Hy4Transport

Delivering fuel cell grade hydrogen from our gas network

Phase 1
Feasibility Study
September 2022

Contents

Message & Acknowledgements

We're working to enable the decarbonisation of transport through new & repurposed gas networks

Our vision is to supply fuel cell grade hydrogen to future refuelling stations around the country using a 100% hydrogen network

Cadent is the UK's largest gas distribution network with a 200-year legacy – ensuring that gas reaches 11 million homes and businesses from Cumbria to North London, and from the Welsh borders to East Anglia. At Cadent we support the Government's plans to reach Net Zero by 2050. That means we're supportive of the introduction of hydrogen as a low carbon alternative to natural gas for the future, as outlined in the UK Hydrogen Strategy. We know people love the controllability of gas and, with our network already in place, hydrogen provides a low carbon option to keep homes and businesses warm for generations to come.

Hydrogen can also play an important role in our ambitions to reach net zero for transport, as the UK has recognised the need to transition from petrol and diesel vehicles. Our Hy4Transport project investigates the challenges that need to be addressed to ensure that network-supplied hydrogen can support the decarbonisation of UK transport.

Phase 1 of the project has explored if, and how, grid-supplied hydrogen can be purified for utilisation in fuel cell electric vehicles (FCEVs) across the UK transport sector. This investigative work is summarised in this report.

We intend to demonstrate this concept in practice throughout a future Phase 2 – to prove that we can provide a reliable, safe, and cost-competitive supply of fuel cell grade hydrogen to support future low carbon UK transport infrastructure.

Cadent
Your Gas Network

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Department for Business, Energy & Industrial Strategy

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ARUP

kiwa

NPL National Physical Laboratory

DNV

Gemserv

Imperial College London Consultants

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Executive Summary

Gas impurity is a major barrier preventing new & repurposed pipelines from providing hydrogen to future transport infrastructure and Fuel Cell Electric Vehicles (FCEVs)

Hydrogen distributed by new & repurposed gas networks, for use in the transport sector, has the potential to become a reality in less than 10 years if the challenges regarding purity and cost are addressed. Due to the inherent contaminants within the current gas network, some form of purification technology will be required at future refuelling stations to enable new and repurposed pipelines within a '100%' hydrogen network to supply fuel cell grade hydrogen to vehicles.

National Grid's latest Future Energy Scenario (FES) 2022 publication forecasts annual hydrogen demand of up to 58TWh for UK surface transport (road and rail) by 2050 in the 'System Transformation' scenario. This could equate to ~13% of total UK hydrogen demand [1]. Investing now in developing innovation opportunities to address this purification challenge will unlock significant potential for hydrogen to decarbonise transport – which has been identified as one of the major growth areas for gas demand via the hydrogen transition. The Hy4Transport project is looking to overcome this barrier and aligns with the government's 10 Point Plan to drive growth of low-carbon hydrogen, accelerate a shift to zero-emission vehicles, and support green public transport [2]. The project could help position the UK as a key innovator in the decarbonisation of transport and eventually enable mass and widespread availability of high purity hydrogen by utilising the gas network - an existing asset. The proposed trial is believed to be a world-first demonstration of this particular application.

Key Findings

This report summarises the breadth of work conducted throughout this 8-month feasibility study by the Hy4Transport consortium – including the definition of a network-distributed hydrogen contaminant standard, technical assessments of purification systems and demonstration sites, analysis of the potential socioeconomic and environmental benefits, and a roadmap to future scaleup and UK rollout. The major findings explored in this report include:

- A broad range of contaminants are currently present within natural gas networks, and many are likely to remain in new & repurposed hydrogen pipelines. A 'contaminant standard' outlining the likely composition of network-supplied hydrogen in the UK was established. The main contaminants typically present include water, oxygen, nitrogen, carbon dioxide, carbon monoxide, sulphur, ammonia, methane, and various other hydrocarbons.
- Various methods of hydrogen purification exist and are proven at scale, but not for this proposed downstream application on refuelling forecourts. The novelty of this project is driven by the various contaminants, restricted availability of space, and the need for efficient waste collection and disposal.
- It is highly likely that a combination of at least two technologies (in the form of pressure swing adsorption, coupled with activated carbon beds) will be required to provide the full solution of reaching the target hydrogen purity, and safely handling the removed contaminants. Two relevant systems were chosen for a future demonstration.
- There are several suitable sites available in the UK for the first demonstration of these technologies in an isolated trial – in which the systems would be exposed to a hydrogen stream replicant of the proposed contaminant standard. A 9 to 12 month trial of the chosen purification systems is estimated to cost around **£5.3m**.
- Grid-supplied hydrogen with downstream purification on-site could be the most economical, and lowest-emission method of supplying FCEV grade hydrogen to a network of Hydrogen Refuelling Stations (HRSs). Over 600 grid-connected HRSs, supplying maximum annual demand of over **35TWh**, could be in operation in the UK by 2050.
- Under a conservative base-case, the early 'price at the pump' of hydrogen from the proposed grid-supply model is expected to be around £7.17/kg in 2035 – and could scale down to **£6.89/kg by 2050**. With a 'low' hydrogen price, prices at the pump could be as low as **£5.30/kg by 2050**. The most significant cost contributor is estimated to be the hydrogen production price (37%) - with purification & compression only contributing (2%) and (11%) respectively to net delivered costs.
- The calculated total cost of ownership (TCO) for the largest FCEVs (HGVs and buses) are lower than both diesel and battery-electric alternatives. Where the TCO is higher, FCEVs could deliver operational benefits to make them the preferred choice.
- The UK job creation associated with grid-connected hydrogen for transport is estimated to be **27,700 jobs in 2050**. The GVA created in the value chain, from hydrogen production through to fuel dispensing and vehicle manufacturing, is estimated to be **£9.3bn in 2050**.
- Over the modelled 16-year period (2035-2050), more than **160 MtCO_2e** could be avoided, the equivalent of taking nearly 6 million cars off the road for the entire 16-year period, by the transition to FCEVs which are supplied by the grid.
- Several UK industrial clusters that will be 'levelling up' as early adopters of hydrogen have been identified for broader end-to-end demonstrations, following the development of the proposed purification solution.

Glossary

Table 1: List of Acronyms

Acronym	Full Name
ACB	Activated Carbon Bed
BEV	Battery Electric Vehicle
CapEx	Capital Expenditure
CO, CO_2	Carbon Monoxide, Carbon Dioxide
CCUS	Carbon Capture, Utilisation & Storage
DNV	Det Norske Veritas
FCEV	Fuel Cell Electric Vehicle
GDN	Gas Distribution Network
GGTP	Green Gas Transport Pathway
GHG	Greenhouse Gas
GVA	Gross Value Added
H_2	Hydrogen
HGV	Heavy Goods Vehicle
HRS(s)	Hydrogen Refuelling Station (s - pluralised)
LTS	Local Transmission System
$MtCO_2e$	Million Tonnes, Carbon Dioxide Equivalence
NOx	Nitrous Oxides
NPL	National Physical Laboratory
NTS	National Transmission Line
OEM	Original Equipment Manufacturer
OpEx	Operational Expenditure
PEM	Polymer Electrolyte Membrane
PSA	Pressure Swing Adsorption
SMR	Steam Methane Reformation
TCO	Total Cost of Ownership
TWh	Terawatt hour

Project Overview

Hydrogen is emerging as a key component of the UK's energy transition to Net Zero emissions by 2050 [3]. The UK's hydrogen projects are progressing rapidly where an accumulating body of evidence is building the case for repurposing the gas network to operate on hydrogen (for heat and industry). Investigating its potential to decarbonise other sectors such as transport provides an opportunity to strengthen the case for conversion to hydrogen.

However, there is a real opportunity to overcome the challenge regarding the role of network-distributed hydrogen in transport - due to cost and purity requirements. Investing now in developing innovation opportunities to address this challenge creates optionality, enabling greater value to be derived in the future from decisions made today.

Cadent has conducted several previous related studies in collaboration with industrial partners - forming the foundations from which the Hy4Transport project has evolved. These include the 'HyMotion' [4], 'Hydrogen Grid to Vehicles' (HG2V) [5], and the 'Green Gas Transport Pathway' (GGTP) [6] studies.

The major conclusions from these reports were:

1) Hydrogen will be largely adopted in the UK as an alternative for petrol or diesel in the transport sector (particularly for heavy transport modes).
2) Enabling future UK hydrogen refuelling stations (HRSs) to connect directly to new & repurposed, '100%' hydrogen gas distribution pipelines could greatly accelerate the development of hydrogen infrastructure for transport applications – supporting the government's ambitious targets.
3) Purification (the removal of network contaminants and odorants) is a major technical barrier currently preventing future connection of HRSs to the gas-grid – but there is an opportunity to overcome this.

The Hy4Transport project aims to deliver essential evidence and demonstrate the technical and commercial viability of purifying grid-supplied hydrogen so that it can be used for FCEVs (Fuel Cell Electric Vehicles). This could link the decarbonisation of both heat and transport in a way that may prove to be more efficient, and economically favourable, than alternative options - further stimulating the growth of hydrogen production and demand.

Our Phase 1 feasibility study aimed to further extend knowledge & understanding of the network's suitability for high-purity hydrogen uses – in addition to identifying both a suitable purification technological solution, and a demonstration site, before concept design. This phase also included an assessment on the socioeconomic and environmental benefits of future commercial rollout of the proposed purification solution, following a successful demonstration.

