The Future Role of Gas in Transport

Green Gas Transport Pathway

Cadent
Your Gas Network

Acknowledgements

A Network Innovation Allowance project report for Cadent, Gas Networks Ireland, National Grid, Northern Gas Networks, SGN, Wales and West Utilities

Executive Summary
Project Background, Aims and Objectives

This is a Network Innovation Allowance funded project overseen by a steering group comprising the UK and Ireland gas network operators (Cadent, Gas Networks Ireland, National Grid, Northern Gas Networks, SGN, Wales and West). The project follows on from previous studies[1] that modelled the role of green gases in decarbonising the GB economy. The role of this study is to understand the transition from the GB economy today to a decarbonised economy in 2050, focusing on how the transition is achieved and the competing and complementary nature of different low and zero emission fuels and technologies over time.

While the project covers the whole economy it focuses on transport, especially trucks, as an early adopter of green gases and as a key enabler of the transition. The study and resulting report are aimed at the gas industry and government, and tries to build a green gas decarbonisation narrative supported by a wide range of stakeholders in order clarify the path ahead and thereby focus future efforts on delivering decarbonisation, through green gases, as quickly as possible. The objectives of the study are:

- Analyse the complete supply chain production, distribution and use of electricity, biomethane, bio-SNG and hydrogen to understand the role of each fuel and the timeline for scaling up of their use.
- Develop a narrative based on these findings to show how the use of these fuels scales up over time and how they compete and complement one another.
- Once a clear narrative to 2050 was developed put together a series of policy asks and stakeholder actions to show what is required to achieve the narrative.

The study included analysis of two scenarios a High Green Gas scenario and a Low Green Gas scenario. The narrative presented here focuses on the High Green Gas scenario, with commentary on the Low Green Gas scenario covered in Chapter 6.

Green gases

This report discusses the future role of 'green gases' which are biomethane and hydrogen produced from low- and zero-carbon sources, each produced via two main methods:

Biomethane from Anaerobic Digestion (AD): A mature technology for turning biological material into a non-fossil form of natural gas (methane). AD plants produce biogas which must then be upgraded to biomethane.

Biomethane from Bio-Substitute Natural Gas (Bio-SNG): This technology is at an earlier stage of development than AD, but has the potential to unlock other feedstocks for biomethane production such as waste wood and residual household waste.

Blue Hydrogen: Hydrogen from reformation of natural gas which produces hydrogen and carbon monoxide. 90-95% of the carbon is captured and stored making this a low-carbon form of hydrogen.

Green Hydrogen: Water is split into hydrogen and oxygen via electrolysis using electricity generated by renewables. No carbon emissions are produced so this is zero-carbon hydrogen.

[1] Navigant for ENA, 2019, Pathways to Net-Zero: Decarbonising the Gas Networks in Great Britain

Key Findings

Biomethane has an important role to play in the pathway to Net Zero but needs to ramp-up quickly to maximise its potential: 120TWh[2] of biomethane production potential in GB is identified in this report, including feedstocks for both anaerobic digestion and Bio-SNG. Quickly ramping up production from ca. 2TWh today to exploit this potential would mean it can be injected into the grid to decarbonise domestic heating and supply gas trucks while low carbon alternatives in these sectors are developed.

There is a short window of opportunity for direct use of biomethane in these areas. Gas trucks are rapidly being adopted already using predominantly biomethane (in 2019 80% of the gas supplied to trucks was biomethane), this is reflected in the rapid growth in Renewable Transport Fuels Obligation (RTFO) biomethane which increased by 80% between 2019 and 2020. Fully exploiting this early opportunity would lead to accelerated decarbonisation in this segment before zero emission options start to become available at scale in the 2030s (see Figure 4).

For heating, the opportunity for direct use of biomethane is likely to last longer into the 2030s or early 2040s as networks convert to hydrogen and biomethane is no longer required to displace fossil natural gas. To meet the 2050 net zero target, nearly all bio-energy resources will need to be deployed with CCS to ensure sufficient negative emissions to offset those that remain. By this point, direct biomethane use in transport and heat will need to end and be diverted to delivering negative emissions through pathways such as blue hydrogen production.

Biomethane- and hydrogen-powered trucks represent a substantial opportunity for green gases to accelerate transport decarbonisation: Most use cases for trucks are beyond the capabilities of battery electric and hydrogen models available today, but trucks running on biomethane can already operate on the highest mileage applications. There is a 10–15-year window of opportunity for biomethane powered trucks to accelerate decarbonisation in this otherwise 'hard-to-decarbonise' segment. A large-scale deployment of these trucks would lead to a 38% reduction in emissions from trucks by 2030, compared to just 6% if decarbonisation efforts in this segment focus solely on zero emission options. Beyond 2030, hydrogen trucks are expected to begin deployment at scale, but they will not initially compete for the same use cases as gas trucks. The economics of gas trucks means that they are being deployed on the highest-mileage routes, while early hydrogen vehicles are likely to be better suited to medium range applications. Deploying gas trucks as quickly as possible in the short term also acts as an insurance mechanism, ensuring that more low emission vehicles are on the road in case of any delay to the deployment of zero emission models. This demonstrates the strong case for an early deployment of biomethane powered trucks to accelerate decarbonisation, followed by a phase-out as viable zero emission alternatives become available.

When looking at what decarbonisation can be achieved by 2030 or 2040 a mixed fuel (electricity, hydrogen and biomethane) approach has a number of potential benefits: These include, the increased use of biomethane offers a pathway to decrease short term emissions, especially in sectors where no other short-term technology decarbonisation option exists. Switching from the combustion of natural gas to the combustion of hydrogen in industrial processes requires smaller equipment changes, than the equipment replacement needed to electrify, potentially helping to speed up the transition. The conversion of heating over to heat pumps will require an upgrade to the insulation in most buildings, while hydrogen boilers can effectively heat a building without major insulation upgrades. While it is certainly the right thing to do to improve building insulation, to improve efficiency and reduce fuel poverty, lifting the constraint of insulating buildings on the timeline to decarbonise heating could help to achieve early emissions reductions.

[2]This study follows on from a previous piece of analysis conducted by Navigant. The Navigant study concluded, based on a review of key literature (analysis conducted by the CCC, Ricardo, ADBA), that by 2050 the UK could access 60TWh of biomethane and 121TWh of Bio-SNG. In this study we wished to focus on biomethane and Bio-SNG from UK derived wastes and residues (this excludes production from energy crops, Power to Gas and imports). This means a reduced biomethane potential of 52TWh (12TWh existing, 40TWh new) and Bio-SNG of 70TWh. This approach gives us a conservative estimate of biomethane/bio-SNG supply but provides a more robust estimate as it avoids competition with food crops (problem with energy crops) and assumes each country will need its own biomethane supply to meet national targets (problem with large imports)

Deploying gas trucks and associated infrastructure in the short-term can support the later transition to hydrogen trucks: Approximately 170 refuelling sites, with 100 of these connected to the gas network, for gas trucks will need to be deployed over the next decade to meet the growing demand from these vehicles and maximise the decarbonisation potential of this fuel within the window of opportunity available. While the equipment used to store and dispense biomethane cannot be repurposed for hydrogen truck refuelling, a national network of gas truck refuelling sites can support adoption of hydrogen trucks. Identifying, purchasing, and developing land that is suitably located for truck operators and close enough for a connection to the gas network is challenging and suppliers of biomethane will have a 10-15-year head-start before hydrogen refuelling is required at scale. After 15 years of use, the refuelling equipment for gas trucks will need a major overhaul, suggesting a conversion to hydrogen refuelling at this point would not impact the economic lifetime of these investments. Biomethane stations that convert early can supply both biomethane from the network and tube trailer delivered hydrogen, while sites that convert later can switch directly to supplying hydrogen from a converted gas network.

Hydrogen refuelling stations fed by pipeline will provide an anchor load to support other transport segments using hydrogen: Refuelling sites for trucks will need to be capable of supplying up to 20 tonnes of hydrogen per day (tH_2/day), but due to safety regulations and operational constraints $3tH_2$/day is the practical limit for supplying sites by tube trailer. For large-scale refuelling sites to supply network delivered hydrogen to vehicles, they will require substantial purification equipment to remove impurities picked up in transit and dispense fuel cell grade hydrogen. These facilities will have a large footprint and sites would need additional adjacent land to accommodate them, or they could be located off the refuelling site, delivering the purified hydrogen back to the site via a short pipeline. With a direct supply of hydrogen from the gas network, the capacity of these facilities could be far higher than the requirements of a single truck refuelling site and excess capacity could be used to supply other smaller sites by tube trailer. In total 100TWh per year of hydrogen could be supplied to all transport modes in 2050 with truck stations (expected to need a network of approximately 600 hydrogen truck stations by 2050 with a third of these being large hub stations with a grid connection) providing an anchor load for a backbone of purification and distribution infrastructure that can then serve other vehicle segments more cost effectively.

Industrial users of hydrogen can provide an anchor load for blue hydrogen production: The regions identified as the most likely early hydrogen clusters are around the main industrial centres of the country. Many of these already produce and use grey hydrogen which could be replaced with green and blue hydrogen as production grows. There are opportunities in these regions for blue hydrogen production due to proximity to gas terminal infrastructure and carbon capture and storage opportunities in the Irish and North Seas. Early demand for hydrogen from trucks will need to be met with small-scale green or existing grey hydrogen producers. As blue hydrogen production becomes available at scale in industrial clusters, this will lead to a step change in the volumes available and the prices paid by users of hydrogen as a transport fuel, helping to drive adoption as hydrogen trucks enter mass production.

Domestic demand for hydrogen for heating can provide an anchor load for hydrogen from the gas network: Heating represents the main demand source for hydrogen in the long term, calculated to be 325TWh by 2050. This demand can begin to be served early in the transition with hydrogen blended with natural gas and biomethane/bioSNG in the network. Later, as hydrogen-ready boilers are deployed at scale, these represent the largest single source of hydrogen demand. Meeting this demand helps justify investment in very large-scale hydrogen production projects and helps to make the case for converting whole regions of the gas network to transport pure hydrogen. This will lead to a further step change in reducing the cost of hydrogen as a transport fuel, supporting wider adoption of the vehicles amongst truck operators, but also other vehicle segments such as cars and vans.

Policy Asks

All Sectors

Act quickly on all policy: Between 2020 and 2030 all the groundwork needed for a rapid decarbonisation of the economy and mass-market rollout of zero-emission technology must be completed. To get industry on-board with large commercial demonstrations starting in 2022-2024, policies must be announced to set the economy on the road to total decarbonisation in the next year.

Gas Trucks

Fuel duty differential: Maintain a fuel duty differential between diesel and natural gas/biomethane that ensures a continued competitive business case for gas truck operation.

Support for biomethane trucks in the Transport Decarbonisation Plan: The plan should make clear the opportunity for gas trucks in the next 10-15 years before zero emission alternatives achieve scale. Other government documents and announcements should align with this message to provide clarity to operators and infrastructure providers on the government's position.

Ministerial Roundtable: Bring together policy makers and leaders in the transport and freight industry to ensure lessons from current biomethane HGV successes are understood, remaining barriers are reduced, and best practice is repeated across the industry.

End to the sale of fossil fuel diesel powered trucks[3] : Setting a date to end the sale of diesel trucks is a key next step on the government agenda (as set out in the 10 Point Plan). European truck OEMs have already highlighted the need to end the sale of fossil fuelled trucks by 2040[4]. This should be the latest date targeted, while a more ambitious end date of 2035, that takes advantage of the momentum already building for the use of biomethane, would encourage greater uptake of gas trucks in the long-haul market and accelerate decarbonisation in this sector, while zero emission options are developed.

Biomethane Supply

Green Gas Support Scheme (GGSS): In the short term a consultation is needed to gain industry feedback on how GGSS and RTFO can be best structured to encourage additional investment in biomethane production rather than competition between the schemes. In the longer term the structure and support levels of the scheme should be regularly reviewed over time to ensure it is effectively driving the market to fully utilise the available feedstock for biomethane and Bio-SNG production.

Support for biomethane under the Renewable Transport Fuel Obligation: The RTFO is already an effective policy with all the methane supplied to buses and 80% of that supplied to trucks in 2019 being biomethane, and this share is expected to continue to grow. However, the structure and support levels of the RTFO scheme should continue to be regularly reviewed over time to ensure it is effectively driving the market to fully utilise the available feedstock for biomethane and Bio-SNG production and ensure that refuellers are able to meet the growing demand.

Hydrogen Trucks

Commercial demonstrations: Commercial demonstrations of hundreds (400-600) of medium and heavy-duty hydrogen trucks needs to be achieved by 2025 in order ensure this product is ready for mass market adoption later in the 2020s.

Local and national fiscal measures: All zero-emission trucks will need financial support to become competitive with the diesel alternative. This could include larger purchase grants (existing £8,000 purchase grant per truck expected to be insufficient with larger grants needed in the short term to kick start the industry), favourable registration tax and vehicle excise duty (as is the case for cars), as well as an exemption for fuel excise duty and local measures such as exemption from congestion charging. Some of this financial support may come about due to the restructuring of tax needed as a result of falling fuel excise duty revenue but these measures will be needed in advance of this to accelerate the early market.

[3]This refers to an end date for the sale of new fossil fuel powered diesel trucks, rather than internal combustion engine (ICE) vehicles, as gas trucks would continue to use an ICE engine. [4]ACEA, December 2020, all new trucks sold must be fossil free by 2040, agree truck makers and climate researchers, https://www.acea.be/press-releases/article/all-new-trucks-sold-must-be-fossil-free-by-2040-agree-truck-makers-and-clim

Truck lengths and weight limits: Truck weight and length regulation should be reviewed to ensure it does not hamper the rollout of zero-emission vehicles or improved vehicle design (such as improved aerodynamic features).

End to the sale of all emitting trucks: Setting an ambitious date of 2035 for ending the sale of diesel-fuelled trucks will require a strong early deployment of trucks running on biomethane. Setting a clear date for ending the sale of all emitting vehicles, including those running on biomethane around 2040 would provide a sufficient market opportunity for gas truck manufacturers and ensure that long-term investment in developing new models is focused on battery electric and hydrogen models.

Hydrogen Supply

Support for hydrogen under the Renewable Transport Fuel Obligation: The structure and support levels of the scheme should be reviewed regularly to ensure the mechanism encourages significant increases in hydrogen production levels. The first stage of this will be a review planned for this year that needs to deliver the step change in hydrogen supply needed for hydrogen demand in large scale transport commercial demonstrations expected by 2025.

Large scale blue hydrogen demonstration: Direct government financial support is needed to ensure the first large scale blue hydrogen projects are delivered by the mid-2020s. As these projects form an important part of early large-scale supply.

Large scale green hydrogen demonstration: Direct government financial support is needed to ensure green hydrogen projects scale up to the size needed to support economy wide demand for hydrogen in the 2030s.

Hydrogen station standards development and demonstration: Hydrogen refuelling stations for HGVs will be significantly larger than any station built to date. The government should encourage and support the development of industry wide standards and provide financial support for early station development to help bring these stations on-line for the commercial vehicle demonstrations

Stakeholder Actions

Refuelling Infrastructure Providers

Rapid CNG/LNG station rollout: CNG and LNG station operators should look to rollout basic national coverage by 2025 by deploying around 70 mostly large-scale refuelling sites on the strategic road network. Some private sites will be deployed in large fleet depots. Full national coverage with 170 refuelling sites will need to be complete by 2030.

Engage with station conversion[5] plans: Engage with truck operators on both CNG/LNG and hydrogen. Develop plans of how the infrastructure will support operators and align plans for station and fleet conversions so that the two happen in tandem.

Truck OEMs

Bring vehicles to market in time with infrastructure and operator readiness: Today, supply of BEV and Fuel Cell EV from car OEMs is behind the infrastructure capability and consumer demand. Deployment of BEV trucks is beginning to ramp up, but the shorter timescale available to convert the truck fleet means we must ensure this momentum is sustained with more models entering large scale production. Development of hydrogen fuel cell trucks is at a much earlier stage, with very limited deployments in Europe. Manufacturers need to accelerate production of FCEV models to ensure they are available at scale to serve medium to long range routes from the early 2030s.

Biomethane Supply Chain

Scale up production: Biomethane producers, with the support of feedstock producers, trade bodies and gas network operators, need to scale up production very quickly over the next 5-10 years. A review of local feedstock availability and suitability should be made, and a strategy put in place on how that feedstock can be best utilised.

[5]As part of the research for this report, a workshop was conducted with 15 stakeholders in the biomethane and hydrogen vehicle refuelling industry to discuss the practicalities and challenges of station conversion from biomethane to hydrogen.

Co-location where possible: Locating biomethane production close to gas truck refuelling sites can be beneficial in providing plants with a sizeable local demand. This helps to avoid constraints in network entry capacity, particularly if gas can be taken by refuellers overnight.

Hydrogen Supply Chain

Connect with demand: Collaboration to encourage hydrogen demand and make sure hydrogen supply grows with demand is very important.

Demonstrate at scale: By 2025 blue and green hydrogen production needs to be demonstrated at scales an order of magnitude larger than we are seeing today.

Gas Network Operators

Accommodate increased biomethane injection: Work with biomethane producers to develop an effective plan to connect more biomethane to the grid. Enact physical actions such as smart pressure control and within-grid compression to ensure there is capacity for more biomethane injection. Gas networks also need to work to develop inter-seasonal storage to overcome seasonal demand swings.

Engage with refuelling infrastructure operators on future sites and connection options: Help infrastructure developers to find potential sites for gas refuelling stations that are suitable for HGV access and grid connection. These should also consider implications for future conversion to hydrogen refuelling sites.

Engage with early large hydrogen production sites to ensure sufficient production capacity for grid blending: Early large blue hydrogen industrial production projects should include plans to blend hydrogen into the grid as the project grows. This will help to increase production volumes and drive down prices for hydrogen customers in the transport sector.

Support analysis into grid conversion to hydrogen and engage in hydrogen heating trials: Significant work has already been done in projects such as Hy4Heat and H21 to understand the potential and challenges of hydrogen to be transported through the gas network for use in heating. However, this work needs to be continued and developed to overcome the remaining barriers to conversion of the grid to 100% hydrogen in terms of the suitability of existing equipment and a clear vision for how sections of the grid (transmission and distribution) will be converted while other sections remain delivering natural gas.

Conversion of the grid to 100% hydrogen means upgrading heating and cooking equipment. Large scale domestic and commercial trials of this are still needed to show how this can be accomplished at scale and what the impacts are for consumers.

Conduct research into hydrogen purification from gas pipelines: Hydrogen that has passed through the gas grid contains impurities that make it unsuitable for use in vehicles. Demonstrations of large-scale hydrogen purification to prove the technology and cost effectiveness are needed.

Overview of the Narrative

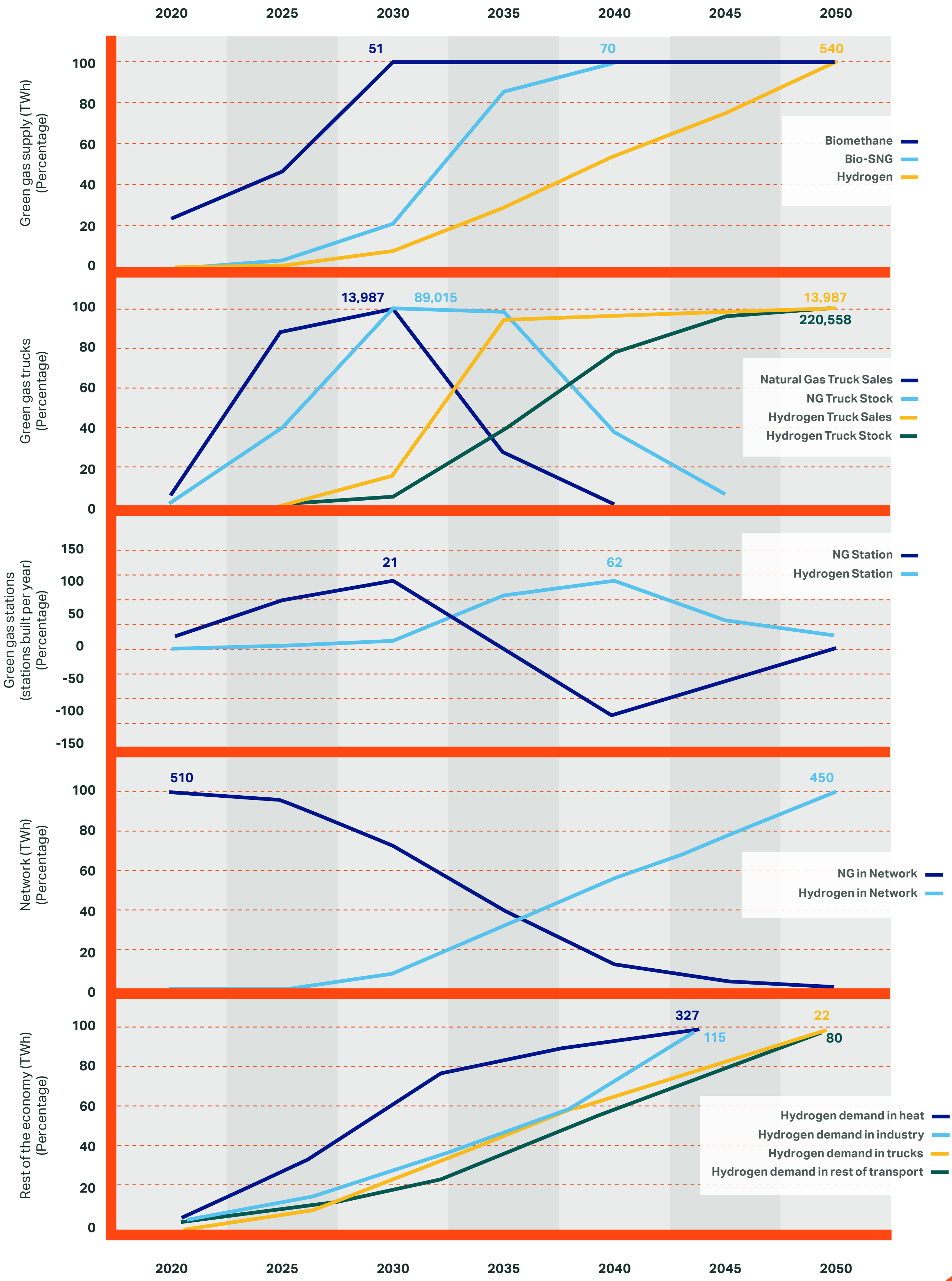


Figure 1 - Green Gas Transport (Percentage)

Biomethane: Production and use of biomethane grows rapidly over the next 10-15 years to reach its maximum GB potential by the mid-2030s. Initially this has a direct use through injection into the gas network to decarbonise heating and gas used in trucks. From the early 2030s demand from gas trucks peaks and then falls as hydrogen vehicles become available. Later biomethane demand from heating peaks and biomethane is redirected to blue hydrogen production, unlocking negative emissions.

