas network operators, gas supply companies and the wider mobility sector. Cadent is working on several related initiatives to deliver this vision. Such innovation could represent a major opportunity for technology export, in line with the Government's Clean Growth Strategy.⁴²



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