It is important to note that the Hy4Transport concept relies on the existing natural gas grid being repurposed for the distribution of hydrogen. For the purpose of this report, it has been presumed that this will largely be driven by the government policy decision on whether to support hydrogen for domestic heating (expected in 2026). The potential future applications of hydrogen in the transport sector are not expected to influence this government policy decision. However, this study shows that if the gas network is repurposed for domestic heat, this will provide the optionality to accelerate the decarbonisation of transport at lower cost - by enabling the supply of high-purity hydrogen from the distribution grid.

The project boundaries, and scope of the purification challenge, can be contextualised in Figure 1 below:

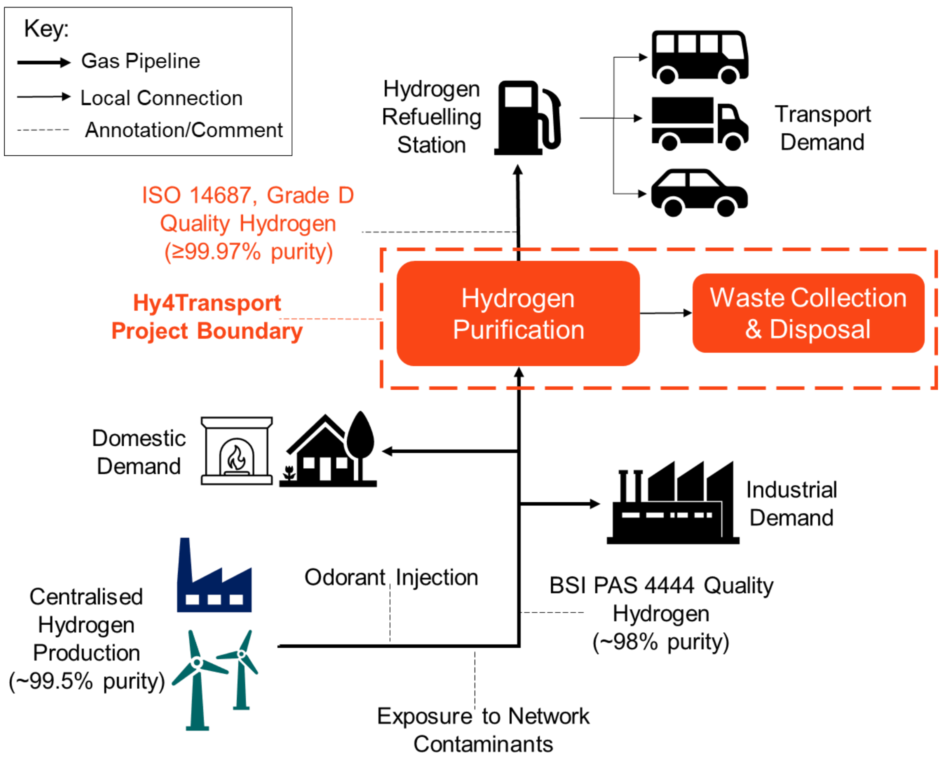


Figure 1 - Hy4Transport Problem Concept Diagram & Project Boundary (relative to simplified gas network supply chain)

As can be seen from this high-level diagram, the Hy4Transport project is focused on enabling fuel cell grade hydrogen (ISO 14687, Grade D [7]) to be accessible from a centralised network supply, via new & repurposed gas pipelines. The key point to address is that the purity requirement of FCEVs (≥99.97% hydrogen) is much higher than for traditional gas-combustion appliances (e.g., domestic heating in homes, electric power generation, and industrial processes) which can tolerate much higher presence of the various contaminants picked up from production processes, odorants, and inherently from the gas network. Such hydrogen-fired appliances will typically adhere to the less stringent BSI PAS 4444 standard [8].

Please note that this reflects current understanding. Other focussed research activities are being conducted across industry to investigate the impact of impurities on other hydrogen appliances - the Hy4Transport project is currently solely focussed on transport/fuel cell applications.

Fuel cells are intricate devices that convert chemical energy from gas into electrical energy – via an electrochemical process – and their performance and lifetime are very sensitive to impurities, in particular sulphur compounds and carbon monoxide [9]. Whereas traditional gas processes utilise simpler combustion processes – converting chemical energy into heat energy. These processes are far less sensitive to impurities – as these are essentially 'burned off'.

However, as transport emerges as a new growth sector of demand for gas (via the adoption of hydrogen FCEVs), there is a clear barrier for grid-supplied hydrogen that must be overcome in the form of purification. If this barrier is overcome by the gas network, we can do our part to facilitate a zero-carbon future for transport fuelled by hydrogen. In the context of various hydrogen trials progressing rapidly in the UK, a window of opportunity therefore exists to realise value from using hydrogen for transport. Timely demonstration of the Hy4Transport concept is therefore recommended to fully utilise these developments of network-distributed hydrogen. The critical path for purification technology development, and the closing window for deployment in order to meet the UK's increasingly near-term climate targets, justifies the need to address the purity challenge within the next 5 years.

Phase 1 Scope

The predominant purpose of our Phase 1 work was to assess various options for purifying grid-supplied hydrogen to FCEV standards, and to plan a transition from the idea towards a real proof of concept demonstration.

Several work packages were completed chronologically over the course of this study, with the following key objectives:

1	**Develop a contaminant standard** This was aimed to be representative of the UK network variability and likely blend of contaminants in a future 100% hydrogen network. This involved a broad literature review of potential contaminants and existing standards for gas grid applications.
2	**Select suitable hydrogen purification technologies** (TRL 4-7 by Q1 2023) This involved an in-depth review of various proposals from several, some globally recognised, technology providers. While traditional hydrogen purification methods are well established industrially, our specific application and blend of contaminants is a novel challenge, which has not yet been addressed. This work also introduced the consortium to new technology developers promoting novel/low TRL systems which may have a future role. The priorities for this technological case were performance, size, ease of operability, and costs.
3	**Select a suitable UK demonstration site for a future demonstration** (Phase 2) Similar to the above, several sites across the UK capable of facilitating a trial of these technologies were identified and reviewed. The priorities for the site selection were based around the reliability and costs of hydrogen supply and storage, ability to replicate network contaminants, accessibility of location, and potential means of downstream application(s) of purified hydrogen.
4	**Develop a full costed plan and schedule for Phase 2** (Q1 2023- Q1 2025) A detailed plan for a full 23-month programme, featuring 9-12 months of live trials, was developed. This programme involves testing the selected purification technologies to their limits, proving that they can cope with various blends of UK contaminants and high demand throughputs for continuous periods – whilst also dealing with any waste by-products. Additional work within the proposed Phase 2 programme includes the identification of any remaining technical or market barriers, a technical qualification, a future exploitation plan, conducting active dissemination activities and maintaining industrial engagement.
5	**Conduct a full analysis of socioeconomic and environmental benefits** This work included assessments of the scalability of grid-connected HRS sites with on-site purification, a hydrogen price-point analysis for FCEVs, the cost-down potential for purified hydrogen 'at the pump', commercial viability, macroeconomic modelling of Gross Value Added (GVA) and jobs creation, and estimated emissions savings. This work also included comparisons against the main counterfactuals – alternative distribution methods of high-purity hydrogen.
6	**Analyse future rollout options** This work involved the identification of likely UK 'first movers' for purification systems – putting real thought into the future next steps - after proof of concept in the proposed Phase 2. This included an assessment of future UK HRS infrastructure and identifying the likely early hydrogen hubs to connect to a 100% hydrogen network.

1) Contaminant Standard

1.1 Overview

This section contextualises the various sources, and amounts, of contaminants that hydrogen could theoretically be exposed to in the journey across the supply chain (as per Figure 1) – from the point of production, through the gas grid, and up to the proposed Hy4Transport purification system on a HRS site, before dispensary into a FCEV.

This work was led by NPL and DNV – who performed an in-depth literature review to define a reasonable 'hydrogen contaminant standard', representative of the likely hydrogen quality that could be received from a gas network supply.

1.2 Primary Sources of Contaminants

There are various means by which network-supplied hydrogen could be exposed to contaminants throughout the 'well-to-wheel' journey. The main sources of contaminants are summarised below:

- **Production Methods:** While there are various established, and developing, hydrogen production methods (or 'colours') proposed as part of the UK Net Zero solution - the two dominant methods aligned with UK plans for 2050 are categorised as 'green' (via electrolysis of water) and 'blue' (via thermal reformation of natural gas, coupled with CCUS). While both processes typically produce a high purity of hydrogen (typically >99%) - green hydrogen can often also contain presence of oxygen, water and nitrogen, and blue hydrogen can often contain presence of carbon dioxide and methane [5]. While trace amounts of nitrogen can be non-impactful on hydrogen fuel cells - all other contaminants are highly undesirable.
- **Injection of Odorant:** Today, mainly for safety reasons, when natural gas is taken from the higher-pressure transmission pipelines (e.g., National Grid) to the lower pressure distribution grids (e.g., Cadent), the gas is injected with sulphur-based odorants to create the familiar and distinct smell of gas. The current HSE position is that a future hydrogen network should employ the same use of odorant, for consumer familiarity [10]. However, any exposure to even trace amounts of sulphur is highly impactful on fuel cell lifetime and performance.
- **Inherent Network Contaminants:** The existing gas network itself is a massive, longstanding asset – with the UK transmission and distribution pipelines totalling around 7,600km and 280,000km in length respectively [11]. Despite regular cleaning & maintenance procedures (e.g. 'PIG' or 'ILI' runs) being conducted, there will naturally always be some residual solid and liquid contaminants contained within the network – which will be picked up in various amounts by the bulk hydrogen passing through at high throughput and velocity.