Hydrogen: Over the next 10 years green hydrogen production is established across the country to support early deployment of hydrogen technologies such as trucks, buses, and trains. Simultaneously in major industry hubs, large scale projects are developed to produce and use blue hydrogen. As blue hydrogen becomes available at scale, hydrogen is mixed with natural gas in gas networks starting with small local areas from 2023 and expanding to large scale regions in the second half of the 2020s. By 2030 small areas of the gas grid around industrial clusters will be supplying 100% hydrogen. Once sufficient hydrogen demand is established in a region through installation of hydrogen-ready appliances, large regions (e.g., the North West) begin converting to 100% hydrogen from the mid-2030s, supplied predominantly with blue hydrogen produced in the industrial clusters.

Green gases for trucks: The sale of gas trucks ramp-ups quickly in the next 5-10 years so that the number of gas trucks in the stock peaks in the mid-2030s. From the mid-2030s, the sale of gas trucks falls rapidly as hydrogen trucks become capable of meeting operational requirements of fleets and begin to be produced at scale.

Gas refuelling infrastructure for trucks: A rapid rollout of gas truck refuelling infrastructure is required in the next 5-10 years to supply biomethane to gas trucks. As the number of gas trucks in the stock peaks, and hydrogen trucks enter the market, these stations will need to convert to supplying both hydrogen and biomethane and ultimately convert fully to serving hydrogen as gas networks convert. In the early years biomethane will be predominantly distributed to stations through the gas grid and hydrogen will be trucked to site in a tube trailer. However, by the early 2040s this situation has predominantly reversed with most dispensed hydrogen coming from the gas grid and the small remaining fleet of biomethane trucks being fed by stations using trucked deliveries.

The role of the gas networks: Over the next 5-10 years the key role for the gas networks is connecting sufficient biomethane production and gas truck refuelling sites to meet the demand from this sector. As hydrogen production ramps up a phased introduction of hydrogen blending on the network will be needed to supply early hydrogen production to users. Later networks will need to convert to transporting pure hydrogen, driving down costs for distribution helping to make hydrogen cost effective, this will require a demonstration of hydrogen purification at scale to ensure that network delivered hydrogen can be used in fuel cell applications.

Risks and future work

There are a number of risks associated with the High Green Gas scenario narrative, including:

- Investment levels in hydrogen are very low and will need to be ramped up very quickly.
- Cooperation across stakeholders in all stages of the hydrogen supply chain needed for early projects to succeed.
- Hydrogen technologies, especially fuel cells, are currently built at low volumes. Production volumes need to ramp up to bring down costs and build confidence in the technology.
- Purification of grid transported hydrogen for transport use has not been demonstrated at large scale.
- There is a short window of opportunity for green gases to demonstrate their potential role in economy-wide decarbonisation. If this is not achieved over the next 5-10 years, their role is likely to be limited.
- The UK vehicle market is likely to struggle to access sufficient supply of zero-emission vehicle production

capacity from European OEMs. For example, the higher power and right-hand drive variants of trucks preferred in UK are likely to cause a delay in supply compared to other European countries. This delay must be mitigated by ensuring the UK decarbonisation strategy does not relay on zero-emission vehicle introduction alone.

The policy asks and stakeholder actions recommendations have been derived in recognition of these risks. However, dedicated future work must be conducted, including on:

- Commercial technology demonstrations.
- Consumer research about potential users of hydrogen vehicles.
- Hydrogen purification from pipeline fed hydrogen.
- Hydrogen life cycle emissions assessments.
- Strategic analysis of how multiple green gases will be introduced across the GB gas network.
- Detailed analysis of how biomethane HGV stations will be converted to hydrogen and how the transition will be managed nationally. This needs to include analysis of how stations that predominantly dispense biomethane will manage increasing hydrogen blends in the gas network.
- Further research to establish whether deblending technology could be deployed to support the use of hydrogen for transport supplied by a mixed gas network.

Contents

Contents

Authors

Richard Riley, Principal Consultant, Element Energy

Oliver Robinson, Consultant, Element Energy

For comments or queries please contact:

richard.riley@element-energy.co.uk

Reviewers

Celine Cluzel, Director, Element Energy

Acknowledgments

We would like to thank and acknowledge all those organisations who have supported the project with data and time through interviews and workshops.

Organisation	Names
Energy Networks Association	Thomas Koller
Air Liquide	David Hurren, Daniel Lambert
Air Products	Hector Wilson, Manish Patel, Frank Schnitzeler
Bayotech	Steve Jones, Jeff Mitchell
BCGA	Jake Lake
CNG Fuels	Philip Eystein Fjeld
CNG Services	John Baldwin
Dnvgl	Martin Brown
Gas Rec	Mark Siddle
Inovyn	Richard Stevenson
NPL	Thomas Bacquart
Gas Vehicle Network	All members

Acronyms

Acronyms	
AD	Anaerobic digestion
BECCS	Bio-Energy Carbon Capture and Storage
BEV	Battery electric vehicle
Bio-CH_4	Biomethane
Bio-SNG	Bio-Substitute Natural Gas
CH_4	Methane
CNG	Compressed Natural Gas
DfT	Department for Transport
GDN	Gas Distribution Network
GGSS	Green Gas Support Scheme
H_2	Hydrogen
Heat	When used without clarification the use of "heat" in this document refers to heating for domestic properties
HGV	Heavy Goods Vehicle
HRS	Hydrogen Refuelling Station
LNG	Liquefied Natural Gas
LTS	Local Transmission System
MSW	Municipal Solid Waste
PPA	Power Purchase Agreement
RTFO	Renewable Transport Fuel Obligation

1. Introduction

1.1 Context of the project

This report forms part of the 2019-2020 Future of Gas Network Innovation Allowance aimed at understanding future opportunities for the gas networks to contribute to decarbonising the UK economy. Until the adoption of the UK's 2050 net-zero target in June 2019, this work focused primarily on the role of green gases (biomethane and hydrogen) in decarbonising heat. The new target has increased the level of ambition required by mid-century and means that more 'hard to decarbonise' areas will need to be tackled sooner, such as heavy-duty transport. This report aims to set out a narrative for the role of green gases as the economy decarbonises over the next 30 years that is consistent with and adds detail to other work that has already been done in this area. In particular, this report adds detail on the opportunity for green gases in low- and zero-carbon heavy goods vehicles (HGVs), and how this can support wider use of green gases across the economy.

Significant progress has already been made in developing battery electric cars and vans, and these are finally now being produced and purchased in increasing numbers after a decade of sustained policy support. Progress has also been made in zero-emission buses with hydrogen and battery electric models becoming increasingly common in response to clean air policies in cities such as London and Birmingham. However, the first polices targeting the carbon emissions of trucks have only recently been introduced and battery and hydrogen powered models are at a much earlier stage of development.

Gas trucks are one technology that is available today and when fuelled with biomethane offers carbon emissions savings of up to 85%[6]. These vehicles are being adopted by fleet operators both to offer their customers lower carbon transportation and to take advantage of the lower duty applied to the fuel. These vehicles have significant potential to decarbonise trucks in the short-term, but ultimately will need to be replaced by zero-emission models to achieve net-zero by 2050. Battery electric trucks are expected to be sufficient in many short-range urban applications and manufacturers are starting to produce these vehicles in small numbers. For larger trucks in heavier duty applications, there are significant opportunities for hydrogen to eventually replace gas- and diesel-powered vehicles, though these models are at an earlier stage of development.

This report sets out a pathway for the gas industry over the next thirty years that maximises the potential of green gases to decarbonise large parts of the economy, starting first with biomethane which is ready to scale up today before ultimately transitioning to a pure hydrogen system. This pathway focuses on the role of trucks because green gas is their only option for significant emissions reductions over the next decade (zero-emission vehicles are on the verge of entering the market today, but while sales will grow significantly by 2030 they will still represent a small proportion of the stock and therefore have a small emissions impact in the short term) and can help provide early demand for hydrogen as that industry scales up. Establishing demand first with trucks can also help to form a backbone of refuelling infrastructure that facilitates adoption of hydrogen in other vehicle segments and can act as a steppingstone to unlock demand in larger sectors such as industry and heat.

The timing of this report coincides with a pivotal moment in policymaking aimed at achieving the net-zero target. In November 2020, the government published its ten-point plan for a green industrial revolution which targets 5GW of low-carbon hydrogen production capacity by 2030. The plan envisages hydrogen being deployed at scale to decarbonise a range of sectors from domestic heating to transport. During 2021 the Department for Transport (DfT) will publish its Transport Decarbonisation Plan, a key piece of policy that will set out how it intends to ensure transport meets the net-zero target. A major part of this will focus on actions required to decarbonise trucks, and the analysis behind this report was submitted to DfT in response to their call for evidence as they developed their plan.

[6]LowCVP, 2020, Low Emission Freight & Logistics Trial (LEFT) Key Findings https://www.lowcvp.org.uk/assets/reports/LowCVP-LEFT_Dissemination_Report-2020.pdf

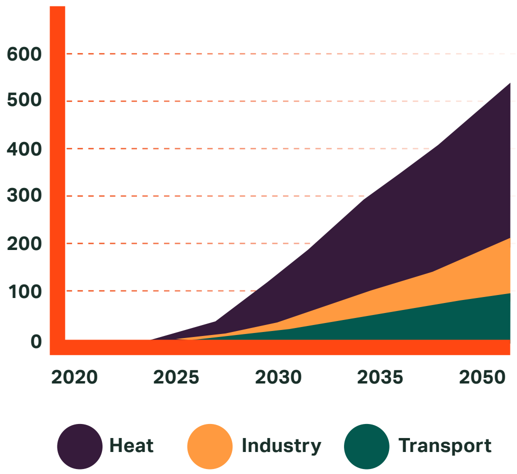


Figure 2 - Hydrogen demand, TWh

1.2 The potential and challenges for Green Gases

By 2050, this report envisages hydrogen playing a major role in supplying net-zero energy across the economy, providing roughly two thirds of the energy consumed in heating, industry and transport with remaining energy demand met by renewable electricity. Of these sectors, heat represents the largest potential hydrogen demand at 325TWh[7] and would mean hydrogen is being produced at sufficient scale and low cost to make it a viable energy source in a range of sectors. In this scenario, industry makes up 115TWh[8] of demand with large scale blue hydrogen production deployed in all major industry clusters and hydrogen used as the key route for decarbonising processes that are not already electrified. In addition, transport makes up 100TWh[9] of demand, with a strong role in heavy-duty transport and a more niche role in light duty vehicles that nonetheless constitutes significant demand due to the scale of this segment.

In the years between now and 2050, biomethane can help deliver emissions reductions before hydrogen is ready to take on this long-term role in the economy. The annual biomethane production potential in GB identified in this report is ~120TWh, including both feedstocks for anaerobic digesters (AD) and bio-substitute natural gas (Bio-SNG) plants. This far exceeds the 2.1TWh that are currently produced which all come from AD plants. This technology has been widely deployed and is ready to scale up, while Bio-SNG is at a lower technology readiness level but would open-up a wider range of feedstocks for biomethane production. Biomethane is already delivered through the gas networks to decarbonise heating and trucks and could play a substantially greater role in the years to come.

It is clear from this that green gases have enormous potential in decarbonising the UK economy, but it is also clear that a lot of work will need to be done by the gas networks, infrastructure providers and gas producers to realise this potential. One of the key challenges is achieving scale. Large-scale blue and green hydrogen production coupled with a gas network supplying pure hydrogen to a wide range of users would lead to drastically lower costs compared to the small-scale projects seen today. Getting to this point will require an incremental and iterative process, deploying hydrogen first in the use cases that make most sense at a smaller scale and then expanding to sectors that require increasingly large scales to bring down costs.

This report identifies five milestones in this process:

1. **Start with biomethane**: Biomethane can be produced and used with technologies available at scale today. These should be ramped up in the next ten years to decarbonise heat and HGVs before other technologies to decarbonise these sectors are available at scale.

2. **Hydrogen for trucks**: As hydrogen trucks become available, they represent an early use case where hydrogen can be deployed at a meaningful but still relatively small scale. Transport fuels are more expensive than natural gas from the grid, and so trucks can more easily absorb higher costs of hydrogen early on. Early refuelling stations can be supplied by tube trailer rather than requiring delivery through the network. A few hydrogen stations may choose on -site production via electrolysis but this is expected to

[7]Based on Element Energy analysis of a high hydrogen future, [8]Based on Element Energy analysis of a high hydrogen future, [9]Based on: Element Energy 2020, Analysis to provide costs, efficiencies and roll-out trajectories for zero-emission HGVs, buses and coaches, https://www.theccc.org.uk/publication/analysis-to-provide-costs-efficiencies-and-roll-out-trajectories-for-zero-emission-hgvs-buses-and-coaches-element-energy/

Detailed modelling of zero emission car and van uptake by Element Energy for the Department for Transport. Element Energy analysis of hydrogen demand from rail and shipping.

play a small role due to the significant additional cost of electricity grid charges.

3. **Hydrogen for industry:** Local industrial users of hydrogen can provide an anchor load for blue hydrogen production, supporting large scale investment ahead of converting the networks to pure hydrogen, reducing the cost of hydrogen available to transport customers.

4. **Hydrogen blending:** Mixing blue/green hydrogen with natural gas on the network can help to provide additional demand and support investment in large-scale production beyond the industrial clusters. This will further reduce the cost of hydrogen as a transport fuel and make it more widely available.

5. **Network conversion:** Once production and demand are established at scale, networks can begin conversion to transporting 100% hydrogen, with major demand for hydrogen heating acting as a base load to justify investment in network conversion and very large-scale production. Gas network delivered hydrogen lowers costs across all sectors including vehicle refuelling, supporting accelerated uptake of hydrogen across all transport modes.

While it is clear what the major milestones are on the pathway from the green gas industry of today to achieving its full potential by 2050, the details of this process are less clear. There is a particular need to understand how the early focus on biomethane for trucks can support a later transition to hydrogen vehicles. Significant work is already underway to build-out a national refuelling network for gas trucks and this will need to accelerate to achieve the full potential of biomethane to reduce emissions from trucks in the near term. However, their role in the longer-term transition to hydrogen trucks needs to be understood to ensure that they do not hinder this process or risk becoming stranded assets as hydrogen trucks come to dominate the market and networks convert to supplying hydrogen.

Similarly, as the timeline progresses, the role of different sectors and stakeholders in supporting the transition to hydrogen will evolve. This will require different development and deployment work to take place which will vary along the timeline and geographically across the country. This report aims to tie all these various factors together into a single narrative to describe how the overall transition to an energy system where green gases have a prominent role and the country's net-zero ambitions are met.

1.3 Objectives

Significant work has been carried out elsewhere to identify how this transition could take place at a high level. This report aims to add to this by developing a narrative that sets out how green gases can contribute to the decarbonisation of transport and place this within the wider context of decarbonising the whole energy system. The chapters of this report describe the steps that must be taken by 2050 with a focus on the next 10-15 years where more detail is required to understand the enabling work that must be carried out to facilitate the longer-term transition to a hydrogen system.

The key objectives of this report are to:

Develop a green gas narrative to 2050: This outlines the steps required to maximise the role of green gases in achieving the UK's decarbonisation goals over the next 30 years. This is broken down into 5-year periods and within each the activities required in 5 areas are outlined:

- Biomethane supply: Sets out the pace required for rollout of biomethane production and determines the quantity of biomethane required in each period to ensure it achieves its potential.
- Biomethane demand: The finite biomethane resource will need to be deployed selectively to maximise its role in decarbonisation. Demand is focused in the early years on areas with limited decarbonisation options, displacing natural gas for heating and serving the gas truck market. In later years this diverts to negative emission hydrogen production as the transition progresses.
- Hydrogen Supply: In each period the supply of low and zero carbon hydrogen grows, starting first with green production in early hydrogen clusters and then spreading across the country. Blue hydrogen takes longer to deploy and appears later in the timeline, but this leads to a step-change in the volumes of hydrogen available.
- Hydrogen Demand – Transport: As hydrogen supply grows, demand will need to grow in parallel. In the early years,

trucks provide an opportunity within transport and as the infrastructure to serve them becomes established, other segments can adopt hydrogen in greater numbers.

- Hydrogen Demand – Other Sectors: Heat and industry will ultimately be the main sources of demand for hydrogen, but they are more challenging to supply at a small scale. These sections set out the work that needs to be done early on to ensure that these sectors are ready to use hydrogen at scale as production ramps up.

Highlight the role of trucks: This report aims to set out how gas trucks can be used in the short term to accelerate decarbonisation in this segment and then how the transition to hydrogen trucks can help support the wider up take of hydrogen in the economy. Gas trucks supplied with biomethane offer an immediate opportunity to reduce carbon emission from trucks while zero emission alternatives are developed. The window of opportunity for these trucks is in the next 10-15 years and their numbers will need to fall again rapidly after this to avoid competing with zero-emission models as they become available. Once hydrogen trucks begin to be deployed at scale, they can serve as a significant early source of hydrogen demand that helps to support initial deployments of hydrogen production. They can also provide an anchor load for refuelling infrastructure that can then be used to serve other transport segments.

Define the evolving role of green gases: Throughout the timeline set out in the narrative, the roles for green gases change, with an early focus on biomethane production and use and a later transition to hydrogen. This report aims to highlight and add detail to this process within both the supply and demand sides of this market. In the early years there are opportunities for biomethane to be deployed to decarbonise trucks and heating, using technologies that are already widely available. As zero emission alternatives for trucks become available the main use for biomethane becomes heating, which will continue to be challenging to decarbonise until gas networks convert to hydrogen. Once they do, direct use of biomethane will fall and be diverted to the production of negative emission hydrogen.

Highlight actions for key stakeholders: Along the timeline of the narrative, a range of actions will need to be completed by all stakeholders to ensure the 2050 goals of the green gas industry are met. This report highlights when these occur and demonstrates how the actions of each stakeholder are inter-dependent. For example, hydrogen refuelling infrastructure providers will be unwilling to invest without clear actions from vehicle manufacturers that they will ramp up production and vice versa. Neither will be able to commit to large scale investments without strong supportive policies from the government to reduce uncertainty.

Highlight the risks of not acting decisively: The existing narratives around decarbonisation tend to focus on electrification. Green electricity has several advantages over green gases: electrified systems have higher energy conversion efficiency, production technologies such as wind turbines and solar panels have already achieved scale and despite the reinforcements that will be required for deeper decarbonisation, there are fewer barriers to putting renewable electricity into the existing distribution grid than there is for renewable gases. Electrified light duty vehicles are also becoming a mature technology, demonstrating that electricity alone can be sufficient for many drivers.

Biomethane by contrast is produced at a modest scale, while green hydrogen is only produced at very small scales. While biomethane can be transported via the existing gas network, there are significant challenges for transporting hydrogen via the same network. As a result, there is a risk that the role of green gases could be limited if their potential contribution is not demonstrated effectively at scale in the next 5-10 years.

1.4 Approach

1.4.1 Focus on HGVs

The narrative set out in this report focuses on the role of trucks to help grow the role of green gases in GB. Trucks represent a major opportunity in the timeline for deploying green gases at scale for five key reasons.

1. **Trucks lack low-carbon alternatives in the short-term.** While battery electric models are becoming widely available

for the light duty segment, development of battery trucks is at a relatively early stage. Some battery electric truck models are beginning to be deployed in small numbers, but these are targeted at short range urban delivery applications driven primarily by urban clean air restrictions. In the heavy truck market models are at an even earlier stage of development, and many manufacturers expect that hydrogen will be necessary to achieve zero-emission trucks capable of matching the utility of diesel or gas trucks. While these trucks are developed towards mass production readiness, gas trucks using biomethane offer an opportunity to drastically reduce the emissions from this segment in the next 10-15 years. These trucks are already produced at scale and manufacturers are rapidly increasing production to meet demand.