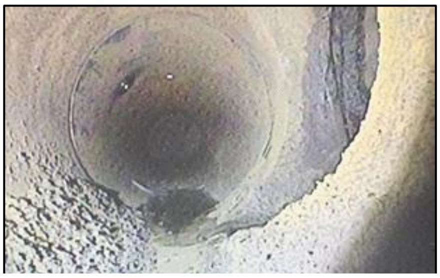


Figure 2 - Cross-section cut of typical metallic distribution pipeline [5]

1.3 Hy4Transport Contaminant Specification

Hydrogen fuel quality for use in fuel cell vehicles is a complex topic. The official ISO standard for hydrogen fuel quality (ISO 14687/EN 17124) quotes a minimum hydrogen concentration of 99.97%, but concentrations such as 'five nines' (99.999%) are often quoted across the industry [7]. However, such quotes can be misleading and require further clarification.

It is important to realise that the actual required hydrogen purity, set at 99.97%, is not the only parameter to consider when measuring if hydrogen is compliant with ISO 14687. The ISO standard is designed to protect fuel cells and provides a list of compounds, each with a specific maximum threshold, beyond which a hydrogen fuel cell vehicle may be damaged.

For example, the requirements for sulphur (<4 nmol/mol) or carbon monoxide (<0.2 µmol/mol), would be equivalent to a hydrogen concentration of 99.999996% or 99.99998% respectively. On the other hand, nitrogen, and other inert gases (e.g., helium or argon) have a threshold of 300 µmol/mol - which is equivalent to 99.97%. These examples highlight the complexity of measuring hydrogen purity for fuel cell applications across all contaminants with equal importance.

In general, between manufacturers and their customers, the term 'number of nines' is colloquially used to indicate purity, with the final concentration of gas followed by a decimal value. In other words, typically 'ultra-pure' hydrogen (five nines) means 99.999% purity. However, a hydrogen purity of '99.999%' alone would allow more than 1 µmol/mol of sulphur, carbon monoxide or ammonia – which would damage the end-user's system.

The literature review from NPL and DNV as part of Phase 1 determined the hydrogen contaminant specification to be as below [4] [5] [7] [12] [13] [14]:

Table 2: Technical Specification of Hydrogen Quality from a gas network for purification, compared with ISO 14687 Grade D

Component	Technical Specification of Hydrogen Quality from a gas network for purification study	ISO 14687 Grade D
Hydrogen Fuel Index (minimum mole fraction) (%)	98	99.97
Water (H_2O)	70 µmol/mol	5 µmol/mol
Oxygen (O_2)	10 µmol/mol	5 µmol/mol
Carbon Dioxide (CO_2)	20 µmol/mol	2 µmol/mol
Carbon Monoxide (CO)	20 µmol/mol	0.2 µmol/mol
Total Sulphur Compounds (S_1 basis)	10 µmol/mol	0.004 µmol/mol
Ammonia (NH_3)	1 µmol/mol	0.1 µmol/mol
Total Hydrocarbons including methane (C_1 equivalent) Methane (CH_4) C_2-C_6 (C_1 equivalent) C_7-C_{11} (C_1 equivalent)	(1% total) 6600 µmol/mol 2000 µmol/mol 1400 µmol/mol	(100 µmol/mol total) 100 µmol/mol 1 µmol/mol 1 µmol/mol
Nitrogen (N_2)	1%	300 µmol/mol

As shown above - there is a wide variety of contaminants that will need removed from network-supplied hydrogen via purification, to enable utilisation by FCEVs. This contaminant specification (Table 2) was used as the basis of the technical specification/functional requirements provided to the various shortlisted purification technology suppliers that were evaluated in Phase 1.

It is likely that this is a conservative scenario, and represents a worst-case of gas quality for the hydrogen network. The presence of some contaminants is expected to be lower and could reduce over time through the future hydrogen transition – this is explored further in Section 1.4 below.

Due to the age of the gas network, there are a number of other trace contaminants present in the pipelines today – including helium, argon, formic acid, formaldehyde and halogenated compounds. Previous work by the Hy4Transport consortium in the HG2V project sampled natural gas from the network for analysis, and showed that these trace contaminants occur in small quantities - not significant to FCEVs. Therefore, we can be certain that the contaminants for evaluation in Phase 1 represent the most significant and challenging contaminants which will be present in new & repurposed hydrogen networks.

1.4 Broader Factors and Variables for consideration

The requirements of the hydrogen purification technology will vary both geographically, and with time. While Phase 2 aims provide first proof of concept of the proposed solution, there are other variables which are currently difficult to measure but could be influential towards any future rollout. These must be monitored in parallel with any technological developments. The main factors for ongoing consideration are:

- **Regional Variation** – analogous to water quality, the quality of gas from the UK network also varies geographically. Therefore, the hydrogen purification requirements may also somewhat vary regionally. At present there is a lack of knowledge on the exact variation of the different contaminants in the UK gas network – so it may be necessary to organise a large-scale investigation (e.g., a sampling and analysis campaign across the UK network) to refine the knowledge of the gas quality, and subsequently map the potential suitable areas (aligned with the Hy4Transport contaminant specification) for further implementation of the purification solution developed in Phase 2.

- **Network Suitability & Materials** – the UK Gas Distribution Networks (GDNs) are currently conducting mass scale, widespread ‘Mains Replacement Programmes’ (MRP) to replace many of the existing metallic pipes with new polyethylene (PE) pipes where appropriate. Cadent has already achieved over 70% conversion in some regions [15]. This is both for maintenance and gas leakage prevention reasons, but also as inherent further preparation for the hydrogen transition. Other research studies are underway to address the general repurposing of the gas network, investigating factors such as material compatibility and leakage. Early indications are that the existing pipeline distribution network is suitable for hydrogen – but especially so in modern PE pipes. The current general stance is that pipes which are ‘leak tight’ for natural gas will also be so for hydrogen. However, more research & evidence gathering is required in this area.

- **Synthetic Odorants** – other hydrogen projects, such as H100 (led by SGN), have recommended that existing gas odorisation regulations are reviewed and consider the use of non-sulphur based synthetic odorants with hydrogen [16]. Sulphur is one of the most damaging components for PEM fuel cells to be exposed to – and hence if a non-sulphur-based odorant is permitted for use, this could significantly reduce the complexity of any purification process.

- **Hydrogen ‘Purging**’ – if a fully 100% hydrogen UK network is adopted, a ‘flushing’ or ‘purging’ phenomena could naturally occur, as natural gas (and other inherent hydrocarbons) is removed from the network over time. This is not yet proven - but could potentially further reduce the complexity of any purification process.

- **Fuel Cell Standards & Increased Tolerability** – it is possible that the current ISO grade standard for usage in PEM fuel cells (ISO 14687, Grade D) may be revised according to new hydrogen sources and distribution methods to reflect the real impact of contaminants present. Similarly, fuel cells themselves may be further developed to improve their tolerance to certain contaminants – easing the purification requirements. The use of hydrogen internal combustion engines (ICEs) is also gaining interest across industry, especially for heavy duty vehicles and construction. It is likely that ICEs will be less influenced by hydrogen purity than FCEVs (if at all), however there are other technical considerations to address (e.g. NOx emissions at the tailpipe).

- **Ambient Conditions & Temperature -** contaminant volatility will be influenced by temperature, but as most of the existing gas pipeline infrastructure is below ground (and any repurposed or new hydrogen pipelines will likewise be) then the gas temperature will remain reasonably constant - as the ground temperature at around 1 metre of depth is reasonably constant across the UK. Hence purification technologies will not be greatly influenced by ambient conditions in different locations, and it is anticipated that any modifications to account for excessively cold or hot conditions will be minor (although it is possible that some additional trace heating or insulation may be required).

While a combination of the above factors is likely to occur over time from now until 2050 it is almost inevitable that some form of purification will always be required on HRS sites as a protective barrier/’safeguard’ between the proposed hydrogen grid and FCEV customers. The optionality of different purification technologies should increase over time, with more advancements of novel solutions (e.g., electrochemical separation & compression, and systems using metallic membranes). Therefore, if it is proven that the challenge can be overcome now - by demonstrating a suitable technology with the most difficult set of present contaminants - then ongoing development and optimisation should allow future iterations of purification systems to make significant advancements in all major aspects - including performance, size, and costs.

2) Purification Technologies

2.1 Overview

This section summarises the purification technology selection (in principle) process that was undertaken by the project team as part of our Phase 1 work – outlining the selection criteria that was used, and the high-level reasons why each OEM was successful in being onboarded for future Phase 2 planning. The work to develop the technical specifications and functional requirements of the desired purification technology was led by Kiwa – but the evaluation group to review the OEM proposals also included members from Cadent, Arup, DNV, NPL and Gemserv for balance.

Previous work conducted in the HG2V project had identified various methods and potential suppliers of hydrogen purification technology for this application. The HG2V project also concluded that, due to cost and technical constraints, there is currently no single technology to provide FCEV-ready hydrogen via a 100% hydrogen network – therefore a mix of technological solutions is required – which may include purification in stages, targeting the removal of individual components (rather than achieving full removal in one step) [5].

While various gas/hydrogen purification technologies are well established industrially – these systems are typically connected onto the end of upstream production processes, with a relatively fixed set of expected contaminants for removal, and usually located within large chemical plants - with less practical and environmental restrictions than vehicle refuelling locations (including noise and size). Conversely, the Hy4Transport project presents a novel and more difficult challenge at the downstream end of the supply chain– as there is a wider and less predictable spread of contaminants within the gas network, and the purification system itself must also integrate non-obstructively with future HRS forecourts - with minimal disruption to consumer habits. Hence, a much greater emphasis must be placed on size/footprint and user-operability – without great compromise to performance, efficiency, or operational costs.

2.2 Selection Process

Prior to developing the funding bid for the Phase 1 Feasibility Study, the Hy4Transport consortium engaged with numerous OEMs throughout Q2, 2021, to share the project challenge and gauge their ability to provide a viable solution. An effort was made to remain agnostic across all technology types, rather than to pre-determine this and target OEMs aligned with one type.

Following an in-depth selection process, in which five OEMs were reviewed over eight weeks in Q2 2022, two OEMs were selected in principle to progress into a potential future Phase 2 demonstration. All remaining work packages in Phase 1, including site selection, the development of a demo plan, and socio-economic assessments, were then based around these two technologies where appropriate. The OEMs selected were:

- **Xebec Adsorption Inc.** – proposing the use of compact PSA (pressure swing adsorption)
- **CPL Activated Carbons** – proposing the use of static carbon beds.

The assessment criteria used to evaluate all OEMs focussed on the supplier’s relevant skills, approach to project delivery, and unit performance, size and costs. This is detailed further in Annex 1.

2.2.1 Xebec Adsorption Inc.– HQ in Montreal, Canada (with growing European base)

While PSA is a proven and established method of hydrogen purification today, this is typically done upstream and at large scale (e.g., vast columns in chemical processing plants, operating at high efficiency). For the downstream Hy4Transport application units must place a greater priority on size/footprint and user operability, to integrate with future HRS forecourts. Xebec's model offers a solution conscious of these additional needs – via a compact PSA unit (enabled through the novel use of a rotary valve), allowing simple operation of the purification system, low maintenance requirements and operational costs, and a very compact size.

There are two continuous output streams from the dynamic system. While, naturally, the supplier has not tested their equipment against the novel Hy4Transport contaminant blend specified in Table 2, they are confident that the units can remove all contaminants listed, and release hydrogen with the required FCEV grade purity. The previous application for these units has been to purify hydrogen produced on-site from small-medium scale SMR units, co-located with HRS dispensers for FCEVs. In such a model, the continuous tail gas stream (secondary output of concentrated contaminants at low pressure) can be recycled back into the SMR unit – but this is not an option for the Hy4Transport application. Hence, the tail gas stream must be managed on-site. Example dimensions of Xebec units are displayed in Figure 3 [17].

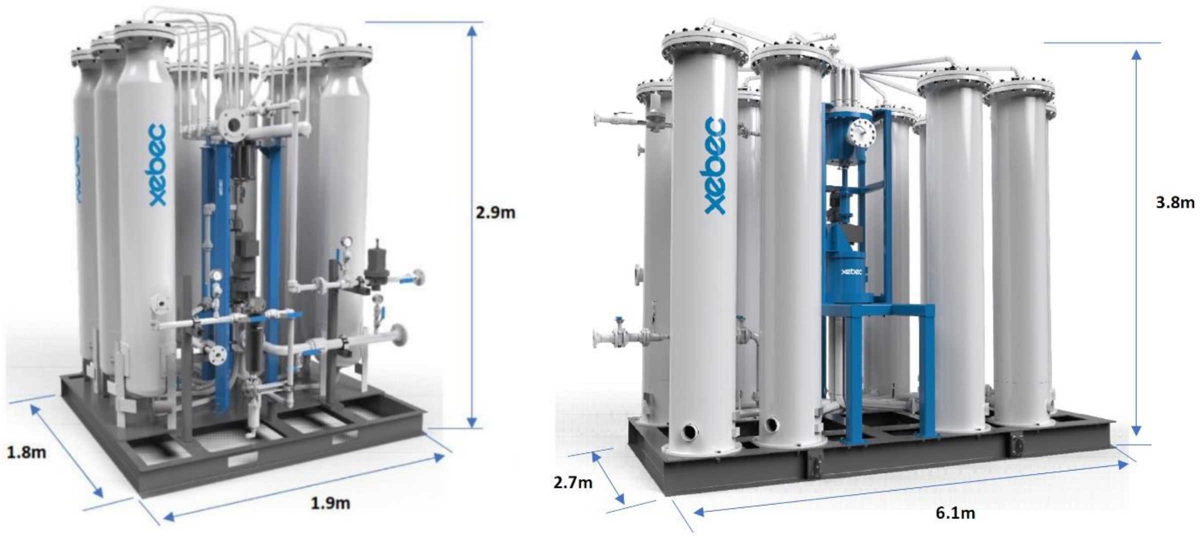


Figure 3 - Xebec Adsorption Inc: G2 & G4 PSA units – capable of 200kg/day and 2000kg/day output of FC grade hydrogen respectively

Potential options to manage the tail gas stream include:

Table 3: Summative comparison of the different approaches to handle a continuous steam of tail gas from a typical PSA system

Approach	Description	Consortium Position / Recommendation
Reinjection	Redirection of the tail gas stream into the gas network – carried to downstream users.	This will not always be possible, as there may not be applications/demand downstream from each HRS, and may be unfavourable as end-users could potentially receive a higher concentration of contaminants as a result.
Flaring	Controlled combustion of tail gas stream on site.	This is unlikely to be economical (unless on-site heat/ power integration is possible), and is unlikely to be permitted in a forecourt setting.
Venting	Release of the tail gas stream to the atmosphere.	This is not economically or environmentally favourable.
Treatment/ Capture of Contaminants	A secondary clean-up process (e.g. via active carbon beds) could remove and store bulk contaminants – for periodic collection and disposal.	This approach is understood to be technically possible, and could be economically viable if units are cheap enough to run and maintain. If this is economically viable, and waste disposal is sustainable, **this would be the favoured approach.**

2.2.2 CPL Activated Carbons – HQ in Wigan, UK

Activated Carbon Beds (ACB) work by passing gas (containing contaminants) through a bed of 'active' solid carbon contained within a vessel, which adsorbs the contaminants – removing them from the gas stream – leaving purified gas to exit the system. The contaminants are retained in the active carbon bed, until eventually no more contaminants can be adsorbed once enough have accumulated. When this point is reached, the 'spent' carbon bed must be removed and replaced with new, active adsorption media. CPL estimate that media could typically need replacing around every three months.

The spent carbon is sent for thermal reactivation - this a high-temperature process. Contaminants released in this process are fed into a thermal oxidiser for combustion, before the off-gas is treated using a caustic scrubber. Fuel for this process is currently provided by natural gas from the main network - but CPL expect to transition to hydrogen fuel in the future. Aside from the off-gas, the process produces almost zero waste, because the reactivated carbons are repurposed for other uses (including soil remediation, flue gas treatment, and wastewater treatment). The reactivation process has pollution abatement systems in place with regular monitoring of emissions. The figure below shows real images of the units:

Figure 4 - CPL Gas Purification Units being loaded (left) and in operation (right)

Typical dimensions of a 4000 kg/day vessel are 1.7m diameter by 3.1m height.

The CPL units have never commercially been operated with hydrogen – with the existing model based around the treatment of natural gas or biogas. As such, CPL are already developing appropriate carbon media to accommodate the purification of hydrogen ahead of the potential Phase 2, aligned with R&D activity. There could be a challenge in removing some of the lighter contaminants from hydrogen – such as methane, oxygen and nitrogen, however this highlights the novelty and the value of a demonstration.

The CPL system was chosen to advance into a potential Phase 2 demonstrator for various reasons – but most notably due to the ability of the technology to achieve very high recovery rates by storing captured contaminants in the carbon media (avoiding a secondary continuous tail gas stream output) – with a sophisticated and circular method of waste collection and disposal. CPL also have a pre-existing business model for installation, storage and replacement, and the unit footprint is appropriate for use in a HRS forecourt.

2.2.3 System Integration

While there is naturally a higher chance of demonstrating a suitable hydrogen purification technology by bringing two systems forward into Phase 2 – there is also an additional opportunity presented in the form of process integration. Both systems will be tested in isolation initially, but dependent on results, there could be great value in also trialling a hybrid solution (which had previously been identified as a likely necessity via the HG2V project). The respective strengths and challenges with each technology should be complementary. It should be noted that as both systems produce pure hydrogen at relatively low pressures, significant compression would be required before storage or dispensary into FCEVs (typically 350-700 bar).

Table 4: Summary of respective strengths/challenges with each system

System	Technical Strength(s)	Technical Challenge(s)
Compact PSA	Reaches required hydrogen purity – removing all contaminants.	Continuous output stream of concentrated tail gas (7-17% by volume).
Activated Carbon Bed	Removed contaminants are collected/stored in carbon bed media.	Potential difficulty in removing 100% of nitrogen, oxygen, and methane from hydrogen.
Hybrid (PSA → ACB)	Reaches required hydrogen purity, whilst also collecting/ storing most (if not all) contaminants.	Increased total system footprint & utility requirements.

The Hy4Transport consortium proposes to conduct a full lifecycle analysis (LCA) study in Phase 2 to further investigate and evidence the broader carbon footprint of both systems.

3) Demonstration Site

3.1 Overview

This section summarises the demonstration site selection (in principle) process that was undertaken by the project team as part of our Phase 1 work – outlining the selection criteria that was used, and the high-level reasons why the chosen site was successful in being onboarded for future Phase 2 planning. The work to outline the site requirements was led by Arup – but the evaluation group to review the shortlisted sites also included members from Cadent, NPL and independent consultants from Imperial College London for balance. Partners from Kiwa, DNV, and Gemserv did not provide any input into the evaluation process, in order to avoid respective conflicts of interest.