2 **Trucks have high fuel demand and simple refuelling patterns:** Due to their intensive use trucks typically require significantly more fuel than other road vehicle types. They are also deployed in fleets that typically operate back-to base operations. This means that a single refuelling site near to the fleet depot can be sufficient refuelling availability to persuade a whole fleet to transition to a different fuel, rather than requiring national coverage from the start. The scale of fuel demand from a single fleet can also be enough to justify investment in refuelling infrastructure, allowing equipment to achieve high levels of utilisation quickly.

3. **Early refuelling stations can be served effectively with tube trailer delivery of hydrogen:** This means it is not necessary to wait until the gas network converts to be able to access a supply of hydrogen. Hydrogen produced at smaller scales and delivered by trailer will be more expensive than when it is produced at scale for distribution through the gas network. Hydrogen used in trucks has more potential to absorb these higher costs than hydrogen used to displace network delivered natural gas. This is because diesel is the fuel that is displaced by hydrogen in trucks and this has a higher cost per unit of energy than natural gas. A significant part of the cost of diesel is also made up of taxes and therefore the government has significant flexibility to control the price difference between that and other fuels, as it does with the fuel duty differential applied to gas used in transport. A small proportion of hydrogen stations may be fed by on-site electrolysis but the scope for this is expected to be limited due to the significant additional costs cased by electricity grid charges, if the electricity comes from the grid, and the challenge of finding enough space if the electricity is produced on-site via renewables.

4. **Fleet operators tend to be early movers in adopting low carbon technologies:** Once there is a clear economic and business case for a new technology, as has been demonstrated with gas trucks, operators are able to move quickly to adopt them. Part of establishing the business case has been to demonstrate lower emissions to customers, which has become increasingly important differentiator in the highly competitive trucking market. Persuading other groups to adopt new technology has been more challenging, such as private car owners who have been slow to respond to economic incentives to adopt electric cars. This is because there are many more choices involved in purchasing a private car than a commercial truck, such as personal preferences which have meant that an electric model may not be suitable even if it is cheaper.

5. **Truck refuelling infrastructure can act as a backbone to provide coverage for other vehicle types:** As will be shown in more detail in this report, large scale truck refuelling sites will require significant capacity to purify hydrogen delivered via the network. This equipment will likely be capable of producing more high purity hydrogen than would be required at a single truck refuelling site and so can be used as a hub to supply fuel cell quality hydrogen to a range of other users including smaller refuelling sites for light duty vehicles.

1.4.2 Regional analysis

The narrative presented in this report refers to Phase 1 and Phase 2 regions for hydrogen deployment. These are based on analysis of potential future demand for hydrogen across GB, as well as opportunities for producing hydrogen at scale. Phase 1 regions are areas where hydrogen clusters are likely to emerge first – they have large potential demand for the gas as well as opportunities to produce it at scale locally. It is in these areas that the first gas networks will transition to distributing hydrogen rather than natural gas. The phase

2 regions are likely to transition later as they are generally more challenging to supply with hydrogen and while there is significant demand potential, it is more dispersed than in Phase 1 regions. Both Phase 1 and Phase 2 regions are expected to transition to hydrogen following the same pathway of hydrogen blending into large areas of the grid, at low levels, and small areas of the grid with 100% hydrogen in the early years, followed by higher blends of hydrogen into large areas of the grid and growing areas of 100% hydrogen, and finally areas of 100% hydrogen connected together to complete the conversion of whole regions to 100% hydrogen. Large areas of the country are not included in Phase 1 or 2 regions and these will be the most challenging for hydrogen to play a role in decarbonising energy use. In these areas electrified systems will have a significant practical and cost advantage over hydrogen.

Phase 1 regions: The six Phase 1 regions represent the six major industrial areas of GB that are also well located for large-scale hydrogen production. This means either that they are close to significant offshore wind generation potential that could be used for green hydrogen production, or that they are close to existing natural gas import terminals and oil and gas fields that could be converted for carbon storage suggesting good sites for blue hydrogen production. These regions cover just 7% of the GB area but represent 39% of HGV registrations and 42% of demand for domestic natural gas in 2019. This means that major sources of potential supply and demand for hydrogen are concentrated in a small area, reducing the challenges of distributing the gas early on. Many of these industrial areas already produce grey hydrogen at scale and could transition to using blue or green hydrogen as these begin to be produced at scale. Industrial users of natural gas for process heat also have the potential to transition to hydrogen which would represent significant demand.

Phase 2 regions: These are typically inland areas that also contain substantial opportunities for hydrogen production and

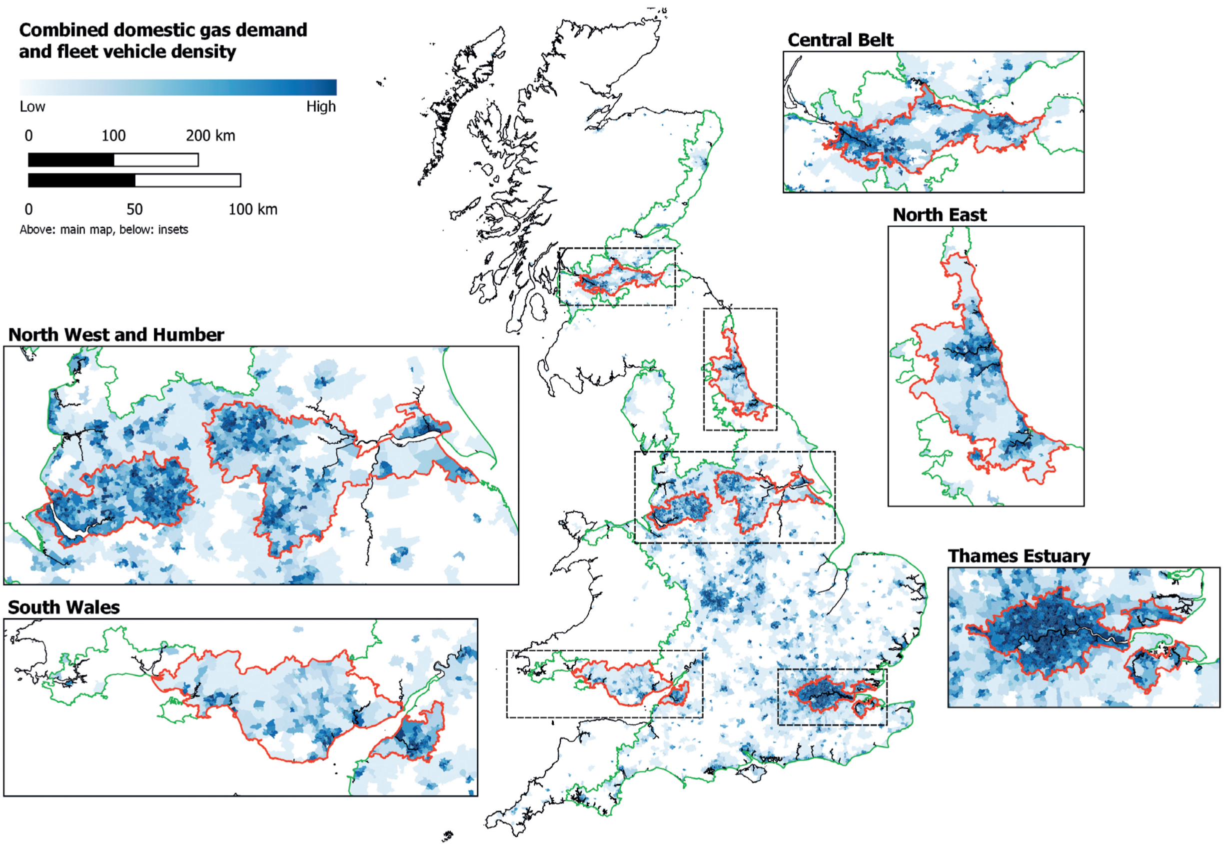


Figure 3 – Map of phased approach to hydrogen rollout – red areas are Phase 1, green areas are Phase 2

use, covering 48% of the GB areas and representing 55% of HGV registrations and 55% of domestic natural gas heating demand in 2019. Adopting hydrogen in these areas would be more challenging than in Phase 1 regions, due to the likely greater distance to large-scale blue hydrogen production and the lower concentration of demand sources. During the early years there are opportunities to locally produce green hydrogen from electricity generated by onshore wind and solar in the Phase 2 regions. Once blue hydrogen is produced at scale in the Phase 1 regions, there will be a role for the gas networks to transport this inland to supply users in the phase 2 regions, helping to support wider uptake. This could be achieved either through conversion of the existing transmission infrastructure, wherever possible, to carry hydrogen, or construction of new hydrogen transmission pipelines where no other alternative exists.

Outside Phase 1 or 2 regions: These areas represent 45% of the GB area but just 6% of HGV registrations and 3% of domestic natural gas demand. These regions are furthest from opportunities for hydrogen production and represent very limited and dispersed sources of potential demand. They will be the most challenging to supply with hydrogen and other decarbonisation options will likely be preferrable.

1.5 Structure of the report

Chapter 2 - Green Gas Narrative: This chapter sets out the narrative for the green gas industry from small scale today to supplying a major proportion of the energy used across transport heat and industry by 2050. This provides detail and the chronological order of the steps that will be required along the pathway.

Chapter 3 - Narrative Outcomes: This section draws out the key themes in the narrative, providing more detail on role of biomethane, gas trucks and the transition to hydrogen within the economy-wide context. This section also sets out in more detail the role of green gases in achieving net-zero emissions by 2050.

Chapter 4 - Policy asks and stakeholder action required to achieve high hydrogen scenario: This section identifies the key stakeholders in the green gas narrative and sets out the policies that will need to be in place and the actions required to achieve the narrative's goals.

Chapter 5 - Narrative Risks: This sets out the various barriers and challenges that will need to be overcome in order for green gases to meet their potential by 2050.

Chapter 6 - Future Work and Conclusions: Identifies the immediate next steps for research that is still required and the conclusions of this piece of work.

2. Green Gas Narrative

The key outcome of this analysis, which adds to the existing net-zero studies, but goes beyond work done to date, is a clear narrative that sets out the role for green gas (biomethane, bio-SNG and hydrogen) in decarbonisation efforts, with a specific focus on the role of HGVs. The narrative developed in this study is presented in this chapter in the following two sections:

1. Overview of key trends along the 2020-2050 timeline
2. Summary of the narrative

The detailed narrative breakdown is provided in the Appendix.

2.1 Overview of key narrative trends

Biomethane Supply

- **Biomethane supply must ramp up very quickly between 2020 and 2030** (double the maximum rate seen for biomethane between 2010 and 2020) in order to keep pace with demand and offer a meaningful level of decarbonisation in heat and transport before direct demand in these sectors peaks between 2030 and 2035. **Biomethane supply must reach its maximum potential by 2030.**

- **Bio-SNG production must be brought up to large commercial scale by 2025** and then be rolled out very quickly (double the maximum rate seen for biomethane between 2010 and 2020) between 2025 and 2035.

- Feedstocks for biomethane/Bio-SNG are finite and this work proposes that the limited supply of biomethane should be applied to different sectors over time in order to maximise its decarbonisation potential:
  - 2020-2035: Trucks and heating as these have limited short-term decarbonisation alternatives.
  - 2035-2045: Focus on decarbonising domestic heat in areas that still have natural gas on the distribution network and decarbonising industrial heat and power generation in areas that still have natural gas on the transmission network.
  - 2035-2050: As gas networks convert to 100% hydrogen, biomethane is increasingly diverted to negative emission hydrogen and electricity production with CCS.

Biomethane Demand

- The sale of biomethane/bio-SNG trucks needs to continue to grow[10] very quickly from 2020 to maximise their impact and reach **peak annual sales by 2030. Sales will then need drop back down to zero by 2040 to ensure that zero emission options are not displaced.**

- This results in the **stock of biomethane/bio-SNG trucks ramping up to peak in 2032** before dropping more slowly back down to **reach zero between 2045 and 2050.**

- Biomethane consumption for heating **ramps up very quickly from today to peak in 2035.** Demand for biomethane in heat remains relatively constant between 2035 and the early 2040s but then begins to fall as the conversion of the gas grid to 100% hydrogen removes the opportunity to supply biomethane to homes and businesses.

Hydrogen Supply

- Early hydrogen supply for heat and transport will be green as it is faster to deploy electrolysers using dedicated or constrained renewable generation than large scale blue hydrogen production. Initially this could either be injected into the network as a blend or delivered to users via tube trailer delivery.

- As large-scale blue hydrogen production starts to take off from 2025, in the industrial clusters, areas around the industrial clusters will use increasing levels of blue hydrogen.

- Most early demand for hydrogen from transport is expected to be in hydrogen clusters - trucks and industrial sites located near to potential production sites either for green or blue hydrogen (Phase 1 areas presented in Figure 3).

- In the long-term a significant proportion of hydrogen will be injected into the transmission network close to current industrial clusters (these sites are already close to existing gas terminals and sit at the source of the current gas networks). This hydrogen is expected to be a mix of blue from the industrial clusters and green from offshore wind

[10] RTFO accredited biomethane grew 80% between 2019 and 2020.

and will form a significant share of the hydrogen dispensed through the gas network.

Conversion of the Gas Grid to Hydrogen

- From the early 2020s small sections of the gas grid are converted to 100% hydrogen to demonstrate the long-term feasibility of this approach. From 2023 hydrogen blending into the grid begins in small regions limited by production capacity.
- From the late 2020s hydrogen begins to be blended at scale into larger areas of the gas network from large production sites in the Phase 1 regions to decarbonise heating and industry, although hydrogen blend percentages are still low at this point due to limited production capacity. Due to outstanding questions around the feasibility of deblending hydrogen, due to equipment footprint, ability to locate near transport refuelling sites and cost , for use in transport applications, this has not been factored into this analysis. As a result, early piped hydrogen is assumed only to supply domestic and industrial buildings for heat. At this time larger trial of 100% hydrogen networks are also expected in regions where production capacity and network architecture allow.
- Between 2030 and 2035 the percentage of hydrogen blended in Phase 1 regions continues to increase and blends also start to be delivered to Phase 2 regions. Growing sections of the Phase 1 regions convert to 100% hydrogen, allowing some new HRS to be fed directly from the grid.
- Between 2035 and 2040 100% hydrogen clusters in Phase 1 regions are connected up allowing whole Phase 1 regions to convert to 100% hydrogen. The blending levels in Phase 2 regions continues to increase and growing sections of the Phase 2 regions convert to 100% hydrogen. This coincides with the development of the first very large HRS which can only be practically supplied through pipeline.
- Between 2040 and 2045 most of the Phase 2 regions (see Figure 3) have completed conversion to dispense 100% hydrogen with the final areas of the grid converted by 2050

Conversion of Truck Refuelling Infrastructure

- A network of CNG and LNG stations are built out quickly between today and 2030.
- Between 2030 and 2035 the earliest CNG/LNG stations built need an overhaul and are converted to dispense hydrogen over a 5-10-year period
- Between 2035 and 2040 the later CNG/LNG stations built need an overhaul and are converted to dispense hydrogen over a 5-year period
- One of the main challenges in introducing a new vehicle technology is providing national refuelling infrastructure. The building requirements for CNG/LNG and hydrogen stations from our modelling show **almost no cross over of construction highlighting the non-competitive nature of these two fuels and the potential for site conversion in the 2030s to support the transition to zero-emission fuels.**

Hydrogen Demand

- The sale of hydrogen trucks should be in the 100s in 2025, to ensure that sufficient vehicles are deployed early to prove the technology ahead of mass production.
- Sales of hydrogen trucks must begin a very **rapid growth from 2030 to achieve their maximum share of sales towards the end of the decade.**

This means the stock of hydrogen trucks will be **very small before 2030 but will go through a very rapid rise between 2030 and 2040,** followed by slower growth between 2040 and 2050 to reach peak stock by 2050.

[11] Costain, 2021, Hydrogen deblending in the GB Gas Network, https://www.smarternetworks.org/project/nia_nggt0156

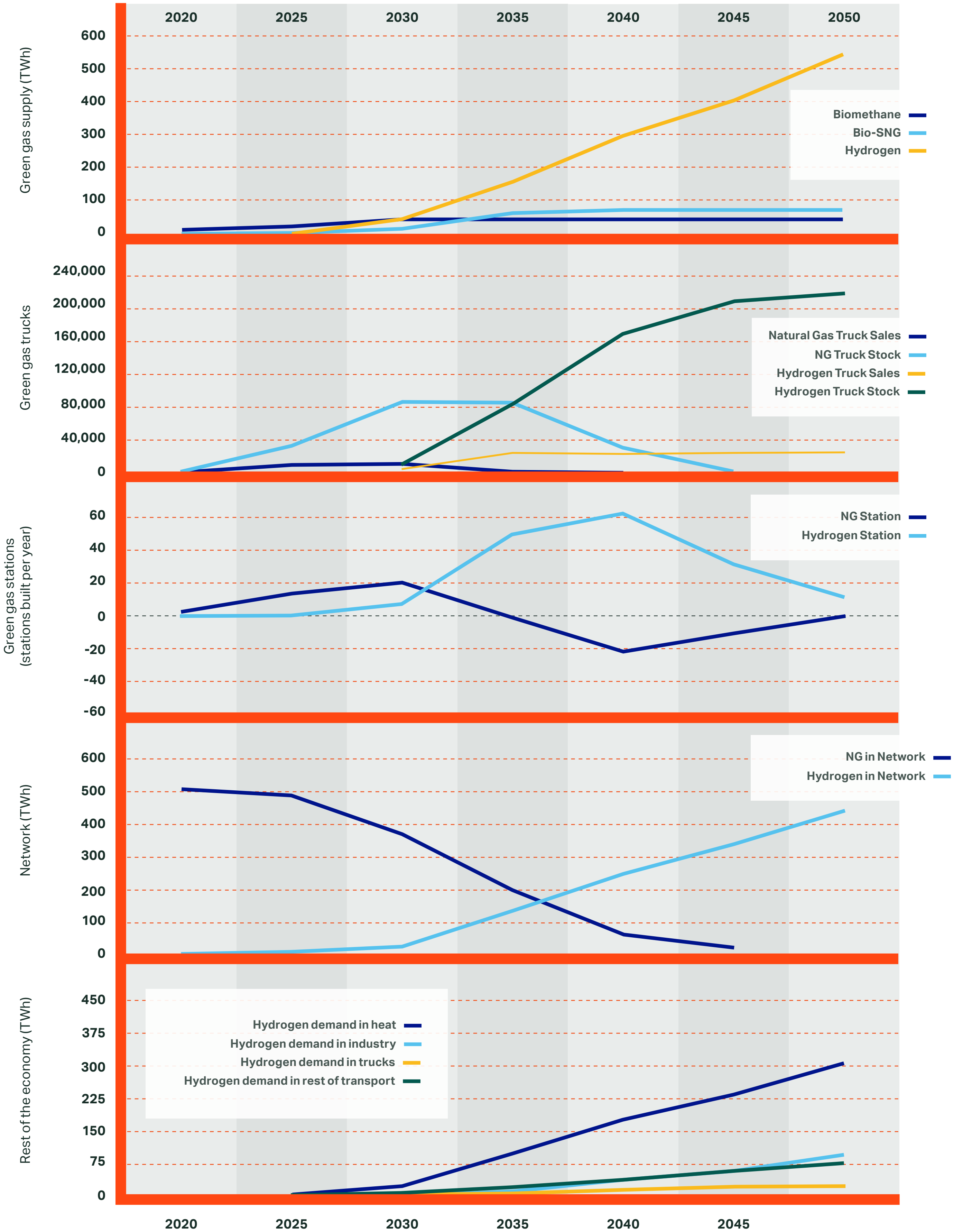


Figure 4 - Green Gas Transport

2.2 Summary of Narrative

An overall summary of the narrative is given in Table 1 with a more detailed description of each step set out in the next chapter.

Year	Fuel	Trucks	Station	Transportation	Production
2020-2025	Bio-CH_4	Rapid rise in gas truck sales (23% sales by 2025)	Rapid rollout of 55 large public stations and 15 large depot stations across the whole of GB	Gas grid in Phase 1 and 2 regions	New biomethane production from collected wastes such as green, food and sewage waste
	H_2	Large commercial demonstration of 100s of medium duty H_2 trucks	Small stations (1t/day) installed at strategic locations for depot clusters	Localised H_2 blending in the grid and trials of 100% H_2 grids in very small regions focused on heating with limited opportunities for transport. H_2 trucked in compressed tube trailers to stations from production sites. Small trials of 100% hydrogen networks started but this is only for heat.	Green H_2 from electrolysers co-located with renewable generation or grid connected with PPA
2025-2030	Bio-CH_4	Gas truck sales peak (27% sales by 2030)	National coverage with 115 large public stations. Completion of 55 large depot stations. No new station built after 2030	Gas grid in Phase 1 region dispensing methane with a small but growing H_2 share introduced to decarbonise heating. Gas grid in Phase 2 region dispensing 100% methane	Biomethane production from all available feedstocks. New Bio-SNG production from collected wastes such as MSW
	H_2	H_2 truck sales accelerate in medium duty applications (7% sales by 2030)	More stations (Up to 3t/day) added to support clusters of depots in Phase 1 regions and to begin national coverage along motorways, possibly co-located with the last generation of CNG/LNG stations built where there is sufficient footprint at the site.	Larger, localised parts of the distribution gas network and sections of the transmission network convert to supplying 100% H2 in the Phase 1 regions. Driven by domestic and industrial heating opportunities but unlikely to co-locate with truck station requirements. H2 trucked in compressed tube trailers to stations from production sites. First station near industrial cluster gets dedicated pipeline	First blue H_2 produced at industrial clusters. Continued ramp up of green H_2 from electrolysers co-located with renewables or grid connected with PPA

Year	Fuel	Trucks	Station	Transportation	Production
2030-2035	Bio-CH_4	Gas truck stock peaks and sales fall until they are limited to only the longest-range trucks	Early stations start to need equipment overhaul. 70 public stations built before 2025 begin conversion to dispensing 100% H_2. Large sites may be able to gradually increase share of H_2 dispensed alongside Bio-CH_4 over time.	Gas grid in Phase 1 region dispensing methane with a high percentage blend of H_2 introduced to decarbonise heating. Gas grid in Phase 2 region dispensing methane with a small but growing H_2 share introduced to decarbonise heating.	Full utilisation of all Biomethane and most Bio-SNG feedstocks
2030-2035	H_2	H_2 becomes the industry preferred fuel for long-haul applications, sales expand rapidly (44% sales by 2035)	Stations (up to 6t/day) added to support clusters and large depots mostly in Phase 1 regions. National coverage along motorways developed as H2 dispensing option added to 50-80 CNG/LNG stations. 230 H_2 stations completed mostly around clustered depots in Phase 1 regions.	Large areas within the Phase 1 regions start to convert to 100% H_2 mostly trucked in compressed tube trailers to stations from production sites. Stations close to large production sites use dedicated pipelines. New larger stations built in Phase 1 areas with 100% network connect to the gas network. Larger stations, outside these zones, use trucked H_2 as utilisation is low but are designed to allow easy conversion to pipeline when available	Ramp up in blue H_2 production to become the main source. Green H_2 production continues to ramp up. The majority of green H_2 is co-located with large renewables, the minority is grid connected
2035-2040	Bio-CH_4	Gas truck sales have ended, and the stock declines	Most stations need equipment overhaul and start 5-year conversion to H_2 to buffer falling CNG/LNG demand	Gas grids in Phase 1 regions complete conversion to dispensing 100% H_2 necessitating the full conversion of most CNG/LNG stations but with some remaining station capacity fed by truck Gas grid in Phase 2 region dispensing methane with a high percentage blend of H_2 introduced to decarbonise heating.	Full utilisation of all Biomethane and Bio-SNG feedstocks, proportion of fuel now directed to H_2 production
2035-2040	H_2	H_2 truck sales grow to take a 45% share of sales by 2040. H_2 is now the dominant fuel for long-haul applications	Stations of all sizes (Up to 20t/day) added to support depot clusters, large depots and daughter depots in Phase 1 and Phase 2 regions. National coverage gained through H_2 dispensing option at all 100 CNG/LNG station conversions. 450 H_2 stations completed	Gas network conversion to 100% H_2, across Phase 1 regions and in small parts of Phase 2 regions, allows larger stations to be fed by pipeline. Smaller stations fed by trucked tube trailer from nearest production site or pipeline fed station. Larger truck fed stations built earlier in Phase 1 ramp up utilisation and switch to pipeline	Blue H_2 dominates the supply feeding new converted pipelines. Large green supply co-located with renewables also feeds pipelines. A small amount of supply is delivered directly to local stations

Year	Fuel	Trucks	Station	Transportation	Production
2040-2045	Bio-CH_4	Almost all gas trucks have left the stock	Almost all stations complete their conversion to H_2	Gas networks in Phase 1 and 2 regions complete conversion to supplying 100% H_2, linked together by a national hydrogen transmission system. Remaining stations fed by trucked biomethane/Bio-SNG from production sites.	Continued utilisation of all feedstocks, proportion of fuel now directed to H_2 production and flexible power generation with CCS
	H_2	H_2 truck market maintains a 45% share of sales, predominantly in the long-haul market (the rest is battery electric)	Stations of all sizes (up to 20t/day) added to support depot clusters, large depots, and daughter depots mostly in Phase 2 regions. 550 H_2 stations completed.	Key Phase 2 regions such a Birmingham see regional gas network conversion to 100% H_2. Pipelines feed large stations in Phase 2 regions which then support daughter stations fed by truck. Larger truck fed stations built earlier in Phase 2 ramp up utilisation and switch to pipeline	Mixed supply of H_2 mostly blue H_2 with a smaller but significant share coming from green H_2
2045	Bio-CH_4	The last gas trucks leave the stock	-	-	-
	H_2	H_2 truck market maintains a 45% share of sales (the rest is battery electric)	Mix of stations from 0.5-22t/day completed, supporting depot, depot cluster and public motorway refuelling. In total 600 H_2 stations built with a third of these from repurposed CNG stations	Large stations fed by pipeline. Small stations fed by trucked tube trailer from nearest production site or pipeline fed station	Mixed supply of H_2 mostly blue H_2 with a smaller but significant share coming from green H_2

Table 1: Narrative Summary

3 Narrative Outcome

The previous chapter set out in chronological order the narrative describing how the role of green gases in decarbonisation could grow from a small role today to providing a major contribution to decarbonisation of the economy by 2050. This section highlights the key outcomes of this narrative, grouping them together into the major themes that appear at various points throughout the timeline. Later sections will then explore the actions required by stakeholders to achieve the outcomes identified in this section and after that identify the risks of failing to do so and what the energy system may look like as a result.

Key Outcome	Summary
The role of biomethane	■ Near term role for biomethane to decarbonise heating and trucks while these sectors lack low carbon alternatives ■ The changing role of biomethane over time to maximise decarbonisation potential ■ The opportunity for biomethane to accelerate the decarbonisation of trucks (see Figure 4)
The green gas transition for trucks	■ Sales of gas trucks need to grow rapidly so that stock peaks in the early 2030s – short window of opportunity ■ Hydrogen truck sales need to grow rapidly from 2030 to ensure emitting vehicles are out of the stock by 2050 ■ The infrastructure deployed to serve gas trucks can support the later rollout of hydrogen trucks
Hydrogen trucks can provide an anchor load to support uptake of hydrogen in other transport segments	■ Fleets of trucks represent large single sources of fuel demand ■ Large-scale gas network connected infrastructure will be required at strategic locations to serve hydrogen trucks ■ The demand from trucks can provide an anchor load and national coverage to remove barriers to uptake of hydrogen in other transport segments
Economy-wide hydrogen pathway	■ Overview of how the various narratives from different sectors relate to each other ■ How green gases can be deployed in different sectors at different scales over time to iteratively ramp up production and use.
2050 Green Gas Future	■ Overview of how the various narratives from different sectors relate to each other ■ How green gases can be deployed in different sectors at different scales over time to iteratively ramp up production and use.

Table 2

3.1 The Role of Biomethane

3.1.1 The near-term role for biomethane

By the end of the narrative laid out in the previous chapter (2050), hydrogen is playing a significant role across heating, industry, and transport. Demand has been established, with hydrogen vehicles a mature technology, along with hydrogen boilers in homes and hydrogen-powered equipment in industry. This has allowed producers to steadily increase volumes and reduce costs, in turn making hydrogen a low cost and widely available fuel. However, in the first decade at least, the picture is very different – industrial users will take time to deploy large-scale hydrogen projects and hydrogen HGVs are still at an early stage of development, with only 100s expected on the road by 2025. Injecting hydrogen into the gas grid for heat will also take time before blue hydrogen is produced at sufficient scale to provide a meaningful blend in the gas grid.

During this early part of the narrative, biomethane has a key role to play in reducing emissions from these hard to decarbonise sectors while zero-emission options are developed. Biomethane is already produced at scale in anaerobic digesters (AD), with 2.1 TWh injected into the gas grid in the UK in 2019[12]. This is just 4% of the ~52TWh per year potential from feedstocks that can be processed by AD plants[13], which is a mature technology that is ready to be deployed at greater scale. Later in the 2020s, with the right support Bio-SNG plants could also be a well proven technology ready to scale, unlocking 70TWh of additional green gas potential[14]. These plants would begin producing at scale in time for the peak demand from gas trucks between 2030-2035 and after that would be well placed to displace natural gas in heating or hydrogen production.

3.1.2 Maximising the decarbonisation potential of biomethane

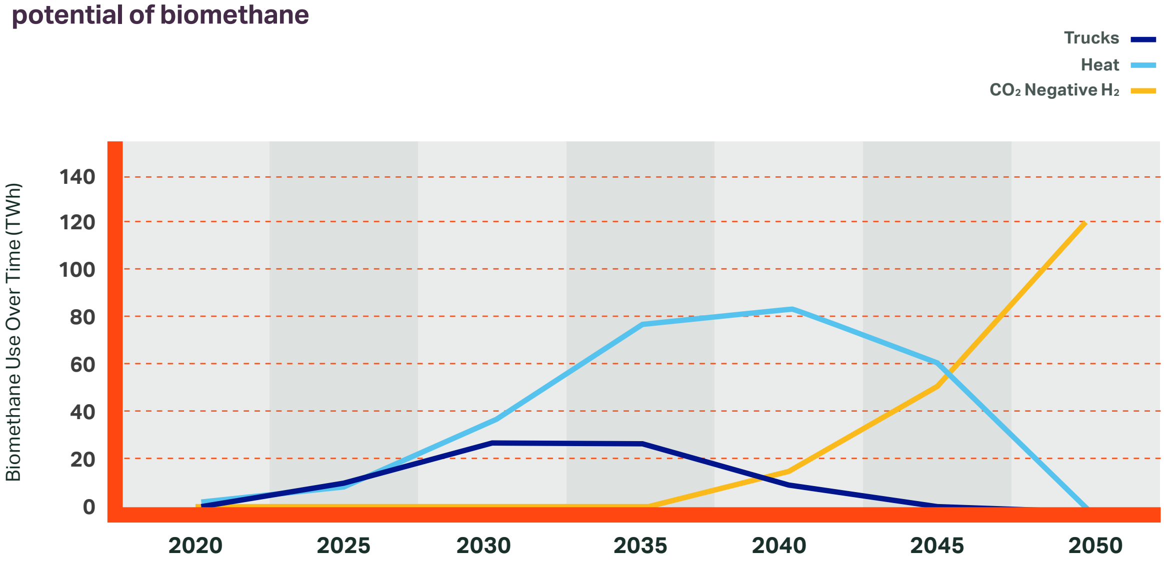


Figure 4 - Biomethane Use Over Time (TWh)

[12] ADBA, 2020, Biomethane: The Pathway to 2030, https://adbioresources.org/docs/Biomethane_-_Pathway_to_2030_-_Full_report.pdf, [13] Analysis by Element Energy, based on feedstocks listed in ADBA, 2020, Biomethane: The Pathway to 2030, https://adbioresources.org/docs/Biomethane_-_Pathway_to_2030_-_Full_report.pdf, [14] Ricardo, 2017, Biomass Feedstock Availability. CCC, 2018, Biomass in a Low Carbon Economy

The feedstocks for biomethane are finite and there will be competition for them from other industries. To maximise decarbonisation potential of the biomethane that is produced, it should be targeted at different sectors over time:

- **2020-2030:** While there are limited decarbonisation options for heating and HGVs, the supply of biomethane is split between them.
- **2030-2035:** Some sections of the gas networks have converted to 100% hydrogen and it is increasingly blended onto the grid to support heat decarbonisation. Biomethane use in heating continues to grow, as the main option for decarbonising heat for buildings connected to the gas network. Biomethane use in trucks plateaus as sales peak in 2032 and begin to drop off rapidly as zero emission alternatives become available.
- **2035-2045:** Biomethane use in trucks falls to very low levels as vehicles leave the stock. Biomethane use in heat peaks in 2040 as gas networks convert to hydrogen and the need to displace natural gas falls. From 2035 as large parts of the gas network converts to hydrogen, biomethane that was used for heating is diverted to reformation plants to produce negative emission blue hydrogen.
- **2050:** Biomethane production is used exclusively for blue hydrogen production, producing significant negative carbon emissions.

3.1.3 Biomethane for HGVs, why it is needed and the CO_2 benefits

Progress is being made on producing zero-emission trucks, with models in development among all the European truck manufacturers. Most are producing very limited numbers of electric trucks primarily for testing with customers ahead of batch production. These typically have short range capabilities (~200km) and are designed for urban delivery applications. Trucks with larger batteries or running on hydrogen that will be capable of the high mileages that the heavier trucks cover, are at an even earlier stage of development and will not be ready at scale until the 2030s.

Gas trucks, however, are a technology that is here today and already capable of meeting the needs of operators in these highest mileage applications. A basic national network of refuelling sites that can serve up to 800 trucks a day each is already being deployed and infrastructure providers are rapidly expanding it. In 2019 biomethane made up 80% of the gas supplied to trucks at these sites, demonstrating significant demand from operators for this low carbon fuel, which typically provides carbon savings of up to 85%[15] compared to diesel on a well-to-wheel basis[16]. The ability to offer lower carbon transport to customers is a key driver of the uptake of gas trucks and so the proportion of biomethane supplied to trucks will remain high as long as production ramps up to meet the expected demand. There are also strong

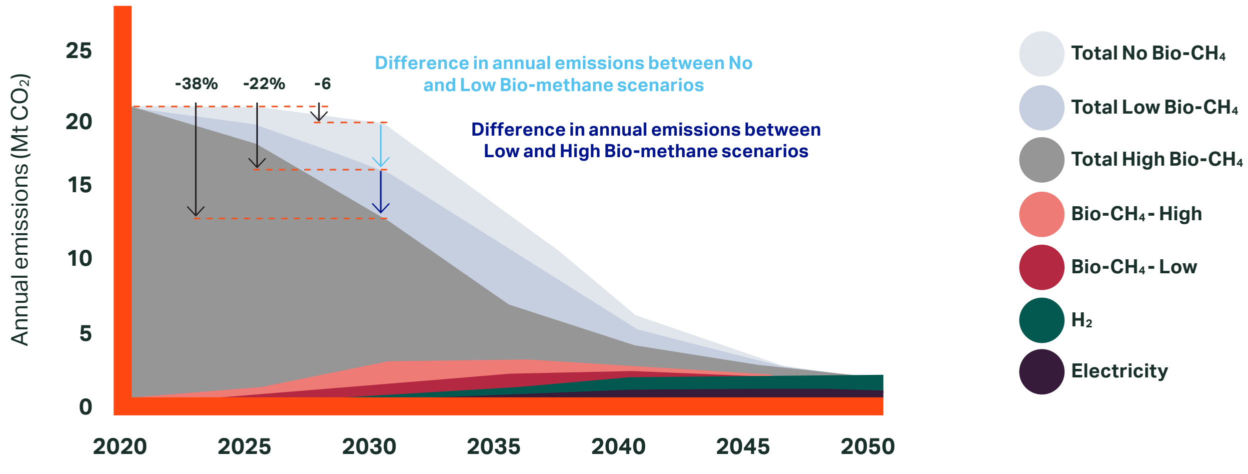


Figure 5 - Well to wheel carbon emissions from trucks by fuel under No, Low and High biomethane scenarios

[15]Exact emissions savings of biomethane used in trucks depends on the feedstock used to produce it, for example the inclusion of biomethane produced from manure can bring the emissions savings beyond 100%, making the resulting biomethane a net-negative emission fuel. [16]LowCVP, 2020, Low Emission Freight & Logistics Trial (LEFT), https://www.lowcvp.org.uk/news,decarbonising-uk-trucks-results-of-threeyear-32m-left-programme-to-cut-freight-emissions-published_4147.htm

economic factors driving this uptake amongst operators on the highest mileage routes, set out in Section 3.2.1.

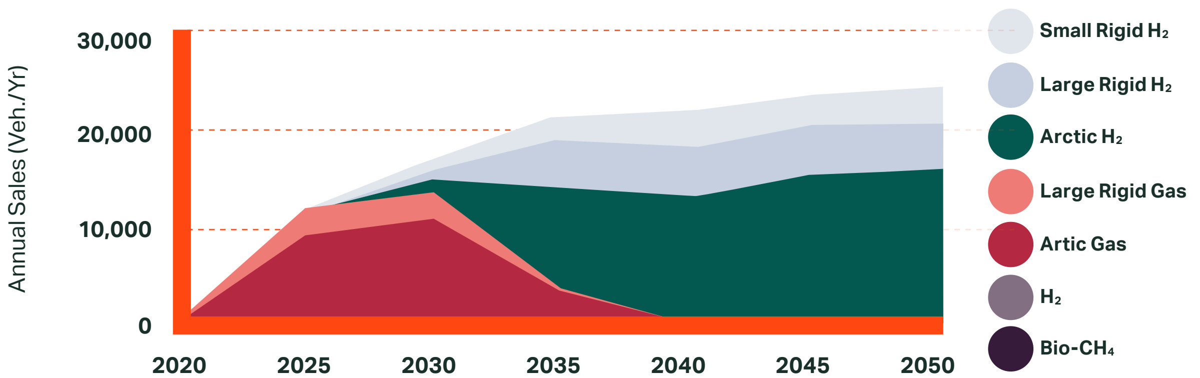
Figure 5 shows the profile of emissions from all trucks as they transition from diesel to zero-emission drivetrains and the impact of adopting gas trucks in the interim. Waiting until zero-emission models are available without deploying any gas trucks would lead to a 6% emissions reduction in 2030 compared to 2020. However, with a rapid deployment of gas trucks over the next 10 years, annual CO_2 emissions from trucks would be between 22% and 38% lower than today.

3.2 The Green Gas Transition for Trucks

There is a clear role for biomethane in trucks in the short-term, but to meet the 2050 net-zero targets these trucks will need to transition to hydrogen at scale from 2030. This will involve not only the development and deployment of the hydrogen trucks themselves so that they become technically capable of replacing diesel- and gas-powered trucks, but will also require conversion of refuelling stations from biomethane to hydrogen. This section lays out the narrative for these two parallel transitions in the use of green gas for transport.

3.2.1 Narrative of transition from biomethane to hydrogen trucks

he next 10-15 years are a window of opportunity for gas trucks running on biomethane to bring down emissions from this sector while no other alternatives exist. The leading gas truck manufacturers Scania, Volvo and Iveco have already made their investments to develop and produce gas trucks at scale and the vehicles are being ordered in growing numbers. The deployment of these vehicles will not hinder the development and deployment of zero emission alternatives in part because as discussed above they will not be ready at scale until 2030 and so sales before then can only displace diesel. In addition to this, early zero emission trucks will be deployed for different applications (low daily mileage applications) to gas trucks (high daily mileage applications) and early adoption of hydrogen trucks is likely to be in different parts of the country to where gas trucks are focused.



[15]Exact emissions savings of biomethane used in trucks depends on the feedstock used to produce it, for example the inclusion of biomethane produced from manure can bring the emissions savings beyond 100%, making the resulting biomethane a net-negative emission fuel. [16]LowCVP, 2020, Low Emission Freight & Logistics Trial (LEFT), https://www.lowcvp.org.uk/news,decarbonising-uk-trucks-results-of-threeyear-32m-left-programme-to-cut-freight-emissions-published_4147.htm

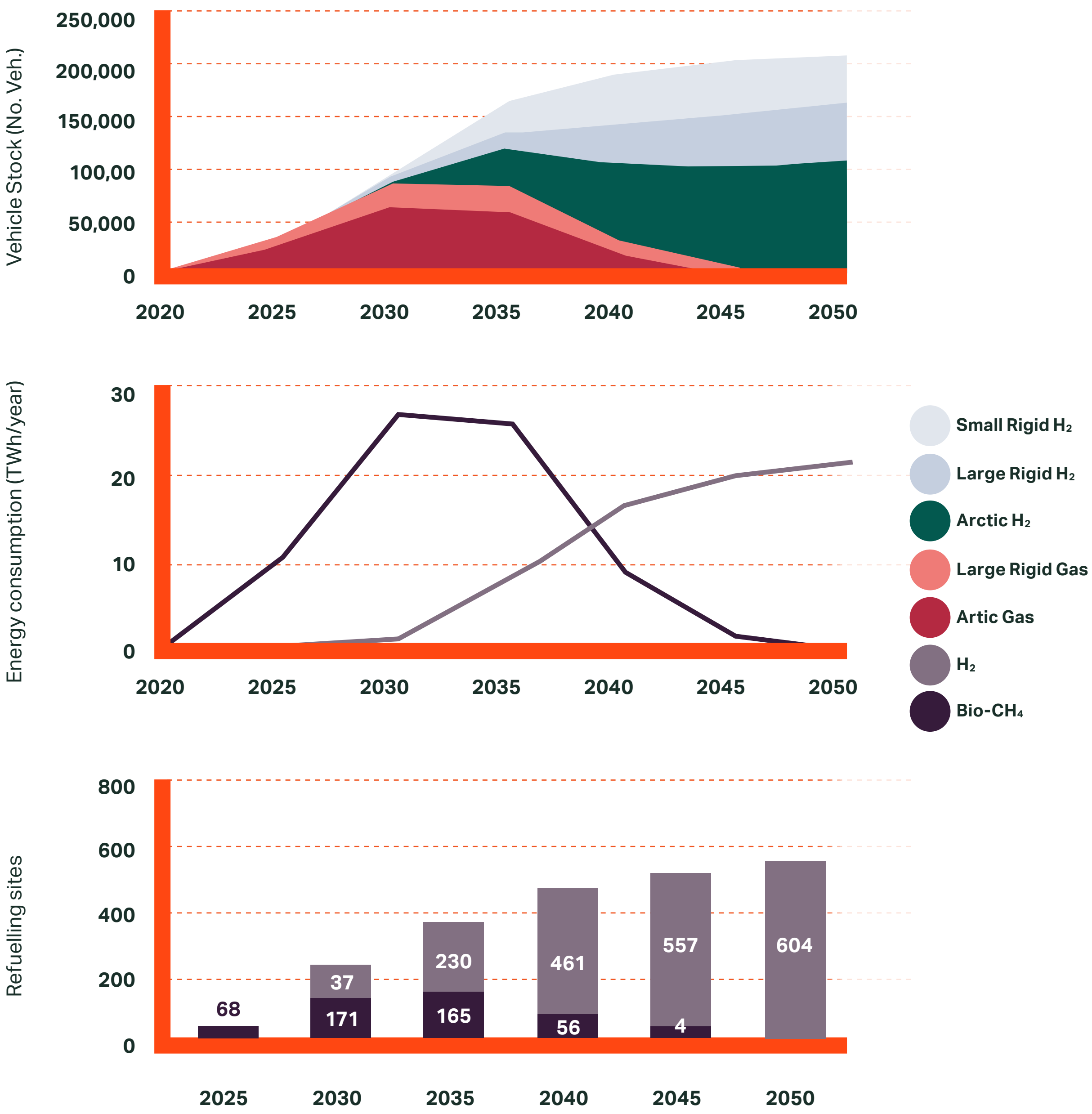


Figure 6 - Deployment of gas and hydrogen trucks and the fuel and refuelling infrastructure (public and private) required to 2050. Small rigid = rigid truck less than 18t, Large rigid = rigid truck >18t. Artic = an articulated truck with a tractor until attached to a trailer

Even when zero emission truck models become available at scale from 2030, the earliest models are expected to have significantly limited ranges compared to gas trucks. The battery electric trucks currently in development typically have a range of 200km, while early hydrogen trucks such as those being deployed in Switzerland will have a range of around 400km. By comparison, gas trucks can have a range of up to 1000km or 1600km depending on whether they run on CNG or LNG, respectively. In addition to this, operators have an incentive to deploy them on the highest mileage routes possible, typically covering 200,000km per year or more. This is because while gas trucks are more expensive to purchase than diesel trucks, the lower level of fuel duty applied to gas compared to diesel means operators can make a saving if the trucks cover sufficient distance over their economic lifetimes.