A stakeholder list, detailing several possible locations to host a future demonstration of purification technology, had been developed from previous aligned work/projects. This list was shortlisted to four for full evaluation – in a similar process to that which was conducted to select the purification technologies. Most of the site selection criteria were largely independent of the chosen OEMs, but naturally some specific points were tailored towards the chosen technologies (e.g., net footprint available, minimum duty requirements, and accommodation of the required operating conditions). The pass/fail criteria used to select the four shortlisted sites were as follows:

- A source of hydrogen must be available on site by Q4 2023, with capacity to supply a minimum of 200kg/day*, available until at least the end of 2025 (if required, for contingency).
- There must be at least 7.5x7.5m of available space on site for the Hy4Transport demonstrator
- The hosts must align with the Hy4Transport project vision/willingness to collaborate with the existing consortium
- The hosts must own the land proposed/provide permission to use this for Hy4Transport purposes
- The site must be acceptably secure and well managed
- There must be a high level of accessibility to Hy4Transport personnel

*200kg/day was deemed a reasonable baseline of demand for unit design for the proposed Phase 2 demonstration – enabling an informative trial of the selected technologies whilst remaining within the £6m budget limit, as the price of hydrogen itself is likely to be a volatile cost.

3.2 Selection Process

The site evaluation process was conducted in a similarly rigorous fashion to the technology selection, with each proposal being thoroughly reviewed, allowing time for clarifications and questions, before final moderation and ratification sessions. The site evaluation group was conscious that there would be advantages and disadvantages with any site chosen, but it made best efforts to identify and choose a site that was as close to optimal as possible. Generally, the optimal site would have been large and secure, in mainland Great Britain, with a dedicated for-purpose supply of low carbon hydrogen at high throughput, significant storage capacity on-site for flexibility/resilience, and a guaranteed source of on-site demand for any hydrogen output from the trial system (tolerant of a range of possible purities from 98-99.97%) to minimise project costs and associated emissions.

The preferred demonstration site was deemed to be Kiwa Limited's hydrogen production, technology demonstration and appliance testing facility, with a dedicated SMR production system on-site, at Kiwa House in Cheltenham, UK. All other sites considered (anonymised due to NDAs) were also deemed to be suitable hosts for the Phase 2 demonstrator, and as a result the consortium has remained engaged with these parties - retaining them as options in reserve in the case of any unforeseen issues or risks with the preferred choice. The assessment criteria used to evaluate all sites are detailed in Annex 2.

3.2.1 Kiwa House - Chosen Site

Kiwa's proposed site scored the highest in the evaluation and moderation process and was deemed to present the closest scenario to the optimum demonstration site. A panoramic view created from two real photographs of the demonstration site is shown below for context:

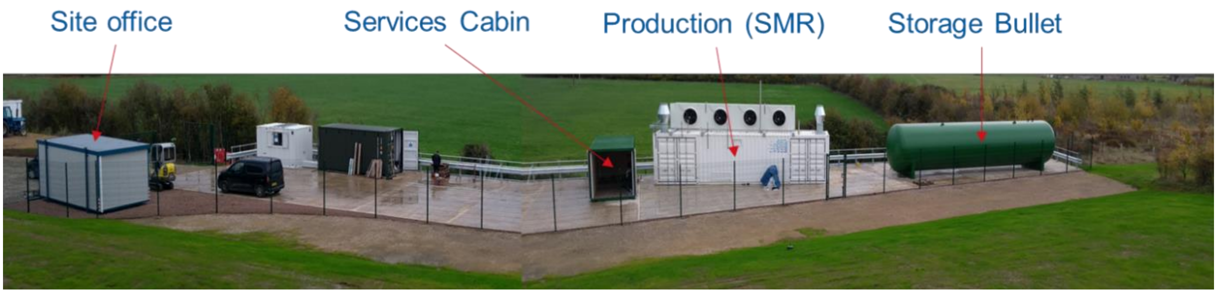


Figure 5 - Labelled panoramic view of the proposed Kiwa site (May 2022)

The Kiwa site can provide a reliable source of 216kg/day of purified hydrogen (≥99.5% purity) from a dedicated 300kW SMR unit. The maximum test requirement of 241 kg/day can still be supplied through use of the storage bullet, the additional hydrogen supplied via the contamination rig (with the injection of contaminants blended in hydrogen), and the ability to control the SMR unit to enable a greater supply rate (at a slightly reduced purity).

While this SMR unit does not have carbon-capture capability, the input natural gas is from a local bio-gas feed. The site also has a hydrogen storage bullet (with a capacity of 66kg at 7 bar) which provides some additional flexibility. Adequate space is available on-site for the Hy4Transport system, although this must be carefully managed, as there is not limited room for future expansion. The site also features a gas odorisation unit, and Kiwa have strong experience with handling the relevant contaminants/injection processes. In addition to the strengths highlighted above, perhaps the most attractive feature of the Kiwa site is the on-site application of output hydrogen which is not reliant upon the guarantee of 99.97% purity (FCEV grade). The Kiwa House appliance test facility (within the wider site) is already connected to the SMR production line, and throughout the Hy4Transport programme various hydrogen boilers, hobs and other appliances will be tested. This enables a more sustainable cycle – where any hydrogen demand for appliance testing downstream can be passed through the Hy4Transport purification system first, with no major risk of spoiling downstream equipment. There is also the potential for a recycle in the process which could allow some hydrogen to be recovered back into the demonstration. This may reduce project costs; however it does carry additional technical risk due to the complexity in achieving a dynamic continuous recycle for 11 gas components. The technical risk introduced by a recycle will be assessed as part of the Phase 2 bid alongside the cost benefits. The system is summarised by the block flow diagram in Figure 6 below:

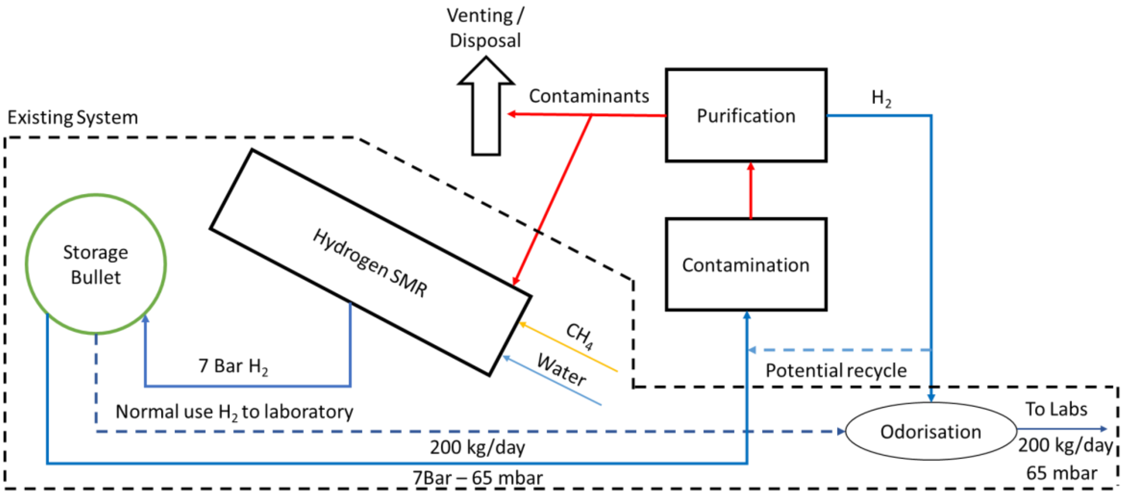


Figure 6 - Simplified block flow diagram of the proposed demonstrator layout at the Kiwa site

The Hy4Transport demonstration aims to align schedules with proposed appliance testing programmes, so that demands can be synchronised where possible, minimising any net losses of hydrogen and subsequent venting/flaring requirements. This could greatly reduce project costs and emissions.

4a) Proposed Demonstration Programme (Phase 2)

4.1a Overview

This section summarises the indicative test programme that is proposed for the demonstration of the two hydrogen purification technologies in Phase 2. The work to develop this programme was led by Kiwa and was heavily tailored to the two technologies that were selected. This test programme is agnostic of the chosen demonstration site.

The selected hydrogen purification technologies will be subjected to various, and increasingly contaminated, streams of hydrogen which would model the level of contaminants that would likely be present in hydrogen from the gas grid (as is defined by Table 2 in Section 1.3). The capability of the technologies to produce ISO 14687 Grade D hydrogen (≥99.97% H_2) for long durations at varying levels of output will be assessed. This programme also includes the potential for testing the Pressure Swing Adsorber (PSA), and the Activated Carbon Bed (ACB) in series. The live demonstration phase is expected to run for roughly 12 months from September 2023 to Sep 2024.

4.2a Contaminant Blends

The test programme has been designed to test both purification technologies to their limits to ensure that they are robust enough to be included in a future gas network. The programme has been designed to slowly increase the level of contamination that the technologies will be exposed to, to assess the performance of the equipment.

The technologies will also be run for prolonged periods to assess the ability of the technology to continue to deliver the required purification and to assess any degradation in the equipment. It is estimated that the 9-month active demo period will require ~34,000kg of hydrogen. The technologies will be tested at three output flowrate levels ‐ high (200-241kg/day), low (96-100kg/day) and variable (96-241kg/day).

4.3a Sampling and Analysis

Initially the technologies will be assessed through purity measurements on the inlet and outlet of the technology. Gas analysers will measure the concentration of the contaminated hydrogen before and after the purification plants. The gas analyser before the purification technology will be used to communicate with the control system, such that contaminant concentrations meet the specification set out in Table 2. The gas analyser after the purification technology will be used to measure whether the concentration of the purified hydrogen meets the ISO 14687 Grade D standard concentrations listed in Table 2 and comparisons with both analysers will determine the impurities removed. During testing where there is a waste gas stream, an additional analyser will be connected to the waste gas to the measure the composition.