As a result, hydrogen trucks entering the market in the 2030s, are not likely to compete for the same applications as gas trucks. The early use cases for hydrogen trucks will be medium-range regional distribution and applications that require high on-board energy storage such as refuse collection or mobile construction equipment. As the technology matures throughout the mid-2030s, the costs come down and refuelling infrastructure is built, hydrogen vehicles will begin to displace gas trucks in the highest mileage use cases, in the end gas trucks will completely leave the fleet, replaced by hydrogen, as the gas fuel tax rebate is removed and the sale of all trucks with tailpipe emissions are phase out. This sets a clear end date for the beneficial use of gas in trucks to accelerate the decarbonisation of HGVs, as sales from this point will be in direct competition with a viable zero-emission alternative.

Finally, the first fleets to adopt hydrogen trucks are likely to operate in different parts of the country to the main focus areas for gas trucks. As deployments of hydrogen trucks scale up in the early 2030s, they will need to be based in depots within the Phase 1 regions to ensure access to the lowest cost hydrogen directly from producers. These regions are industrial clusters near the coasts, while the deployment of gas trucks is currently centred on the Midlands, where the major distribution centres for the country are located. As can be seen in Figure 6, the refuelling network being deployed for gas trucks focuses on the central transport corridors from London to Birmingham and the cities of the north. These are essential routes for long distance trucks, but at least initially will not be essential for early hydrogen trucks on regional back-to-base operations that can refuel near their depots.

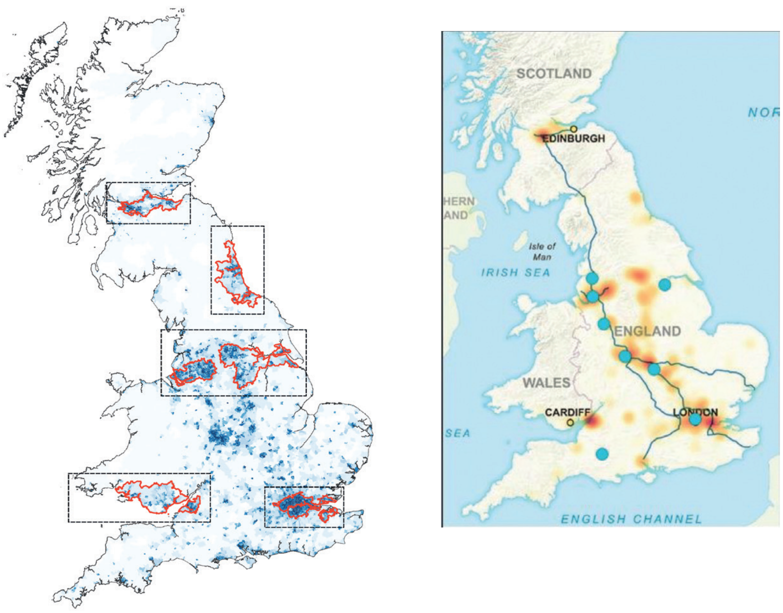


Figure 7 - Comparison of regions covered by hydrogen and public gas refuelling infrastructure

3.2.2 Narrative of transition from biomethane to hydrogen refuelling infrastructure for trucks

As biomethane and then hydrogen trucks enter the fleet at scale, refuelling facilities will need to be in place across the country to supply them with fuel. The focus over the next 10 years will be on building out gas truck refuelling infrastructure, but this process will need to be complete by 2030 to maximise the decarbonisation potential of gas trucks. Any equipment for dispensing biomethane to trucks deployed after 2030 will be at risk of becoming stranded assets, either because within its economic lifetime the gas network transitions to hydrogen or falling demand from fleets makes it uneconomic.

From 2030 the transition from biomethane to hydrogen refuelling infrastructure will need to begin, as the volume of gas trucks in the stock peaks and demand begins to fall. There is unlikely to be any equipment for dispensing biomethane to trucks that can be repurposed to dispense hydrogen. However, since dispensing equipment has an economic lifetime of 15 years before a major overhaul is required, conversion to hydrogen at this point does not necessarily curtail the investment case for this infrastructure, as long as it is deployed by 2030.

The land that the gas truck refuelling sites occupy will be the most important asset in the transition to supplying hydrogen to trucks. By occupying land that is conveniently located for truck operators, and has a connection to the gas network, these sites could flexibly support the hydrogen refuelling network as demand grows. Many hydrogen refuelling sites will need to be built from scratch but adding the option to refuel with hydrogen at established sites will help provide national refuelling coverage more quickly.

	NG STATION	HYDROGEN STATION
2050	0	11
2045	-11	26
2040	-22	62
2035	-1	50
2030	21	7
2025	14	0
2020	3	0

Figure 8 - Green gas stations (stations built per year)

3.2.3 Benefits of transitioning rather than just waiting then going to H_2

Section 3.1.3 above highlighted the carbon emission benefits of deploying gas trucks ahead of a later rollout of hydrogen trucks. In addition to this there are several practical advantages to deploying gas truck refuelling infrastructure now and then converting these to dispense hydrogen as demand grows rather than transitioning directly from diesel to zero emission refuelling.

Firstly, acquiring land that is suitably located for truck refuelling is a time-consuming process. Sites need to be close to where fleets are based because operations are generally time-critical and there is little appetite to detour for refuelling. Most operators currently refuel in-depot from diesel purchased in bulk and so any change to public refuelling will mean additional time compared to the current refuelling set up. Sites also need to be on or close to busy sections of the road network and be suitable for a connection to the gas network. The refuelling network established for biomethane will therefore have a 10-year head-start on identifying and purchasing adequate sites and completing the groundwork to make them accessible to trucks. Sites with sufficient footprint or adjacent space can then begin dispensing tube trailer delivered hydrogen flexibly as demand grows. This will help to provide early access to refuelling opportunities in phase 1 regions and fill in gaps in national coverage across phase 2 regions.

Secondly, large-scale public access gas refuelling sites will already have a connection to the gas grid. As demand for hydrogen grows and gas networks convert to supplying 100% hydrogen, these sites will be well placed to convert to dispensing large volumes of hydrogen. These sites will require significant additional footprint for the purification and storage capacity required to process network-delivered hydrogen on-site. Alternatively, these sites would be fed via a short (<5km) dedicated pipeline from a centralised purification facility. Such facilities would be capable of serving multiple refuelling sites and other markets for high purity hydrogen, helping to improve their business case.

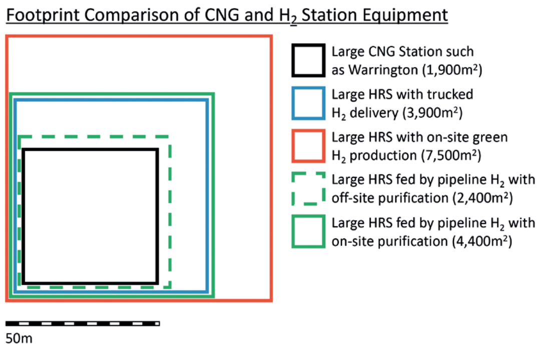


Figure 9: Footprint comparison of a large (capable of supplying 500-700 trucks a day) CNG and hydrogen station (station equipment only, does not include area for parking, truck turning circles etc. as this is assumed to be constant between station designs)

Finally, the transition to public refuelling is likely to be challenging for many operators compared to current in-depot diesel refuelling. However, due to the higher cost of hydrogen refuelling infrastructure, this will be an essential operational change for most fleets to access affordable hydrogen. By taking this step first with biomethane, operators can gain familiarity with the operational changes required to refuel at public facilities. The subsequent adoption of hydrogen vehicles will involve further operational changes due to the shorter range of these vehicles compared to gas or diesel, so familiarity with public refuelling will help reduce barriers at this stage.

Figure 10: Example large scale CNG refuelling station operated by CNG Fuels in Warrington. Image courtesy of CNG Fuels

3.3 Hydrogen trucks can provide an anchor load to support uptake of hydrogen in other transport segments

Investing in refuelling infrastructure for hydrogen vehicles is challenging, because currently there is no guarantee that demand will materialise and in the light duty segment BEV models have proven to be sufficient for most drivers. However, there are several reasons why focusing on supplying hydrogen to trucks first can help to unlock refuelling for other vehicle segments. Firstly, as shown in Figure 10, each truck consumes significantly more fuel than other vehicle types and they also operate in fleets. This means that persuading just one fleet to convert can be enough to justify investment in refuelling infrastructure. Secondly, most trucks operate back-to-base operations, so a single refuelling site conveniently located close to the depot, can be enough to support a whole fleet to transition. Thirdly, unlike passenger cars which operate across the entire country and will eventually need convenient refuelling near to each neighbourhood, trucks operate predominantly on the major road network. As a result, the quantity of refuelling sites required to give national coverage is significantly lower.

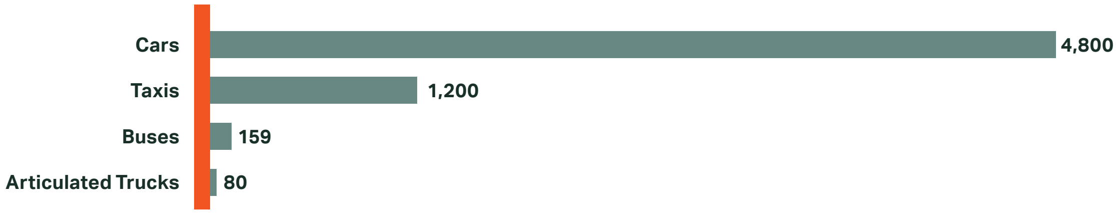


Figure 11 - Comparison of the number of vehicles of a single type required to achieve 80% utilisation at a 3t/day station

Hydrogen trucks will require refuelling infrastructure on a different scale to that which has been deployed to date for buses and cars. These refuelling stations have typically been small, with the capacity to supply 100s of kilograms of hydrogen per day. As can be seen in Figure 11, a fleet of just ~80 trucks would require a refuelling station with a 3 tonne per day capacity which is the practical limit for a refuelling site that is supplied via tube trailers. Beyond this, the quantity of tube trailer deliveries required per day becomes prohibitive. In addition, the Control of Major Accidents and Hazards (COMAH) regulations limit the storage of hydrogen at such sites to 5 tonnes, meaning a 3t/day station would have limited redundancy if deliveries are delayed.

Refuelling sites with a capacity greater than 3 tonnes a day will need to be supplied via the gas network, as on-site production will require significant neighbouring land and alternative distribution methods become impractical. To dispense network-delivered hydrogen will require additional processing equipment to achieve the high level of purity required for use in fuel cells. This equipment would require additional footprint, so could be deployed at refuelling sites with available adjacent land. Otherwise, they would need to be deployed off-site and delivered via a short pipeline. With a supply of gas from the network, such sites would be capable of purifying more hydrogen than required at any single refuelling site and able to serve multiple local markets for high purity hydrogen such as refuelling stations for light duty vehicles and other fuel cell powered systems.

These large sites would only begin to become a possibility once large sections of the gas networks begin supplying 100% hydrogen in 2030-2035. By this point, with sales of cars and vans that use petrol or diesel (including plug in hybrids) ending by 2035, demand for hydrogen fuelled vehicles in these segments is expected to grow quickly. The last petrol and diesel vehicles purchased will be those least suited to BEV models and will require hydrogen to meet their needs. At this point, the purification facilities deployed for trucks would be able to ramp up to supply growing demand from HRS for light duty vehicles.

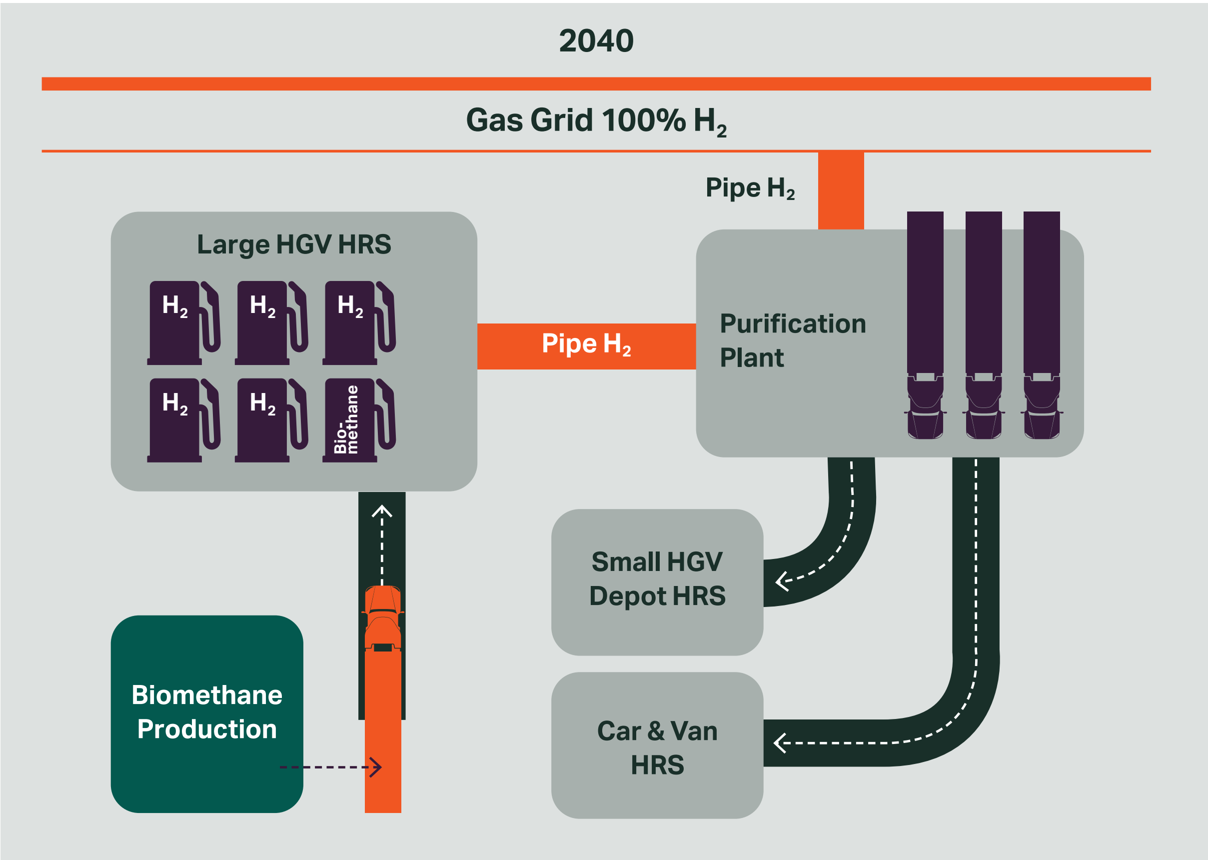


Figure 12 - refuelling infrastructure across all road transport

3.4 Economy Wide Hydrogen Pathway

Electricity and biomethane currently have an advantage over hydrogen as low carbon fuels because dedicated infrastructure to distribute them is already in place. Hydrogen is challenging because low carbon production is currently small scale, making it expensive and while the pipeline infrastructure exists to transport it, there is significant work to be done to re-purpose it for this use. Without this it is difficult to justify investment to scale up production and without scale, it will not be possible to bring the cost down enough to demonstrate the case for converting the gas grid to hydrogen. The narrative developed for this report aims to identify a way forward from this situation that allows hydrogen to achieve scale and lower costs incrementally and iteratively until it is able to fulfil its potential as a major source of low carbon energy. This narrative can be summarised:

- **Early/Mid 2020s:** Early deployments of hydrogen trucks and home heating trials kick start green hydrogen production in the hydrogen clusters (Phase 1 regions). Hydrogen refuelling stations can be supplied by tube trailer so do not need a grid supply, but significant subsidies are required to get operators on-board. The first small, localised sections of the gas network in Phase 1 regions convert to 100% hydrogen, mostly serving buildings for heat.

- **Late 2020s:** Industrial projects to produce and use blue hydrogen are developed throughout the 2020s but take until the end of the decade to ramp up to large scale. Blue hydrogen produced at scale then becomes available to other users in Phase 1 regions. As production ramps up hydrogen starts to be blended at low levels into the gas network across the Phase 1 regions, around large production sites. Larger scale trials of 100% hydrogen networks take place, again focused on supplying heat applications.

- **Early 2030s:** As hydrogen production nationally ramps up, hydrogen distributed by trucks opens up a large market for hydrogen as a transport fuel. Hydrogen production scale lowers the cost of hydrogen sufficiently to begin blending at high blend rates into large areas of the Phase 1 gas grid, and smaller parts of the Phase 2 grid, to support decarbonisation of heating. Large areas of the Phase 1 regions convert to 100% hydrogen.

- **Mid-Late 2030s:** Completed rollout of hydrogen-ready boilers in Phase 1 regions allow 100% hydrogen network clusters to be joined up for region-wide sections of the gas network to convert to 100% hydrogen. At the same time hydrogen blending proportion continues to grow in Phase 2 regions and several areas of the Phase 2 regions convert to 100% hydrogen networks. Centralised purification plants supplying large-scale truck HRS are deployed, also providing access to low-cost hydrogen for other vehicle segments.

- **2040s:** As costs fall, gas networks in Phase 2 regions begin to connect smaller sections of the gas network that have converted to H_2 resulting in most of the gas network supplying 100% hydrogen. This gives hydrogen producers access to a large customer base outside the Phase 1 regions and increasing supply to industry and heating. This further reduces the cost to supply vehicle refuelling stations in these regions, making hydrogen a widely used fuel across all vehicle segments.

- **2050:** Gas networks in Phase 1 and Phase 2 regions have all converted to 100% hydrogen, supplying 75% of the TWh used by transport, heating, and industry.

3.5 2050 Green Gas Future

If the narrative set out in the preceding sections is achieved, by 2050 hydrogen would be a major energy source used across the economy. By this point hydrogen would be produced at scale, with the bulk of production coming from blue hydrogen production sites at the coasts taking advantage of offshore CCS opportunities. The scale achieved at these sites allows hydrogen to be produced cheaply enough to replace natural gas for heating in most homes with the remainder using electric heating systems. This forms the main source of demand for hydrogen in 2050 at 325TWh per year.

By 2050 the main industrial clusters have had 30 years to decarbonise and since early hydrogen projects were focused in these areas, they have developed significant expertise in hydrogen. Nearly all processes that were not already electrified have been converted to hydrogen, representing an annual GB demand of 115TWh per year. Most of this still comes directly from the local blue hydrogen production sites that the industrial users supported in the early years by providing an anchor load. Now this role is performed by heating, allowing industrial users much greater flexibility in when and how they purchase hydrogen and helping to bring down the cost to an internationally competitive level.

Within transport, by 2050 hydrogen is the main fuel for long-haul trucks, while medium duty trucks are split between hydrogen and electricity and local distribution trucks are almost exclusively battery electric.

Shown in Figure 12 is the national hydrogen refuelling station (HRS) network that would be required to fuel these trucks, made up of just over 600 locations. 170 (calculated based on station size and proximity to the high-pressure gas network, transmission and distribution) of these are large stations connected either directly to a production site or the gas network (many of these will be the 100 grid connected CNG stations converted to hydrogen). These are large sites with significant purification facilities, allowing them to process significantly more hydrogen than is required by trucks at each site. From these sites, hydrogen is trucked to the remaining 430 smaller truck HRS located in depots or along less busy

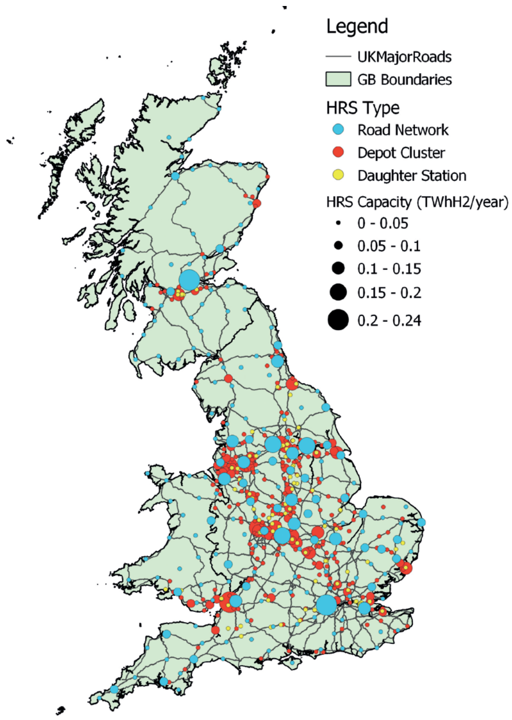


Figure 13 - 2050 HRS network for trucks

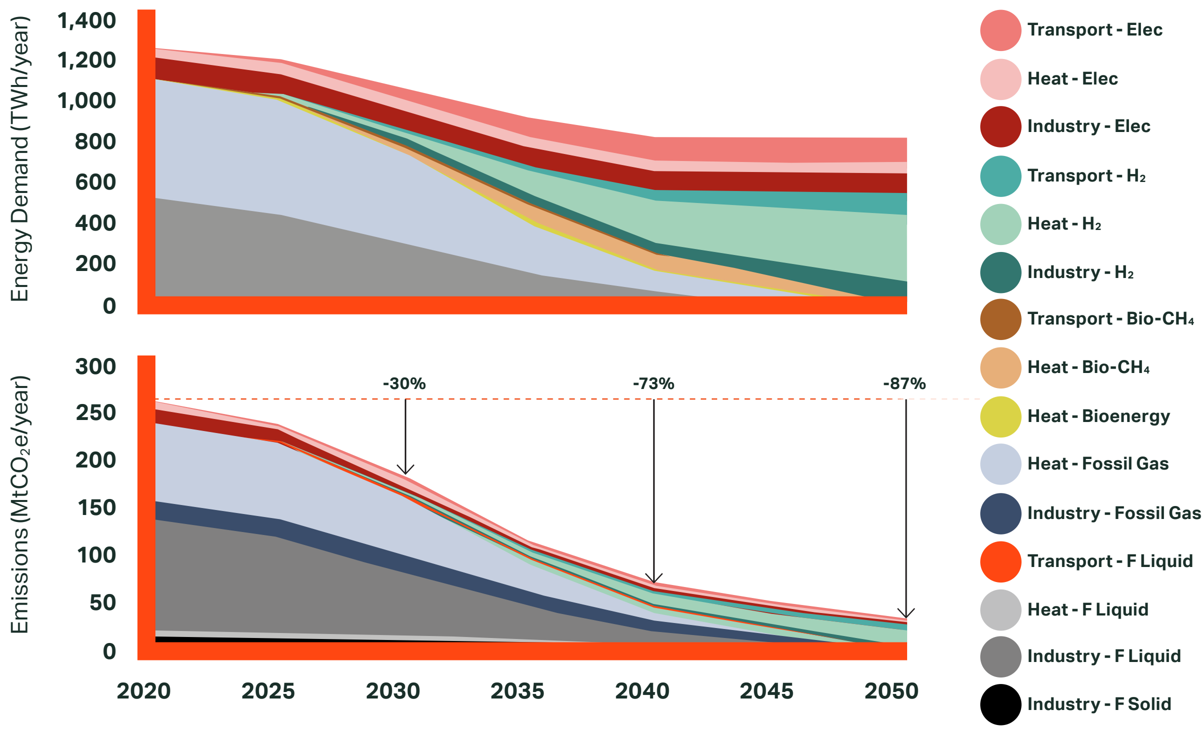


Figure 14 - Economy-wide energy demand and well to wheel CO_2 emissions profile under high hydrogen high biomethane scenario 2020-2050

3ections of the road network. They also provide hydrogen for HRS serving buses and coaches, light duty vehicles and other markets for high purity hydrogen.

By 2050 hydrogen has come to play a niche role for high-mileage light duty vehicles and those requiring short refuelling times or additional on-board energy storage. Although niche, the scale of the light duty segment means these vehicles represent significant hydrogen demand. In total 100TWh per year of hydrogen is used in transport (road vehicles, rail and domestic marine), which is a widely used transport fuel due to the large scale of production and the backbone of purification and distribution infrastructure established first for trucks.

This economy-wide transition to hydrogen would lead to a deeply decarbonised economy, emitting carbon emissions at a level that is 87% lower than today across transport, heat, and industry. Including the negative emissions from biomethane used to produce negative emissions blue hydrogen would raise this figure to 90-95%.

4 Policy asks and stakeholder action required to achieve high hydrogen scenario

The 2050 vision described in the previous chapter is very different from the reality of the biomethane and hydrogen industries today and there are multiple actions that need to be taken by a range of stakeholders over the next 30 years to achieve this vision. The following section sets out who the key stakeholders in the narrative to 2050 are and what each of them needs to do and when to make green gases a viable fuel for a decarbonised economy. This includes not only policy makers, but infrastructure providers, equipment manufacturers, gas producers and transmission and distribution network operators, to make the narrative a reality.

4.1 Government and policy makers

Government and policy makers have a key role to play in ensuring that targeted policies are in place that create a supportive environment as the gas industry pivots to supplying green gases. As described in the narrative, the next ten years will require a focus on ensuring that biomethane can reach its full potential and that the groundwork is done to allow large expansion of hydrogen in the 2030s.

4.1.1 Support for gas trucks

- **Fuel duty differential:** The reduced fuel duty applied to gas used in transport should be maintained until 2032 at a level that ensures a continued competitive business case for uptake of gas trucks amongst HGV operators. Certainty of this policy remaining in place until hydrogen alternatives become available at scale will ensure operators and infrastructure providers can invest in vehicles and refuelling stations over the next 10 years. A gradual reduction over time would provide this certainty while also giving a clear end date for support, signalling that the industry must act fast to take benefit, but also plan for a longer-term transition to hydrogen.
- **Support for biomethane trucks in the Transport Decarbonisation Plan**: The plan should make clear the opportunity for gas trucks in the next 10-15 years before zero emission alternatives achieve scale. Other government documents and announcements should align with this message to provide clarity to operators and infrastructure providers on the government's position.
- **End to the sale of diesel trucks:** Setting a date to end the sale of diesel trucks is a key next step on the government agenda (as set out in the 10 Point Plan). An ambitious end date for the sale of diesel trucks of 2035 will encourage greater uptake of gas trucks in the long-haul market.

4.1.2 Support for biomethane

With the ending of Feed in Tariffs and Renewable Obligations for biogas plants there is a significant opportunity for existing biogas plants to invest in additional biomethane upgrading facilities. This should be reflected in policies aimed at encouraging investment in biomethane production:

- **Renewable Heat Incentive:** Biomethane production needs to grow at twice the rate seen over the previous decade. The level of tariff support provided to existing biomethane production sites should be reviewed regularly for potential increase to ensure sufficient incentive for continued production.
- **Green Gas Support Scheme:** It is essential that this scheme is deployed to support continued investment in new biomethane production capacity and that producers can flexibly claim the tariff and RTFO payments for biomethane.
- **Improved collection of biomethane feedstocks:** Nation-wide collection of separated waste streams as envisaged under the Environment Bill would significantly expand the availability of feedstocks for both AD and Bio-SNG plants. This could also have the benefit of increasing gate-fees for biomethane producers, improving the investment case and reducing dependence on tariff support.
- **Support for Bio-SNG:** Support is required to demonstrate Bio-SNG plants at scale in the early 2020s so that they can become a major source of biomethane in the 2030s.
- **Green Gas Levy:** A green gas levy on fossil fuel gas suppliers is under consideration by BEIS for introduction in Autumn 2021. This will increase the cost of fossil fuel gas making biomethane more competitive and will raise funds to support low carbon heating schemes.

Policy support will also be required over the next 10 years to ensure that by 2030 the foundations are in place for the hydrogen industry to expand rapidly. This will include support for projects demonstrating use cases for hydrogen, as well as the development of large-scale green and blue hydrogen production capable of supplying these users as demand grows. Initially, the costs of producing and using hydrogen will be significantly higher than incumbent technologies and subsidies will be required to ensure investment takes place to achieve scale. As this narrative sets out, once at scale hydrogen can provide a cost effective, low carbon energy source for a large part of the economy that will no longer require subsidy.

4.1.3 Support for hydrogen use

Trucks

- **Large scale commercial demonstrations:** Operators will need to see vehicles in operation before they will commit to investing in them. Manufacturers will conduct trials with smalls number of vehicles to prove the technology, but large-scale trials with 100s of vehicles will be needed to demonstrate the vehicles in real world conditions. Early users should be geographically clustered so that effective refuelling and maintenance can be achieved.
- **Local and national measures to make zero-emission trucks cost competitive:** Zero-emission trucks will initially be more expensive than diesel incumbents and there are a range of policies that government can enact to achieve this, including increasing taxes paid by diesel vehicles and exempting zero-emission vehicles, creating zero-emission charging zones and providing purchase grants for zero-emission trucks.
- **Flexibility in HDV weight and size restrictions:** Zero-emission powertrains are challenging to package within the current size and weight restrictions of truck bodies. If these restrictions are not adapted for zero-emission trucks their payload capacity will be reduced, further reducing their ability to compete with diesels.

Other sectors:

- **Industry:** Government will need to support the deployment of early hydrogen industrial clusters, as the early investment cases are likely to be challenging. Once these clusters are established, the scale achieved will help to lower costs for hydrogen in heating and transport, reducing the need for subsidies in these areas.
- **Heat:** Government support is required to ensure that hydrogen is blended into the gas grid in at least one network by the mid-2020s. This will require support

for early demonstration projects so that blending can contribute meaningfully to decarbonisation by 2030. Over this period policies will be required to ensure hydrogen-ready appliances are installed ahead of the first network conversions to 100% hydrogen. With hydrogen transported through the gas networks to serve large-scale demand for heat, transport users will benefit from lower hydrogen prices, improving the economics of hydrogen vehicles across all segments.

4.1.4 Support for hydrogen production

- **Green hydrogen:** Action needs to be taken in the next 5 years to get early green hydrogen projects off the ground to supply demonstrations of hydrogen technologies in Phase 1 regions. Later focus of green hydrogen production will need to shift to Phase 2 regions to ensure national access to hydrogen for vehicles and to establish demand ahead of network conversions.

- **Blue hydrogen:** Government support is needed to ensure work begins in the early 2020s on the first blue hydrogen production site with associated CCS so that it is operational by 2030 when demand from local industrial users is ready to ramp-up.

4.2 Refuelling infrastructure providers

Companies working to deploy refuelling infrastructure for gas trucks today must ramp-up quickly in the next five years to ensure that the national network is complete by 2030. During this period, significant research and development is needed to understand the requirements for hydrogen refuelling and how the transition can be managed. This learning should be included in criteria for identifying sites that are suitable both for biomethane refuelling and future hydrogen stations. The key actions required from infrastructure providers are:

- **Rapid deployment in the 2020s:** Infrastructure providers will need to install ca. 170 biomethane refuelling stations by 2030 to ensure there is sufficient capacity to supply the peak potential demand from gas trucks during the first half of the 2030s.

- **Research and Development:** Refuelling infrastructure providers need to understand the implications for purifying hydrogen that is delivered via the gas network before first gas grids transition 2035-2040

- **Considerations for hydrogen conversion:** When selecting sites for biomethane truck refuelling, infrastructure providers should consider the implications for future conversion to hydrogen refuelling including:
  - **The proximity to potential future sources of hydrogen.** This is particularly true for sites in Phase 1 regions where dispensing hydrogen alongside biomethane could become an opportunity within the next 5-10 years and will need to be trucked from green hydrogen production sites.
  - **The additional footprint required** to supply both hydrogen and biomethane during transition period in 2030s. Initially sites will require additional footprint for trailer deliveries of hydrogen[17], but as the grid converts sufficient adjacent or nearby (<5km) land will be needed for purification facilities (see Figure 7).

4.3 Truck manufacturers

To maximise and accelerate the use of green gases to decarbonise HGVs, it is essential that manufacturers produce the vehicles in sufficient volumes and within the required timeframes. Early in the narrative the focus is on taking advantage of the potential of gas trucks, which will need to run in parallel with development of hydrogen vehicles. Manufacturers will need to work closely with infrastructure providers so that both have confidence that demand for their products will materialise.

4.3.1 Gas trucks

- **Production ramp-up:** Production of gas trucks needs to grow rapidly in the next 5-10 years to maximise the role of these vehicles before zero emission options become available.

[17] Trailer delivery bays and hydrogen storage, cooling and compression equipment will require additional land on top of the equipment space already taken up for the CNG compression and storage. This is expected to be in the region of 20% more space needed for the delivery, compression etc. equipment for a CNG and hydrogen station compared to a CNG station alone. The dispensing area size is expected to remain unchanged as a small number of CNG dispensers will be removed and replaced with hydrogen.

- **Investment focus on production and refinement:** Support for gas trucks is likely to end in the early 2030s as zero emission models become available so there is a short window to achieve a return on investments in existing gas models. Further investment in these models should be limited to refinement and increasing production, while the investment focus should be on in developing zero emission drivetrains for large scale deployment from 2030.

4.3.2 Zero-emission trucks

- **Vehicle demonstrations:** in the early 2020s, demonstrations involving 100s of hydrogen trucks in various real-world use cases will be required to prove the viability of the technology.

- **Batch production:** From 2025, 100s of hydrogen trucks per year will be needed for the GB market alone, growing to several 1000s per year by 2030 for deployment with early adopter fleets to gain familiarity ahead of mass adoption.

- **Mass production:** Hydrogen trucks need to begin mass production in the late-2020s and early-2030s to ensure the vehicles are able to replace remaining diesel and gas trucks in the fleet ahead of the 2050 net zero target.

- **End production of all tail-pipe emission vehicles:** Daimler has announced 2039 for the end of sale of its diesel trucks and Volvo has a similar target for 2040. All production of trucks producing tailpipe emissions need to end by 2040 at the latest.

- Types of zero emission trucks required to maximise decarbonisation potential:
  - **Gas trucks:** Focus on long-haul applications which will be most challenging for zero-emission alternatives.
  - **BEV trucks:** Best suited to short-range urban delivery and distribution
  - **Early hydrogen trucks:** While gas trucks dominate the high mileage market during the 2030s, hydrogen trucks will have opportunities in medium-range applications and will need a range of 350-400km to provide a meaningful benefit compared to battery models. Uses include regional distribution and vehicles requiring additional power for on-board equipment such as refuse collection trucks, particularly those on higher mileage rural routes.
  - **Later hydrogen trucks:** From the late 2030s hydrogen trucks will be required with range capabilities of 800km, allowing them to cover most real-world daily truck operations in GB. With nationwide coverage of refuelling infrastructure, a single refuel will allow them to match the 1000+km range of gas trucks today and displace the last gas and diesel trucks operating on the longest and most challenging duty cycles.

4.4 Gas producers

The 2020s will be a critical period for establishing green gases as a large-scale decarbonisation option. During this period, biomethane production from AD plants needs to expand to meet its full potential, while production from Bio-SNG needs to become an established industry that is rapidly scaling towards achieving its full potential by the late-2030s. The next ten years will also be critical for hydrogen producers, who will need to lay the groundwork for low- and zero-carbon hydrogen to meet the huge potential demand from heat, industry and transport as these sectors rapidly decarbonise in the 2030s and 2040s.

4.4.1 Biomethane Producers

- **Biomethane production from AD:** Needs to ramp production quickly in the 2020s to meet early growth in demand from trucks. With the end of Feed in Tariffs and Renewables Obligation Certificates for biogas there could be a significant opportunity amongst sites established under these incentives to invest in biomethane upgrading equipment.

- **Conversion of gas networks will affect producers of biomethane from AD and plans will need to be made to manage this transition depending on the location of the AD plant:**
  - Network-connected sites in Phase 1 regions will lose access to the gas grid earliest and would then need to truck biomethane – could be an opportunity to supply blue hydrogen or truck refuelling sites nearby.
  - Centralised injection facilities will also no longer be an

option when the network converts to hydrogen, but sites already set up to deliver their biomethane to these facilities by tube trailer will have some flexibility to divert them to injection facilities in Phase 2 regions or to truck refuelling sites.

- Biomethane production in Phase 2 regions has lower medium-term risks of network converting to hydrogen, but once it does options will be more limited. Later in the timeline there will be limited opportunities to supply refuelling stations and Phase 2 regions are furthest from the blue hydrogen producers in the Phase 1 areas.

- **Biomethane production from Bio-SNG:** The first full-scale plants need to be developed by 2025 for a rapid deployment to take place in the second half of the decade.

- **Bio-SNG plants need to plan for conversion to hydrogen production:**
  - In Phase 1 regions this could occur relatively early in the lifetime of a Bio-SNG plant and will need to be considered before investment is made in biomethane production equipment
  - Plants in Phase 2 regions will have a longer window of opportunity to produce biomethane and later invest in converting the plant to hydrogen production in time for conversion of the grid.

4.4.2 Hydrogen producers

- **Green hydrogen:** Projects need to be established in the Phase 1 regions in the next five years to support the first deployments of hydrogen vehicles in these clusters. Throughout the 2020s these projects will also need to be deployed in the Phase 2 regions national coverage can begin to be established for hydrogen refuelling.

- **Blue hydrogen:** Establishing the first large-scale reformation plant connected to CCS will take time to plan and build. Work on the first site will need to begin early in the 2020s to ensure low-carbon hydrogen is ready at scale as demand grows in the 2030s. During the early 2030s large scale blue hydrogen production will be required in all Phase 1 clusters so that hydrogen can be blended into local gas networks, and later in the decade supply 100% hydrogen for the network.

4.5 Gas Network Operators

The gas network operators have a significant role to play in ensuring that green gases can be transported from production sites to users. They will also need to conduct substantial research and development work to understand the safety and practical implications of blending and eventually converting to 100% hydrogen on the gas network.

4.5.1 Connecting producers and users

- **Connecting biomethane production:** A key role of the gas networks during the 2020s will be supporting the rapid increase in production of biomethane. This will mean providing connections for new biomethane producers, or centralised grid injection facilities to ensure access to the network does not constrain the growth of this industry.

- **Connecting gas truck refuelling sites:** During the next decade over 100 gas truck refuelling sites will need to be built across the country and connected to the gas network. This will need to happen ahead of the deployment of vehicles to provide certainty of refuelling availability, so many of these connections will need to be completed by 2025.

4.5.2 Research and development

- **Hydrogen blending:** This will need to begin in the mid- to late-2020s to provide a large source of demand for hydrogen producers in the Phase 1 regions. This means work needs to be done now to demonstrate the safety of hydrogen blending for all users on the network and to understand and overcome the practical challenges.

- **Hydrogen conversion:** From the mid-2030s networks in Phase 1 regions will need to begin converting to 100% hydrogen. In the interim, demonstration projects need to be completed in small sections of the network so that larger areas can be made ready ahead of a wider conversion.

- **Purification:** For network-delivered hydrogen to be used in transport applications, the processes required for purifying hydrogen to the high standards required for fuel cells will need to be well understood. Purification equipment will need

5. Narrative Risks

to be ready for large-scale deployment as network-supplied refuelling stations become possible. This will require scaling up of the technology, cost reductions and shrinking the equipment footprint to make it easier to fit on a station site.

As set out in the introduction, this report aims to provide a clear narrative for the transition from today's energy mix to a future, where green gas plays a major role in supporting economy wide decarbonisation. For this reason, the earlier chapters of the report only focus on a future where green gas has gained a significant proportion of the energy mix.

However, it is important to recognise that there is uncertainty about the future energy mix with many studies presenting scenarios with high green gas use, as we have presented here, but also scenarios dominated by green electricity, with relatively low green gas use (for example the CCC 6th carbon budget sees hydrogen demand vary between ~150TWh and 400TWh, and electricity demand vary between ~600TWh and 900TWh in 2050 across their 5 scenarios). To understand these two possible futures this study modelled the energy mix across the GB economy under a High Green Gas scenario and a Low Green Gas scenario. The rest of this chapter will describe these two possible scenarios in more detail, highlighting their benefits and drawbacks, and discussing the risks in each case.

5.1 High and Low Green Gas Scenarios

The High Green Gas scenario has been described in detail in the earlier chapters of this report, but in summary this scenario assumes that stakeholders see a significant role for green gas across multiple sectors. Early investment and a large potential market see the production of green gas ramp up very quickly. This helps to bring down prices to a competitive level, and also offers an alternative decarbonisation option to electrification before further development in electrification technology makes electrification suitable for many applications (such as heavy-duty transport and industry).