In addition to the gas analysis either side of the purification technologies, sampling points will be installed so that discreet gas samples can be taken periodically to be sent to NPL for analysis. The frequency of these targeted analyses is generally one sample per purification system per key gas blend, under different flowrate conditions. These more intensive sampling and analysis tests will be used to provide very accurate measurements of the contaminants present in the purified hydrogen and, if required, verify the impurities entering the purification equipment.

4.4a Test Programme Phases

The test programme has been split into three phases. The first two phases will focus on the two technologies individually - to ensure that they can deliver the level of purification required. This will begin with initial tests with each contaminant to assess the performance of the purification equipment before the system is operated for extended durations with all the required contaminants. The first two phases are expected to last around 3 months each. Following the successful completion of these first two phases the technologies will be subjected to further tests in a hybrid system, which will assess the effects of long-term operation on maintenance, contaminant break through and operating costs.

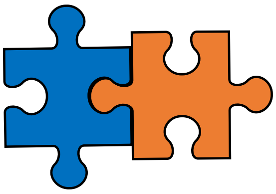
Block 1 (12 weeks) – Testing of CPL ACB Unit

Test 1	**Test 2**	**Test 3**
7 weeks of testing with 200 kg/day of hydrogen	2 weeks of testing with 100 kg/day of hydrogen	3 weeks of testing using a variable flowrate of hydrogen
Exposure to all contaminants	Exposure to all contaminants (except ammonia)	Exposure to all contaminants (except ammonia)

Block 2 (12 weeks) – Testing of Xebec PSA Unit

Test 1	**Test 2**	**Test 3**
7 weeks of testing with 241 kg/day of hydrogen	2 weeks of testing with 96 kg/day of hydrogen	3 weeks of testing using a variable flowrate of hydrogen
Exposure to all contaminants	Exposure to all contaminants (except ammonia)	Exposure to all contaminants (except ammonia)

Block 3 (12 weeks) – Prolonged Testing of Hybrid Solution (PSA → ACB in Series)



Dependent on the outcome of Blocks 1 & 2 – the programme may need to be reconfigured to allow further individual testing. However, if both technologies provide positive results, then the site can be reconfigured to allow for hybrid testing in series. This phase of testing will assess if the technologies can work together, with the PSA unit doing the bulk purification, and the ACB unit performing a ‘clean-up’ role with the tail gas stream. The output gas from the ACB unit could potentially be recycled to the PSA, to improve net hydrogen recovery rates. If additional storage is required, this will be installed before the start of this testing phase.

Test 1	Test 2
11 weeks of testing with a variable flowrate of hydrogen Exposure to all contaminants (except ammonia)	1 week of final stress-testing with 200 kg/day of hydrogen Exposure to all contaminants

There will be 9 months in total of live tests, however the net demonstration schedule has been planned around 12 months to allow time to swap between the technologies, and for shutdown/start-up procedures. High, low, and variable hydrogen flowrates are being used to demonstrate that the equipment can operate with the varying demands that occur at vehicle refuelling locations where daily demand fluctuates over a 24-hour period (with reduced activity overnight and in the early mornings). Running with varying outputs will enable testing of these demand profiles.

4b) Costed Development Plan (Phase 2)

4.1b Overview

As part of Phase 1 - an indicative cost model and schedule for the potential subsequent Phase 2 of the project was prepared. This was informed by lessons gathered through engaging with various suppliers of purification technology, and demonstration sites, which allowed the Hy4Transport consortium to refine the appropriate Phase 2 scope and objectives. This work was led by Arup.

Please note – the initial production of this preliminary Phase 2 plan preceded the official publication of BEIS Phase 2 ITT (released on 22nd August 2022). Hence the work scope and respective budget that has been outlined can only be considered indicative at this stage – and is currently subject to change via further review throughout September and October. This indicative plan was also prepared under the proviso that a change control process will be implemented.

The work to deliver this cost model began in March 2022, when discussions with the shortlisted OEMs, together with the consortium's collective understanding of purification solutions, was rapidly progressing. OEMs subsequently shared quotes for providing the necessary equipment to undertake a FOAK (first of a kind) demonstrator in Phase 2. In addition to this, the shortlisted sites provided indicative costs for trial operation and site rental, and Kiwa (an existing technical consortium partner) provided ancillary equipment costs for the general testing programme (agnostic of host location). From the subsequent selection of technologies and preferred demonstration site, high-level indicative costs for Phase 2 were captured and are summarised in this section.

4.2b Scope and Objectives

Between April and August, the Hy4Transport consortium worked collaboratively to further establish the objectives, scope and respective work packages that would be included in Phase 2. This model was built 'from the bottom up' in principle. Subsequently, partner organisations with the appropriate expertise were assigned to respective work packages. Having conducted various workshops between the different partners, the inclusion of additional partners was considered, but deemed unnecessary to deliver the outlined scope to the desired high standard. The exception to this was the inclusion of the two OEMs selected – who are providing the purification systems for trial (the primary component of the demonstration programme).

The major objectives of the Phase 2 programme are as follows:

1	**Technology Development** The Phase 2 project aims to demonstrate, evaluate, and evolve the proposed hydrogen purification systems. This includes achieving the following key aims: • Purify contaminated hydrogen (representative of delivery from the gas network) to the current required standard for application in FCEVs (ISO 14687, Type 1, Grade D) • Propose & trial a strategy to manage all by-products/waste produced • Identify & understand future requirements for wider integration with HRS forecourts
2	**Future Planning/Exploitation** The Phase 2 project aims to further progress from the platform of socioeconomic analysis and rollout strategy that has been provided from Phase 1 work, and plan for the future beyond Phase 2 closure in 2025. This includes achieving the following key aims: • Outline rollout from 2025 (of the developed system in Phase 2) – demonstrating what this could deliver for the UK economy and broader industry • Assess and project the commercial viability of the developed system (from First of a Kind to 'nth of a Kind)
3	**Industrial & Public Engagement** During the Phase 2 project the consortium aims to greatly increase engagement with relevant industrial stakeholders and increase wider dissemination activities. This work will prove the market need/desire for grid-supplied, high purity hydrogen across the supply chain, and establish strong working relationships with likely or suitable collaborators for a future 'Phase 3' programme. This work will particularly target further engagement with HRS operators, FCEV manufacturers, and users of FCEV fleets. A Hy4Transport website will be developed, updated, and maintained throughout to share wider learning and findings from the programme publicly.

An initial breakdown of budget has been prepared, with lead responsibilities being allocated to each partner in the proposed expanded Phase 2 consortium. Various combinations of partners will support each work package as required.

4.3b Budget

Phase 2 work has been split into three generalised categories – project management, physical demonstration activities, and broader 'desk studies' running in parallel to, or following, the main trial. The cost estimates were requested at different points during the financial year (FY) 2021/2022. The indicative total budget required to deliver all Phase 2 work has been estimated as ~£5,315,000.

The total anticipated cost captures all capital and operating costs, desk studies, labour and services required to deliver the proposed Hy4Transport Phase 2 demonstration. The value to BEIS and the UK economy is driven by the potential for this solution to be further developed from FOAK/proof of concept and accelerate applications of hydrogen in transport. PMO activities are expected to use ~9% of project budget over the two years, with the vast majority of budget (~73%) attributed towards the physical demonstration itself, supplemented by wider desk-based studies (~18%). This aligns well with BEIS requirements of ≥50% of total Phase 2 costs being associated with physical demonstration work.

4.4b Timelines/Schedule

A high-level timeline to deliver the scope outlined for Phase 2 was developed, with the hard-stop of 1st February 2025 required by BEIS in mind for the programme. At the original time of writing, successful projects were expected to commence from January of 2023. If the project is successfully awarded Phase 2 funding, procurement of relevant equipment will begin as soon as possible.

The preliminary, high level Gantt chart is displayed below for context:

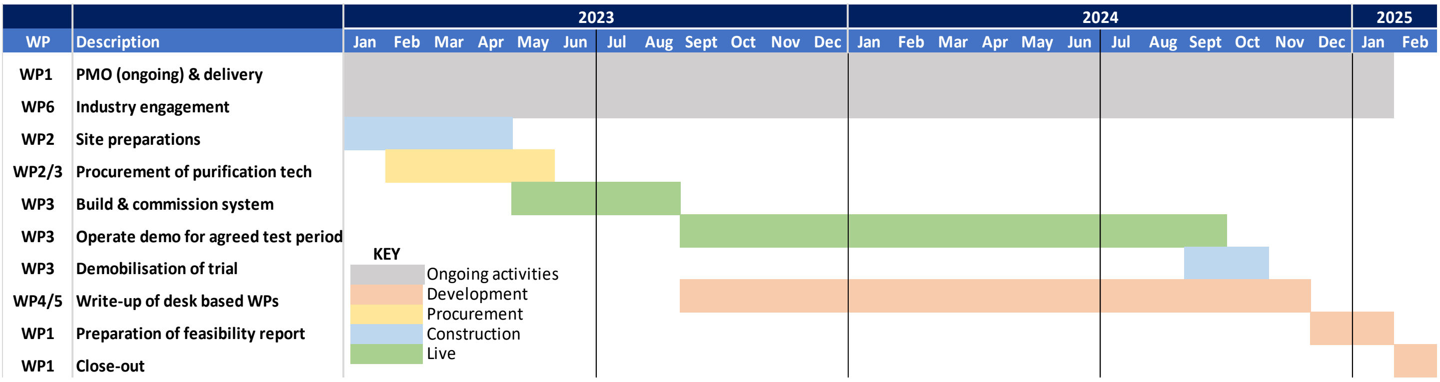


Figure 7 - High level Phase 2 Gantt chart (from Jan 2023 to February 2025)

5) Benefits & Barriers

5.1 Overview

As part of Phase 1 - a full socioeconomic assessment was conducted, tailoring macroeconomic models from previous studies with new cost/size information from the two chosen Hy4Transport technologies, and with more updated UK hydrogen economy projections. This work was led by Gemserv and was supported by independent consultants from Imperial College London.

The assessment was conducted with the aims of addressing the following:

- Scalability of grid-connected refuelling stations with on-site purification
- Cost reduction potential for purified hydrogen 'at the pump'
- Hydrogen price point analysis for range of fuel cell vehicles
- Commercial viability
- Macroeconomic modelling of gross value added (GVA) and gross job creation
- Emissions savings

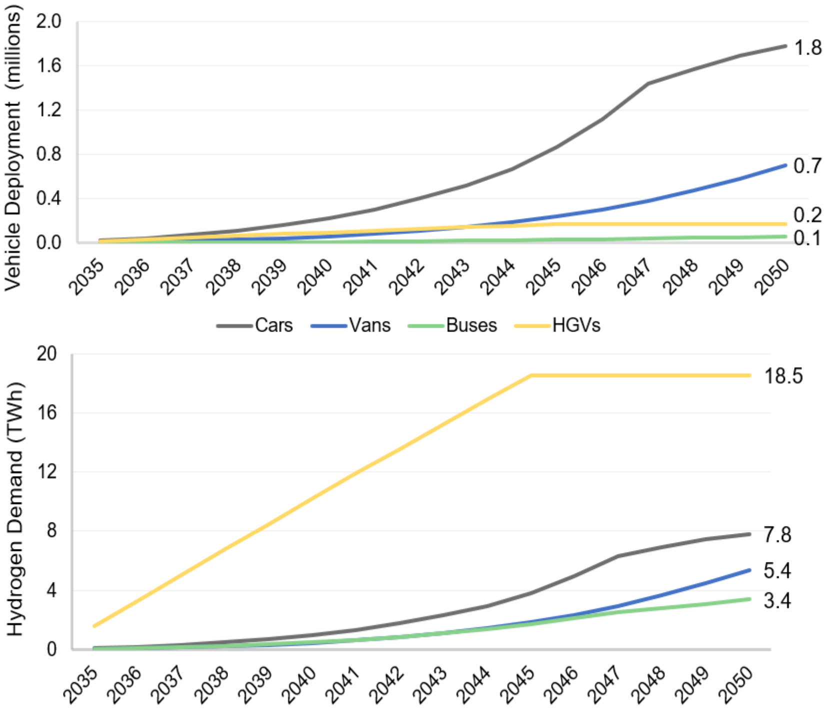
The 2021 edition of National Grid's Future Energy Scenarios (FES) publication, and Cadent's 'Green Gas Transport Pathway' report (GGTP, also published in 2021) were used as the basis for the analysis and projections of demand for hydrogen for transport. Naturally, this analysis required the use of various assumptions across the future hydrogen supply chain. All notable assumptions are detailed in the dedicated section at the end of the report – but the major points are:

- The 'UK' focus boundary is limited to mainland Great Britain (Scotland, England and Wales) - as the FES and GGTP study were bound to this area.
- The Hy4Transport concept relies on the natural gas grid being repurposed for the distribution of hydrogen. For the purpose of this report, it was assumed that this will be initiated - based on a positive policy decision in 2026 to support hydrogen for domestic heat, and that all associated disruption for existing customers is suitably mitigated.
- Hydrogen demand for road transport was modelled from 2035 - as this is considered a credible future date when '100%' hydrogen supplied by the grid could be widely available. It was assumed that all FCEV vehicle deployment from this date is serviced by hydrogen distributed through the gas network.
- An average cost for purification (based on the two chosen technologies) was used, and the cost associated with waste handling was inherently included in the purification cost range.

5.2 Demand

While it is difficult to estimate the deployment that could occur because of hydrogen being available from the gas network, the System Transformation (ST) scenario from National Grid's FES is the best aligned with this eventuality - given the assumption within the ST scenario that the gas network is repurposed for hydrogen and there is much higher uptake of hydrogen vehicles than in the other FES scenarios. This scenario was used to develop the deployment assumptions for FCEV cars, vans, and buses – while the figures from the GGTP were used to develop the HGV deployment assumption.

As such, this analysis should be seen as an optimistic but possible view of hydrogen vehicle deployment. Naturally, the true outcome will depend on how consumer preferences, FCEV technology and hydrogen costs develop against alternatives - such as BEVs.



Figures 8 & 9 - Cumulative UK Surface Transport FCEV Deployment & associated demand (from 2035)

Demand was estimated for each mode of road transport using the deployment numbers in Figure 8 and data for average mileage [19] [20] and fuel efficiency [21]. The annual demand for hydrogen broken down by transport mode is shown in Figure 9 - showing that demand for HGVs could contribute more than 50% of the total for road transport.

5.3 Price at the Pump

The estimated price of delivered hydrogen 'at the pump' was calculated based on previous work carried out in the HG2V project, updated with latest input data from industry, and with the addition of new cost data from the purification technologies under consideration for the proposed Phase 2 demonstration. Purification was found to not be one of the major contributors to delivered hydrogen cost, at less than 2% for the 'Base Case' in 2050*. This analysis is summarised by the figures below:

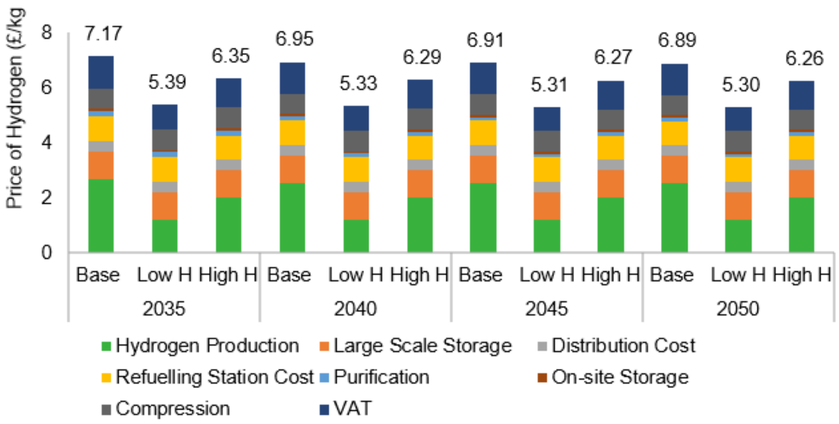


Figure 10 – Estimated price of hydrogen at the pump (under various hydrogen production prices) from 2035 to 2050

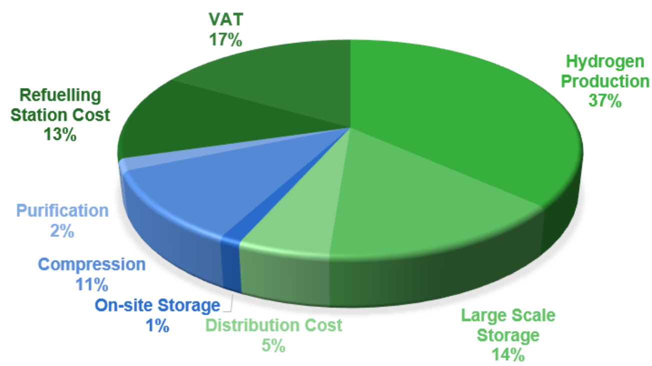


Figure 11 – Cost contributions to the price of purified hydrogen at the pump for the Hy4Transport Base-Case in 2050

*The 'Base' case is an average of the BEIS Levelised Cost of Hydrogen with a 50/50 split between CCUS-enabled and electrolytic hydrogen (produced from dedicated offshore wind) due to the assumption that hydrogen generation from curtailed renewable energy is absorbed by other sectors. This price falls over time due to reductions in the price of electrolytic hydrogen. The 'Low

H' and 'High H' scenarios are based on the HG2V project scenarios which have more optimistic hydrogen prices at £1.2/ kg and £2/kg respectively.

The hydrogen production price is the single largest contributor to delivered hydrogen price (37%) for the Base Case in 2050, with large-scale storage as the second largest contributor (14%). These are both common to all delivery modes and are not unique or sensitive to the Hy4Transport grid-connected solution. The main driver of compression costs is OpEx related to electricity requirements for the various steps – production to grid, grid to purification, and post-purification to on-site HRS storage. Opportunities to reduce costs at each of these steps exist and would be investigated in the proposed Phase 2 programme.

5.4 Counterfactuals: Economics

The HG2V project found that purification costs could have a significant impact on the final pump-price of hydrogen. It is therefore the goal of the Hy4Transport project to develop and demonstrate a hydrogen purification system which can deliver hydrogen at a cost competitive with the counterfactual modes of distribution. Numerous studies have been conducted comparing the relative merits of alternative delivery methods, with the most relevant to mainland Great Britain being from road deliveries: either tube trailers carrying compressed hydrogen, or tankers carrying liquefied hydrogen. These methods can also be combined with upstream pipeline delivery and bulk purification, in a 'hub and spoke' model. Hence, four different counterfactual delivery modes were analysed*:

- No Grid (CH_2) – compressed gas delivered exclusively by tube trailers
- Hub & Spoke (CH_2) – combination of delivery by pipeline & compressed gas by tube trailers
- No Grid (LH_2) – liquefied hydrogen delivered exclusively by tankers
- Hub & Spoke (LH_2) – combination of delivery by pipeline & liquefied hydrogen by tankers

*The co-location of electrolysers on HRS sites was not considered to be feasible at scale for widespread rollout due to the significant footprint requirement of the electrolyser and balance of plant equipment. Furthermore, economies of scale favour centralised production of hydrogen - especially relevant given the contribution of production to the price at the pump. However, it must be acknowledged that for very large transport hubs, with guaranteed means of constant demand and space availability (e.g., major ports), co-location of electrolytic production is likely a viable alternative – but such sites could also be further supported by a grid-supply for increased resilience and to boost production.