The Low Green Gas scenario demonstrates that the decarbonisation of the GB economy with low levels of green gas is possible. This scenario reflects different investment decisions made in the 2020s. In this case, the current growing interest and investment in electrification continues to grow at an ever-increasing rate, bringing down costs and improving the technology to allow its use in applications where it is not suitable today. The confidence in electrification's future potential shifts future investment away from green gases. This has a compounding effect over time as a smaller initial investment reduces green gas volumes which increases prices, which in turn reduces future confidence, investment, production volumes leading to further increases future price. This spiralling effect leads to a significantly reduced role for green gases in the future.

The differences between the two scenarios are presented for each sector in Table 2 and summarised in Figure 12 and Figure 13.

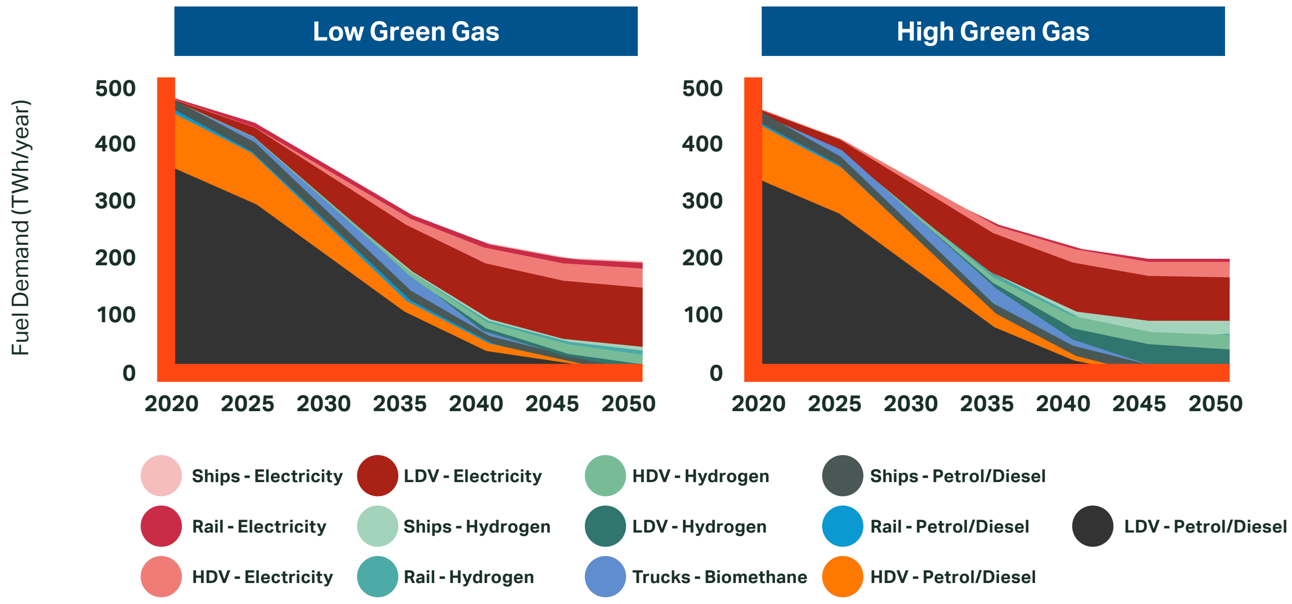


Figure 15: Transport fuel demand in the high and low green gas scenarios

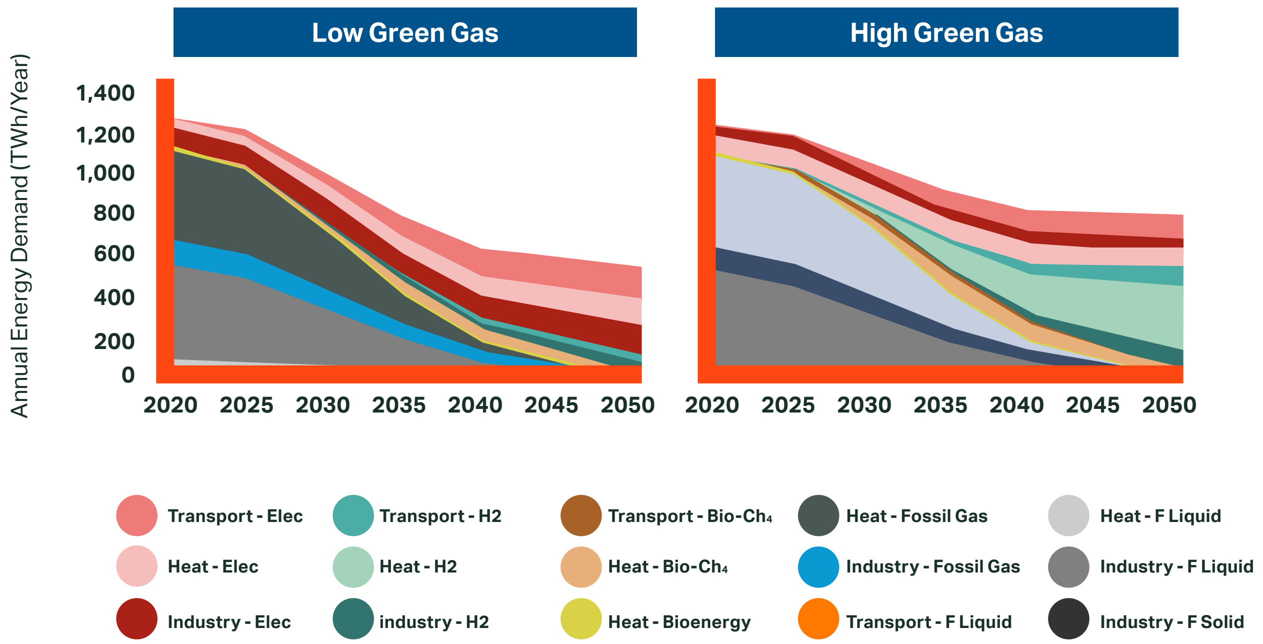


Figure 16: Transport, heat, and industry fuel demand in the high and low green gas scenarios

Sector	High Green Gas Scenario	Low Green Gas Scenario
Fuel Production	Biomethane production ramps up very quickly in the 2020s and full commercial scale Bio-SNG plants start to be built from 2025 Hydrogen is supported as a major decarbonisation fuel in transport, heat and industry, driving up production volumes and driving down prices	Solar and wind project development prices continue to fall, and the technology is rolled out at large scale both at large energy farms and at a community and household level. Hydrogen is supported for niche applications but never gains enough scale to bring prices down to a competitive level
Fuel Distribution	Hydrogen for heat supports the business case for converting the gas grid to hydrogen helping to overcome the issue of distributing large quantities of hydrogen across the country for heat, transport, and industry demand	Smart electricity grids help to support the introduction of renewables at all voltage levels
Fuel storage & supply /demand balancing	Cavern storage proves a cost-effective option for hydrogen storage allowing hydrogen to play a key role in seasonal energy storage	Increasing energy supply at the local level coupled with smart houses, electric vehicles and low-cost electricity storage allows the electricity grid to be balanced at very low cost
Car	The market is dominated by battery electric cars, hydrogen fuel cell cars gain a small but significant share in high mileage applications	The market is dominated by battery electric cars. Hydrogen fuel cell cars are available, but usage is limited to a very small number of specialised fleets
Van	By 2050 the market is a roughly evenly split between battery electric and hydrogen fuel cell vans	The market is dominated by battery electric vans; hydrogen fuel cell vans gain a small but significant share in high mileage applications
Truck	Biomethane becomes the fuel of choice for the long-haul truck market Hydrogen trucks are tested and commercialised in the 2020s taking a significant proportion of the medium duty truck market from the late 2020s, moving into the long-haul truck market from the mid-2030s. Battery electric trucks remain the technology of choice for short range applications	Biomethane takes a significant share of the long-haul truck market but many operators stick with diesel until a zero-emission option is available Battery electric trucks are tested and commercialised in the 2020s taking a significant proportion of the low and medium duty truck market from the late 2020s. Battery electric trucks also take a share of the long-haul truck market from the mid-2030s in application where midday recharging is convenient. Hydrogen trucks are commercialised slightly later taking over the remainder of the long-haul truck market from the mid-2030s.

Sector	High Green Gas Scenario	Low Green Gas Scenario
Bus	Battery electric buses are used for approximately half of bus applications mainly on shorter urban routes. Hydrogen fuel cell buses take the other half of the market on longer routes, routes in rural areas and urban routes where the density of bus routes is low making the business case for opportunity charging more challenging. Biomethane buses remain niche, due to air quality concerns in urban areas and the increasing availability of zero emission options	Battery electric buses take over the majority share of the bus market supported by opportunity and flash charging on bus routes. Hydrogen fuel cell buses take a smaller but significant share of higher speed routes, especially in more rural locations
Coach	Battery electric coaches take over approximately one third of the market in 2050 focusing on applications where limited public recharging is needed. Hydrogen fuel cell coaches take the remainder of the market due to improved operational flexibility	Battery electric coaches take over approximately two thirds of the market in 2050 using the public refuelling infrastructure rolled out for trucks and buses. Hydrogen fuel cell coaches take the remainder of the market in applications where route variability makes it very challenging to organise public charging
Industry	Hydrogen industrial clusters producing blue hydrogen prove successful in the 2020s and the model is replicated in all industrial clusters in GB. The conversion of a significant area of the gas grid to hydrogen makes hydrogen available to industrial applications outside the main clusters. Electricity use in industry remains close to today's levels in 2050	Low-cost electricity and high-cost hydrogen sees a shift in industrial equipment to run on electricity with applications reliant on combustion connected to CCS. Hydrogen becomes a niche fuel for applications where combustion is necessary and local hydrogen production is available leaving hydrogen use limited to small geographical areas
Domestic and Non-Domestic Energy Use	Hydrogen is initially blended in the gas grid for heating use. Over time, region by region the gas grid is converted to 100% hydrogen as the local production capacity ramps up to meet demand. Most homes on the gas grid switch over to hydrogen boilers	The majority of buildings switch over to heat pumps and are disconnected from the gas grid resulting in large areas of the gas grid being decommissioned. Some areas of the gas grid remain to supply hydrogen to industry or transport and in these areas, heating is supplied by hybrid heat pumps

Table 3 - Overview of the high and low green gas scenarios by sector

5.2 Drivers and Barriers to Achieving the Two Scenarios

As introduced in the previous sections the two scenarios are both achievable but face different investment, technology, policy, and stakeholder barriers. These will be discussed in detail in this section to highlight the role of different stakeholders to realising these different futures.

Table 3 summarises the drivers and barriers for each of the two scenarios. In many respects both scenarios face the same barriers as they both represent the situation of a new technology trying to displace an incumbent technology which benefits from scale, technology lock-in and public acceptance. A key difference is that the technologies needed for the Low Green Gas Scenario have made further progress to date and now benefits from some of the scale, confidence, and industry buy-in of a more commercially advanced technology. While we are currently well placed to transition along the Low Green Gas Scenario there are a number of factors that may suggest a mixed technology future as shown in the High Green Gas Scenario may still attract major support.

The first of these factors, and the most important, is that decarbonisation efforts are accelerating. When looking at what decarbonisation can be achieved by 2030 or 2040 a mixed fuel (electricity, hydrogen and biomethane) approach may have a number of potential benefits.

1. Increased use of biomethane offers a pathway to decrease short term emissions, especially in sectors where no other short-term technology decarbonisation option exists, such as for long-haul trucks.

2. Switching from the combustion of natural gas to the combustion of hydrogen in industrial processes requires smaller equipment changes, than the equipment replacement needed to electrify, potentially helping to speed up the transition.

3. The conversion of heating over to heat pumps will require an upgrade to the insulation in most buildings. Each year that this task is not begun in earnest delays the decarbonisation of buildings. Hydrogen boilers can effectively heat a building without major insulation upgrades. While it is certainly the right thing to do to improve building insulation, to improve efficiency and reduce fuel poverty, lifting the constraint of insulating buildings on the decarbonisation of heating could help to achieve early emissions reductions.

The second of these factors is that the changes needed for green gas deployment are more on the infrastructure and business side and will lead to less disruption for consumers. This can make policy intervention easier as these actors are more heavily regulated, and the smaller number of stakeholders involved means that getting a relatively small number of people on-board can quickly have a major impact.

Sector	High Green Gas Scenario	Low Green Gas Scenario
Drivers	■ Acceleration of decarbonisation efforts forces sectors to make use of existing technology and assets making green gas more competitive in heavy duty transport, heating and industry ■ Scenario offers an investment opportunity for a wider range of stakeholders. Once all these stakeholders engage with decarbonisation this should allow rapid investment	■ Continued rapid improvement in battery price and energy density makes battery electric options more competitive in all transport sectors ■ Falling renewable and battery prices will make local energy management at the household, community, or regional level an attractive and price competitive option for consumers to power their house and cars ■ The falling cost of renewables and batteries has resulted in increased industry confidence and investment, accelerating this market
Barriers	■ Current investment levels are very low and will need to be ramped up very quickly to match those going into electrification ■ The hydrogen supply chain is less efficient than the electricity alternative requiring more investment in production and distribution infrastructure for the same emissions benefit ■ Cooperation across stakeholders in all stages of the supply chain needed for early projects to succeed ■ The technology, especially fuel cells, are currently built at low volumes and have not seen mass market use. Production volumes need to ramp up to bring down costs and build confidence in the technology ■ Purification of grid transported hydrogen for transport use has not been demonstrated at large scale	■ This scenario will require greater behavioural change. For example, truck and coach drivers will need to stop and recharge more often ■ Industry requires a switch to completely new equipment ■ Insulating most of the GB building stock in time to allow a switch to heat pumps

Table 4 - Overview of the drivers and barriers to the high and low green gas scenarios

5.3 Scenario Risks

The ultimate goal of the transition is to decarbonise the economy. The two scenarios both achieve this ambition, meeting the UK net-zero target in 2050. However, the two scenarios pose different risks to achieving the target. Table 4 summarises these risks for both scenarios.

Risk	High Green Gas Scenario	Low Green Gas Scenario
Technology	■ Hydrogen technologies promise major cost reductions with scale but until production scale begins to build and costs are seen to come down in line with projections, there is a risk that a hydrogen pathway remains significantly more expensive than electrification. These higher costs will slow down decarbonisation risking the target	■ Relying predominantly on one fuel increases the risk as no backup options exist if the technology that uses that fuel does not meet users' requirements. For example, if battery energy density does not improve then battery electric vehicles will not be suitable for long distance trucking applications ■ If UK Government policy on building insulation is not significantly improved very quickly then it will be very challenging to insulate all buildings quickly enough to allow conversion of gas boilers to heat pumps
Infrastructure	■ Hydrogen that passes through the gas network picks up impurities from the gas pipes and odorants will need to be added when it enters the distribution system. These impurities need to be extracted from the hydrogen before the hydrogen can be used in transport fuel cell applications. If purification cannot be shown to work at large scale and low cost, then hydrogen distribution for transport will be far more complex and expensive ■ Hydrogen production, distribution and utilisation pathways are less energy efficient than those for electricity. This means significantly more energy production infrastructure needs to be built to support greater hydrogen use. This risks the infrastructure not being built in time and increases the requirement for offset emissions (emissions from infrastructure production)	■ Under current UK Government decarbonisation pathways CCS will be an essential part of the decarbonisation transition providing negative emissions through options such as Bioenergy with Carbon Capture and Storage (BECCS). Under current regulation CCS has little value of its own and it has therefore never reached the scale and cost reductions needed. Blue hydrogen production provides a new impetus for CCS and without this CCS may not be ready in time to support negative emissions ■ An electrification dominated system supplied almost entirely by renewable generation could have 'peakier' supply and demand, leading to higher whole system costs from lower capacity factors, constrained generation and storage requirements and grid reinforcement requirements. This risk can however be largely mitigated through demand side response (e.g. smart charging of electric vehicles)
Emissions	■ Hydrogen can be produced and distributed through a wide range of different pathways. These pathways have very different life cycle emissions. To ensure hydrogen delivers real emission benefits these life cycle emissions must be understood and correctly assigned to the different hydrogen steams	■ CO_2 emissions build up cumulatively in the atmosphere making early decarbonisation very important. In key sectors there are unlikely to be effective electrification decarbonisation solutions in the near term risking missing decarbonisation targets by leaving significant decarbonisation actions until the 2030s

Table 5 - Overview of the risks to meeting the UK net-zero target following the high and low green gas scenarios

6. Future work and conclusions

6.1 Future Work

The findings of this analysis show that there is a clear potential role for green gases in helping to support economy wide decarbonisation but key stakeholders including government and industry must invest in this future now if it is to be realised. To overcome some of the risks and barriers to a high green gas future there is a need for future work in several areas to better understand the practical applications of all the technologies in the pathways and the costs of delivering this transition. The areas of future work are:

Commercial technology demonstrations. There are a number of pieces of the hydrogen narrative which have not been demonstrated at scale. Commercial demonstrations are needed as a next step with the findings shared as widely as possible to build confidence and encourage investment. This has started to happen with the announcement in the UK Government 10 Point Plan "We will invest £20 million next year in freight trials to pioneer hydrogen and other zero emission lorries, to support industry to develop cost-effective, zero-emission HGVs in the UK". Similarly, the announcement of 300 homes in Fife to be connected to 100% hydrogen for heating and cooking is an import step in bringing this technology to mass market scale. However, there are still technology barriers such as the fact that there is no industry standard for high-speed truck refuelling with hydrogen and purification of hydrogen (discussed in detail in the next point) from the gas network for transport use has not be demonstrated at scale. These are not major barriers, but they must be addresses quickly if investment is to be made in time.

Hydrogen purification. As hydrogen passes through repurposed natural gas pipelines it picks up impurities. This is not a problem if the hydrogen is burned for heating in homes, but it is a problem for fuel cells used in vehicles. It is therefore necessary to purify the hydrogen as it exits the pipes before it is fed to the refuelling station. This purification step has been shown to be possible, but it must be demonstrated at scale to show that it can be rolled out across the country and can be achieved at a price that allows hydrogen to compete with other fuels. Future research in this area should also consider if fuel cells with lower purification requirements can be developed and bought to market at scale.

Hydrogen deblending. Recent work has demonstrated that blending hydrogen and methane on the gas network and then deblending at strategic locations to provide customers with their preferred gas; pure hydrogen, pure methane, or a mix of the two could help support the transition to green gases. In the workshop with hydrogen and biomethane refuelling stakeholders, on-site deblending of hydrogen was highlighted as unsuitable with existing technology. This is due both to the footprint required for the equipment, and the need to re-inject the unwanted methane gas back into the network. Further work is needed to understand whether a system of centralised deblending facilities would be capable of supplying pure hydrogen directly to vehicle refuelling stations. This work assumes that this will not be possible, and that conversion of the local network to 100% hydrogen would be required before a refuelling site could dispense network delivered hydrogen.

Transition from biomethane to hydrogen for trucks. This report has demonstrated that there is a significant opportunity to deploy biomethane trucks at scale over the next 10-15 years to accelerate the decarbonisation of this segment. It has also shown that rapid deployment of refuelling infrastructure for biomethane trucks over the next 10 years to service this market can be consistent with a later transition to hydrogen refuelling infrastructure. Further work is required to understand this process in more detail, to ensure that it is coordinated to minimise the risk of stranded assets and ensure that decarbonisation occurs at the fastest possible rate. This should include an examination of the technical feasibility and economics of supplying both biomethane and hydrogen at the same site during the transition period, whether this is an attractive option and what barriers would need to be overcome to make this possible. Other future work mentioned here on deblending and purification will also be applicable to understanding this transition for refuelling station providers.

Hydrogen life cycle assessments. Hydrogen can be produced and distributed in a very large number of different ways. The life cycle emissions of hydrogen can therefore vary significantly. To provide confidence to consumers and policy makers that hydrogen is providing the emissions benefits claimed, detailed analysis of hydrogen life cycle emissions is needed and a system to track hydrogen's production source to ensure it is as low emission as claimed.

Customer research on future hydrogen truck operators. This report has identified that the various technology options for decarbonising trucks (biomethane, battery electric and hydrogen trucks) are likely to have advantages and disadvantages depending on operators' requirements. Further research is required to understand which use cases are likely to be suitable for hydrogen trucks so that deployment projects and policies can be designed to maximise the decarbonisation potential of green gases in this segment. This will include identifying suitable fleets, understanding their operations, and designing possible business models for adopting hydrogen vehicles that will meet their needs.

6.2 Conclusions

Biomethane has an important role to play in the pathway to Net Zero:

- Window of opportunity for the direct use of biomethane to decarbonise heat and trucks while no alternatives exist.
- To maximise the direct use of biomethane for decarbonisation, production needs to ramp up very quickly during the 2020s and early 2030s.
- Without biomethane, GB CO2eq emissions would be significantly higher.
- Long-term biomethane has a role in producing negative emission blue hydrogen.

Deploying gas trucks and associated infrastructure in the short-term can support the later transition to hydrogen trucks:

- For the next 10-15 years gas trucks will only displace diesel trucks because zero-emission trucks with equivalent capabilities will not be available
- Early hydrogen trucks will target different market segments to gas trucks and be deployed in different regions of the country.
- A national network of gas truck refuelling sites can support early hydrogen refuelling and does not necessarily reduce the economic life of gas refuelling equipment:
  - After 15 years equipment will need replacing – gas refuelling equipment is not suitable for hydrogen refuelling.
  - Land is the key benefit and gas refuelling infrastructure providers will have a 10-15-year head-start on identifying and developing suitable sites for truck refuelling.
  - Early refuelling for hydrogen trucks can be supported via tube trailer delivered hydrogen dispensed from sites mainly serving gas trucks.
  - Later, network-connected gas truck refuelling sites can become large-scale hydrogen purification and refuelling hubs are the gas network converts.

Hydrogen refuelling stations fed by pipeline will provide an anchor load to support other transport segments using hydrogen:

- Truck fleets represent a large single source of fuel demand that can help to justify investment in refuelling infrastructure.
- The demand for refuelling from trucks is likely to be concentrated at a relatively small number of refuelling sites around the country compared to the number of refuelling sites required for light duty vehicles.
- This concentrated demand means that many sites will require a supply of hydrogen that is up to ~20t/day and beyond what can practically be delivered by tube trailer (max. ~3t/day).
- These large sites will require a network-delivered supply of hydrogen which must be purified before it can be dispensed to vehicles.
- Network-connected hydrogen refuelling sites for trucks will be capable of purifying more hydrogen to fuel cell quality than trucks would require at a single location.
- Demand from trucks can provide an anchor load for these purification facilities, allowing additional capacity to be used to serve other transport demand such as light duty vehicles via tube trailer deliveries.

Industrial users of hydrogen can provide an anchor load for blue hydrogen production:

- Early hydrogen clusters are likely to include large industrial areas that are close to opportunities for blue hydrogen production.

- Blue hydrogen production will need to begin at scale and industrial users can provide an anchor demand for such projects ahead of conversion of the gas networks to supply pure hydrogen.

Domestic demand for hydrogen for heating can provide an anchor load for pure hydrogen networks.

- Before gas networks can convert to supplying pure hydrogen, large scale demand needs to be established amongst existing users of natural gas from the network.
- With hydrogen-ready boilers deployed in advance, hydrogen heating for homes can provide a major source of demand as soon as conversion takes place.
- Unlocking hydrogen production and distribution at sufficient scale to displace natural gas for heating will provide hydrogen that is cheap and readily accessible to many other users.

7 Appendix - Detailed narrative breakdown

7.1.1 Narrative in 2020-2025

Biomethane Supply

Ramping up biomethane supply in the next 5 years is a key challenge as demand looks set to increase rapidly and it is important supply does not constrain the potential emission saving.

- UK waste and residue derived biomethane/biogas has a total potential of 52TWh. 12TWh of this potential has already been developed, a further 13TWh needs to be developed by 2025, requiring a doubling of the peak build rate of biomethane AD sites seen in the last decade. This will be a major challenge but achievable given the increasing ambition required under the new UK net-zero target.
- UK waste and residue derived Bio-SNG has a total potential of 70TWh. 2TWh of this potential needs to be realised by 2025, highlighting the need for immediate action today.
- Biomethane and bio-SNG injected into the grid can be accessed by heat or transport (through credits) anywhere in the UK, overcoming distribution challenges. However, co-locating biomethane production with large sources of demand such as gas truck refuelling sites where possible, can help avoid constraints in network entry capacity.
- Companies working to deliver CNG and LNG refuelling infrastructure are ready to ramp up rollout and deliver the first 70 stations by 2025.
- These stations are expected to be predominantly public stations on the strategic road network (55 stations) with a smaller number (15 stations) in very large depots that have converted to gas.

Biomethane Demand

Biomethane as the only decarbonisation option for long-haul trucks has gained support, initially from truck operators with climate change goals, but increasingly also from all very long-haul truck operators for whom a good business case exists. This growing demand has great potential as long as biomethane supply and refuelling infrastructure can be scaled up at the same rate.

- Iveco, Volvo and Scania have already made significant investments to bring gas trucks to market. With this investment already made, OEMs will want to scale up production volumes to gain a return on this investment. Significant increases in production volumes expected by 2025 to meet the growing interest across Europe.
- Westport, who current supply gas technology to Volvo, expected to supply to other OEMs allowing more OEMs to offer gas technology without requiring significant further investment.
- Given continued confidence in the gas HGV market this could grow to 12,000 CNG/LNG truck sales in 2025 (23% of sales) in our high scenario.

These sales are focused on the longest range, most highly utilised vehicles, where the business case is best, the overall sales figure represents 10% of rigid sales and 40% of artic sales by 2025.

Hydrogen Supply

Hydrogen supply in this early period will be predominantly from existing production and new electrolysis facilities. Although the first blue hydrogen (reformation plus CCS) at one of the UK industrial clusters will need to be going through planning and construction in this period.

- Early hydrogen production from existing SMRs and from new electrolysis plants connected to renewables via co-location or power purchase agreements.
- Hydrogen delivered to transport customers via trucked tube trailers from production sites.
- A commercially viable pathway for the purification of hydrogen from existing gas pipelines is understood.
- Several small (~1t/day) stations are developed to support clusters of depots that have signed up to government led commercial demonstrations of the technology.

Hydrogen Demand Transport

Hydrogen demand in transport is currently dominated by bus and car fleets.

- Hydrogen demand growth kick started by the scaling up of hydrogen bus projects which have been in development and scaling up for the last couple of years.
- Large scale commercial demonstrations of hydrogen trucks needed by 2025 representing the real-world operation of 100s of medium duty hydrogen trucks in normal day to day fleet operation. This will build on the experience in the bus sector resulting in a step change in hydrogen demand in transport.

Hydrogen Demand Other Sectors

Other sectors play a key role in the availability of hydrogen for transport applications.

- The first blue hydrogen from reformation and CCS developed to supply industry and a surrounding hydrogen cluster under development.
- Large scale demonstrator pilots of hydrogen for heating and electrification of heat need to occur by 2025.

7.1.2 Narrative in 2025-2030

Biomethane Supply

Between 2025 and 2030 the supply of biomethane and Bio-SNG remains the main constraint in its effective use as a decarbonisation tool.

- UK waste and residue derived biomethane/biogas has a total potential of 52TWh. By 2025 25TWh of this potential needs to be realised. Between 2025 and 2030 the rate of production increases must be maintained at double the peak build rate of biomethane AD sites seen in the last decade, resulting in the full 52TWh available by 2030.
- UK waste and residue derived Bio-SNG has a total potential of 70TWh. By 2025 2TWh of this potential needs to be realised. From 2025 production capacity must scale up very quickly if bio-SNG is to contribute to transport and heat, where the demand for this fuel will peak in 2035. This should lead to 15TWh of bio-SNG available by 2030.
- Opportunities to inject biomethane into the low-pressure grid, close to feedstocks, is expected to diminish as the easier projects are delivered early. In this timeframe, more projects will need to consider a hub-based model where biomethane is collected together from a wider area and injected into the high-pressure grid where grid capacity is less constrained.
- Companies working to deliver CNG and LNG refuelling infrastructure need to continue station building to deliver a total network comprised of 170 stations by 2030. This will complete national coverage and station construction should stop by 2030 to ensure no stranded assets are created.
- These stations are expected to be predominantly public stations on the strategic road network (115 stations) with a smaller number (55 stations) in very large depots that have converted to gas.

Biomethane Demand

As business climate targets become an increasingly required aspect of doing business, the demand for biomethane and bio-SNG by HGV operators, who have no other decarbonisation option, is expected to continue to increase.

- OEMs expected to further refine gas truck technology to deliver continued emissions improvements. This investment will be worthwhile as it will help to improve the product while not significantly impacting the investment in zero-emission vehicles, as this investment will be at a completely different, and much larger, scale.

- The gas HGV market could grow to 14,000 CNG/LNG truck sales in 2030 (27% of sales) in our high scenario.
- These sales are focused on the longest range, most highly utilised vehicles, where the business case is best, the overall sales figure represents 10% of rigid sales and 50% of artic sales by 2030.
- The overall sale of gas trucks is expected to peak in 2030 with sales dropping through the 2030s as zero-emission vehicles take over an increasing proportion of the market.

Hydrogen Supply

Blue and green hydrogen production ramps up leading to falling prices. The industry is expected to be focusing on the lowest cost hydrogen pathways at this time when hydrogen use is expensive, and the business case is very sensitive to fuel costs.

- In the search for cheap hydrogen, supply is expected to be focused around industrial clusters producing blue hydrogen (the considerable expense of early CCS projects are expected to be supported by Government funding, these sites also benefit from scale) and large-scale green hydrogen produced from electrolysers co-located with large scale wind (electrolysers co-located with renewables avoid significant grid charges helping to make affordable hydrogen).
- This will focus early hydrogen production on the coast where it is near to industrial clusters and offshore wind connection sites.
- The first large public hydrogen HGV stations in the region of hydrogen production sites (industrial clusters) will be connected to production sites via dedicated H_2 pipeline.
- The purification of hydrogen transported in existing gas pipelines is demonstrated at commercial scale.
- Smaller hydrogen stations and those further away will continue to be supplied by trucked compressed H_2 tube trailers.
- Hydrogen supply, focused on the Phase 1 regions, draws focus to these regions leading to the next tranche of stations (up to 3t/day in size) being built in the Phase 1 areas to supply clusters of depots introducing hydrogen trucks through an aggregated procurement program such as that being completed to Switzerland today.

Hydrogen Demand Transport

Hydrogen in transport starting up a very aggressive growth curve in this period as it readies for a large-scale expansion in the 2030s.

- The sale of hydrogen trucks accelerates to 3,500 per year in 2030 (7% of sales), representing mostly medium duty vehicles. This is achieved through the co-ordination of an aggregated procurement program, similar to that being run by H_2 Energy in Switzerland today, where Hyundai will supply 1,600 hydrogen trucks between 2020 and 2025.
- This is a significant change relative to today but total zero-emission trucks in the stock is only expected to reach 5% by 2030 and these vehicles will be focused on the shorter-range applications meaning these ambitious growth forecasts for zero-emission trucks will still not impact the biomethane/bio-SNG case which is focused on the longest range applications.
- Hydrogen bus sales take off from 2025 as cities drive bus fleets towards zero-emission vehicles. This growth helps to drive a shift to almost 100% zero-emission bus sales by 2030.

Hydrogen Demand Other Sectors

Transport has been an early adopter of hydrogen but by the late 2020s other sectors begin to catch up.

- Planning, development, and construction in the early 2020s leads to the first industrial blue hydrogen production sites. These early blue production sites are very important as they represent a step change in hydrogen production volumes, removing hydrogen supply as a key limiting factor in the growth of hydrogen use in industry and transport.

- Clusters of homes/industry demonstrate large scale use of hydrogen for heating fed by pure H_2 pipelines.
- In the Phase 1 regions hydrogen starts to be blended at low concentrations in the gas grid to displace natural gas and to start decarbonising heating.

7.1.3 Narrative in 2030-2035

Biomethane Supply

Direct demand for biomethane and bio-SNG in heat and transport is expected to peak by 2035 when these fuels displace a significant proportion of the diesel (transport) and natural gas (heating) that would otherwise have been used.

- Supply of biomethane peaks in 2030, with additional demand post 2030 being fully met by increasing bio-SNG supply. By 2030 15TWh of the total 70TWh bio-SNG potential has been delivered, this needs to be ramped up to 60TWh by 2035 in order for biomethane/bio-SNG to play a significant role in the direct decarbonisation of heat and transport.
- Stations built along the strategic road network in the early 2020s (70 stations) will be 10 to 15 years old in this time period. By this point the investment in land and equipment will have been paid off and the equipment is expected to require a major overhaul. At this point stations can begin being refitted to dispense CNG/LNG and hydrogen, gradually converting to 100% hydrogen. For stations in the Phase 1 region local hydrogen demand is expected to ramp up quickly and stations will convert to predominantly hydrogen within 5 years. For stations in the Phase 2 region, local demand will continue to be CNG/LNG dominated and conversion to predominantly serving hydrogen may take 10 years.

Biomethane Demand

The sale of gas trucks peaks in 2030 with the remaining market increasingly concentrated in the longest range and most highly utilised fleets.

- Gas truck sales drop to 7% of sales by 2035. All these sales are in the articulated truck segment and even within the artic trucks segment gas sales are focused on the high utilisation fleets.
- Gas truck stock peaks in 2032 with the demand for biomethane and bio-SNG in trucks almost the same in 2030 and 2035.
- Remaining gas truck demand expected to be focused on the midlands around Birmingham stretching up to Liverpool and down to London.

Hydrogen Supply

In this period blue hydrogen ramps up to become the main hydrogen source although production is limited to coastal locations near gas terminals and offshore CCS potential. Green hydrogen supply also ramps up quickly, although at lower scale, offering the potential to supply the grid and stations directly across a wider area of the UK.

- Blue hydrogen developments across all industrial clusters making large scale hydrogen production available in all Phase 1 regions.
- Blue hydrogen becomes the main source of hydrogen although green hydrogen production continues to ramp up in this period to support increased demand.
- Large public hydrogen HGV stations in the region of hydrogen production sites (industrial clusters) will continue to be connected via dedicated H_2 pipeline.
- Most hydrogen stations will continue to be supplied by trucked compressed hydrogen tube trailers. Where tube trailers are used to supply larger stations, the stations are designed to switch to pipeline supply in the future when higher station utilisation requires more hydrogen than can be easily supplied by tube trailer and local pipelines switch to 100% hydrogen.
- Stations (up to 6t/day in size) deployed to support clusters of depots and large depots. This occurs mostly within the Phase 1 region where hydrogen can be easily trucked from production sites.
- Partial conversion of 50-80 CNG/LNG stations to hydrogen provides national refuelling coverage for hydrogen truck fleets mostly housed in depots within the Phase 1 areas

Hydrogen Demand Transport

Hydrogen trucks which have up to this point predominantly served in medium duty applications start to be used for long-haul applications replacing CNG/LNG. This is supported by the national coverage of hydrogen refuelling infrastructure facilitated by CNG/LNG station conversion.

- The sale of hydrogen trucks ramps up very quickly in this period from 7% of sales to 40% of new sales. Representing a flip in the market that must be driven by policy in order to meet the 2050 net-zero target.
- By 2035 hydrogen trucks have taken a significant proportion of biomethane/bio-SNG sales in the long-haul market, although hydrogen has yet to impact the demand for biomethane/bio-SNG from the stock.
- All new bus sales are zero-emission with hydrogen representing close to 50% of sales. Sales of zero-emission coaches also grow rapidly in this period with hydrogen coaches taking more than 50% of sales helped by the partial national refuelling coverage driven by the HGV market.
- Demand for hydrogen from cars and vans, which remains at very low levels in the 2020s, begins to grow from 2030, as the successful scale up of hydrogen in industry and HGVs makes cheaper hydrogen more readily available.

Hydrogen Demand Other Sectors

By 2035 hydrogen is a common fuel in the large industrial clusters and it is rapidly expanding as a fuel for heating as hydrogen is blended at a high percentage in the Phase 1 regions and starts to be blended in the Phase 2 regions.

- All industrial clusters with CCS potential now producing significant qualities of blue hydrogen to feed industrial demand, with excess produced to supply transport and for blending into the grid.
- Hydrogen blending on the network is ramped up very quickly during this period to supply heating for buildings. The scale of heating demand makes hydrogen blending in the gas grid worthwhile. However, due to the current uncertainty around the viability of the deblending of hydrogen for use in transport applications, this has been excluded from the analysis.

7.1.4 Narrative in 2035-2040

Biomethane Supply

All available biomethane and bio-SNG feedstock is utilised for production.

- The sale of gas truck ends in this period and the stock declines back down to 2025 levels.
- The drop in demand for biomethane and bio-SNG from trucks initiates a major increase in station conversions. The faster drop in demand means these stations will transition more quickly with most stations switching to 100% hydrogen in less than 5 years.
- Bio-SNG sites in Phase 1 areas are repurposed to produce hydrogen and continue to feed directly into the grid.

Biomethane Demand

The demand for biomethane and bio-SNG in transport and heating has peaked.

- The demand for biomethane and bio-SNG in transport drops away quickly from 2035 as the gas truck stock falls.
- The demand for biomethane and bio-SNG in heating remains at peak levels throughout this period.
- Excess biomethane and bio-SNG supply created by dropping direct demand in transport is directed towards blue hydrogen production to produce negative emission fuels and help offset remaining emissions.

Hydrogen Supply

Conversion of gas network to 100% H_2 in certain regions (supplied from blue and green H_2) encourages development of H_2 HGV stations connected to the gas network. By this time large hydrogen refuelling stations capable of refuelling 400-800 trucks a day appear requiring piped hydrogen as the only practical H_2 delivery option.

- Stations continue to be supplied by a mix of blue and green hydrogen. The mix is mostly blue hydrogen supplied from an expanding blue hydrogen industry around the industrial clusters.
- Regional gas networks, especially those in the Phase 1 areas convert to 100% hydrogen.

- Larger stations built in this period and larger stations built earlier in the Phase 1 region connect to the gas network which supplies 100% hydrogen.
- Smaller stations still fed by compressed tube trailer truck delivery from the nearest supply point which may be a production site, or a large grid connected station.
- Stations up to 20t/day start to be built to supply depot clusters, with smaller stations being built as daughter stations.
- A significant proportion of the hydrogen truck stock operates in the long-haul segment by the end of this period requiring full national refuelling coverage. This is supplied by the CNG/LNG station conversions which accelerate in this period to provide good coverage and greater hydrogen dispensing capacity at each station.
- Larger stations in the Phase 2 areas are developed in this period to provide national coverage, without a piped connection these stations will need to rely on trucked supply from local production of green hydrogen from solar and onshore wind or from hydrogen produced on-site by reformation of biomethane. The largest of these stations will only be able to operate in this way to start off with while utilisation is low. As utilisation grows, these stations will need to switch to a piped connection highlighting the need for a co-ordinated approach to the infrastructure rollout.

Hydrogen Demand Transport

Hydrogen truck sales in the long-haul market have continued to grow making hydrogen the main fuel for long-haul trucks in the stock.

- The sales share of hydrogen trucks has peaked at 45% of sales but the share of hydrogen trucks in the stock continues to grow, increasingly replacing CNG/LNG and diesel trucks in the long-haul segment of the stock.
- Bus sales remain unchanged, but a growing hydrogen coach market helps to end the sale of diesel and diesel hybrid coaches before 2040. Sales of hydrogen coaches remain strong supported by the national refuelling station coverage.
- The demand for hydrogen in cars remains a growing but small proportion of the market. However, demand in vans grows strongly in this period in long distance and varied route applications. This is strongly supported by the growing network of hydrogen stations along the strategic road network which is rolled out to support HGVs.
- While the proportion of cars and vans using hydrogen is much lower than for HGV, buses or coaches, the large number of cars and vans means that the demand for hydrogen from these vehicles is still very large.

Hydrogen Demand other Sectors

Driven by the demand from heating, large regions (Phase 1) of the gas network convert to 100% hydrogen fed by supply hubs around the industrial clusters.

- The quantity of blue hydrogen produced and used in industrial clusters continues to increase. The availability of 100% hydrogen in areas of the gas network opens up hydrogen use to industrial sites away from the large clusters.
- Conversion of section of the network to 100% hydrogen requires a program of upgrades to boilers and cookers in millions of homes.

7.1.5 Narrative in 2040-2050

Biomethane Supply

Supply of biomethane begins to fall as injection options onto the network are taken away as the network converts to hydrogen.

- Biomethane producers close to gas power stations with CCS or hydrogen reformation sites with CCS feed their biomethane to these sites by truck. More remote biomethane production sites close down.
- Bio-SNG sites in Phase 2 areas are repurposed to produce hydrogen and continue to feed directly into the grid.

Biomethane Demand

The demand for biomethane and bio-SNG in transport has dropped significantly and the demand in heat begins to fall.

- The demand for biomethane and bio-SNG in transport falls to zero.
- The demand for biomethane and bio-SNG in heating begins

by falling slowly in this period but this drop accelerates as the conversion of the gas network to hydrogen is completed. By the end of this period no biomethane is delivered through the grid for heating.

- Excess biomethane and bio-SNG supply created by dropping direct demand in transport and heat is directed towards blue hydrogen production to produce negative emission fuels and help offset remaining emissions.

Hydrogen Supply

Conversion of additional areas of the grid to 100% hydrogen in the Phase 2 regions brings piped hydrogen to large stations across the country.

- Regional gas networks and the national transmission system, across the most the populated areas of the Phase 2 regions convert to 100% hydrogen.
- Larger stations built in this period and larger stations built earlier in the Phase 2 region connect to the gas network which supplies 100% hydrogen.
- Additional stations are added to the network with large stations fed by pipeline and smaller station fed by trucked delivery. Most new stations added in this period are in the Phase 2 regions.

Hydrogen Demand Transport

The hydrogen transport market has reaches maturity and changes in technology within the stock reached steady levels.

- The hydrogen truck market continues to grow but at a slower rate than the previous 10 years.
- The bus, van and car markets which shifted to zero-emission sales earlier than trucks are beginning to reach steady state with the share of BEV and FCEV in the stock remaining approximately constant by this time.

Hydrogen Demand Other Sectors

Emissions from industry and heating reach very low levels during this period as hydrogen becomes available for the vast majority of users thanks to conversion of the gas network across the most populated regions of the country.

Cadent Gas Ltd,
Ashbrook Court,
Central Blvd,
Coventry,
CV7 8PE
www.cadentgas.com