In general, previous studies all conclude that for increasing hydrogen demand and increasing transportation distance, the most cost-effective option is pipeline delivery. However, the transportation costs, both absolute and relative to other delivery modes, are sensitive to a range of inputs and assumptions, and therefore unique to the scenario being considered. The results from this study have shown that the proposed Hy4Transport model can provide the lowest cost option for the delivery modes analysed.

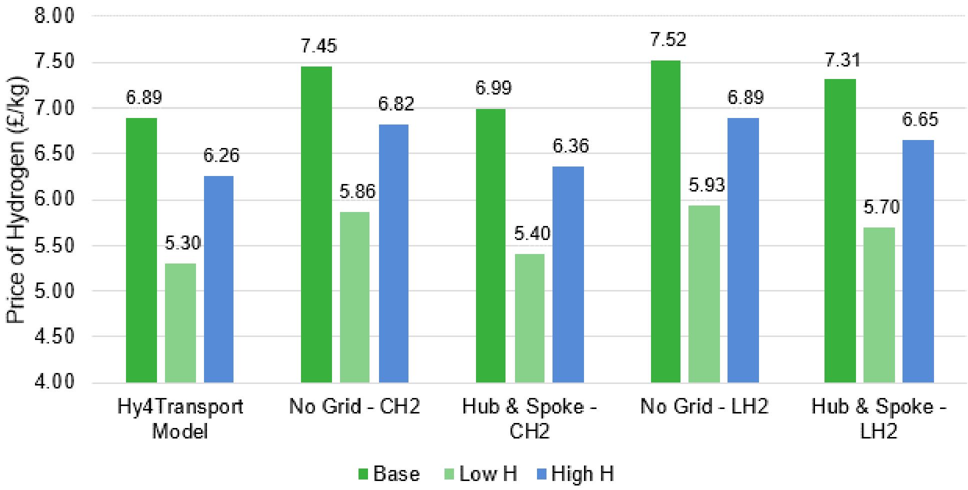


Figure 12 – Hydrogen price at the pump for the studied delivery modes (2050 cases)

5.4.1 Counterfactuals: Logistical/Practical Considerations

In addition to being the lowest cost, the grid delivery model provides further benefits such as avoiding significant numbers of delivery trucks on the roads every day to service the HRS network and enabling the distributed use of hydrogen in other sectors: such as heat, power and industry. Several major differences exist for Great Britain when compared to international applications, most notably the availability of an existing and extensive gas network which could be repurposed for use with hydrogen, at lower cost than a new-build network - but also the lesser suitability of large trailers on the UK road network when compared to for example, the US. The exact number of trailers required on-site at any one time is a function of the operational logistics of each particular site and should take into account variables such as peak demand flows, duration, round trip time from production hub to HRS, and number of hours available at the HRS for trailer-swapping activities. For the proposed Hy4Transport HRS network (of over 600 refuelling stations), tube trailer delivery of compressed hydrogen could require a minimum of 5,600 active trailers every day to provide the daily demand for transport (for context, the UK road fuel tanker fleet is currently estimated to be around 1,000–1,500 vehicles). However, in reality, it could require double this number (~11,200) to be able to maintain a system of concurrent filling and emptying to avoid situations where no hydrogen was available at the HRS. This is contextualised by the table below, providing an insight into the number of tube trailers (carrying compressed hydrogen) that could be required to facilitate various sizes of HRSs:

Table 6 – Logistical requirements for compressed gas tube trailer delivery mode

HRS Size Class	HRS Size (max. tonnes H_2/day)	No. HRSs	No. Trailers Req. (/HRS/day)*	Total No. Trailers Req. (/day)	Swap Time (hours/HRS/day)
4XL	22	16	35	558	53
3XL	17.5	48	28	1,332	42
2XL	12.5	79	20	1,586	30
XL	7.5	95	12	1,142	18
Large	2.5	111	4	444	6
Small	1.2	285	2	548	3
	Total	**634**	**Total**	**5,611**	

*Rounded to the closest whole number, trailers were assumed to have capacity of 500kg, and delivered volume calculated assuming 80% utilisation of HRS max. size.

The compressed gas tube trailer delivery model is not feasible for large depots, where 35 deliveries would be required every day for sites dispensing over 20t/day. Other studies have recognised this logistics constraint and discounted compressed gas tube trailer delivery for stations with daily capacity of above 1 tonne. Since HRS costs benefit from economy of scale, a network of more numerous, but smaller capacity individual HRS, suffers from an increase in the £/kg of delivered hydrogen, resulting in a higher price than the Hy4Transport grid-based model. Such a model is also disadvantaged by the requirement to have a larger fleet of trucks (more than 5,600) shuttling between production sites and HRSs every day of the year to be able to meet the daily demand for hydrogen just for transport. This is a significant freight volume added to the roads and does not provide for any additional supply to other end-use cases of hydrogen. The hub and spoke delivery model would alleviate some of the cost penalties incurred by tube trailer delivery, however it would still cost more (per kg of delivered hydrogen) than the grid options (as seen in Figure 12) and requires a fleet of more than 2,000 trucks shuttling daily between hub and spoke sites.

5.4.2 Counterfactuals: Tanker Delivery of Liquefied Hydrogen

Fewer trucks and trailers would be required than the compressed gas tube trailer model due to the significantly larger inventory that can delivered within the same trailer volume. However, the capital cost and associated energy costs for liquefaction and regassification more than offsets this saving.

5.4.3 Counterfactuals: Total Cost of Ownership

The results of the hydrogen price point analysis support the hypothesis that hydrogen is more likely to be cost competitive in larger vehicle modes. As the vehicle mode becomes heavier and the utilisation rate increases, the requirement for fast charging and large energy capacity grows, and thus the hydrogen price for cost parity between FCEVs and BEVs is higher. A similar, but slightly less evident trend is seen between FCEVs and diesel vehicles (though diesels LGVs and cars were excluded from this study as their planned ‘phase-out’ date is before 2030).

Table 7 - Hydrogen Price at which FCEVs Reach TCO Cost Parity with Battery Electric and Diesel Vehicles

Vehicle Mode	Hydrogen Price for TCO Cost Parity with BEV (£/kg)	Hydrogen Price for TCO Cost Parity with Diesel (£/kg)
HGV (Long Haul)	9.28	6.85
HGV (Regional)	8.35	7.39
Bus (Single Decker)	7.49	5.39*
LGV (Light Van)	3.60	N/A**
Car	3.28	N/A**
* Expected phase out of diesel buses between 2025 and 2030 [22], ** Phase out of diesel cars and vans in 2030 [23]		

The hydrogen prices to achieve cost parity in the heavier vehicle types are likely achievable with future cost reduction. Financial concerns are not the only influencing factor when selecting a vehicle, with FCEVs able to offer consumer appeal where cost parity is not achieved. The flexibility around charging time is an advantage, but only with a sufficient network of HRSs, including those suitable for larger vehicles.

5.5 Economic Impact

A macroeconomic model was created to estimate the gross impact on jobs and gross value added (GVA) of this investment. The impact of this capital and operational expenditure was captured directly in the specified industry, and indirectly through the wider supply chain impact. Costs for sectors were broken down into subcomponents using a range of literature sources, and Standard Industrial Classification (SIC) codes were used to classify costs by the relevant two and four-digit code. This analysis relied on datasets from The Office for National Statistics (ONS) including input-output tables, and supply and use tables. This process was undertaken for the hydrogen value chain including production, transmission, distribution, storage, transport infrastructure and vehicles.

The number of gross jobs and GVA in 2050 in the entire Hy4Transport Scenario value chain was estimated at 27,700 and £9.3bn respectively in 2050 - with the total cumulative gross employment years and GVA created in the value chain estimated to be more than 288,000 FTE years and £101bn respectively between 2035 and 2050.

5.6 Environmental Impact

Greenhouse gas (GHG) emission savings were estimated by calculating the emissions associated with the fossil fuel vehicles that FCEVs would replace and comparing these to the emissions associated with hydrogen use. The analysis assumes that cars and vans replaced with FCEVs run on petrol, while buses and HGVs are powered by diesel. The efficiencies of vehicles are based on data from the Climate Change Committee (CCC) in which fuel cell vehicles are assumed to be 61% efficient with compression (resulting in losses of 9%) to give a total efficiency of hydrogen transport of 54.6%. In comparison, internal combustion engine (ICE) efficiency is modelled at 30%. This results in each kWh of hydrogen displacing 1.8 kWh of fossil fuels.
The emissions associated with fossil fuel consumption for the number of each vehicle type were multiplied by BEIS scope 1 and scope 3 emission factors - to give total well-to-tailpipe emissions of the ICE vehicles. Over the modelled 16-year period from 2035-2050, more than 160 MtCO2e could be avoided by the transition to FCEVs which are supplied by grid hydrogen, equivalent to nearly 6 million cars off the road for the entire 16-year period.

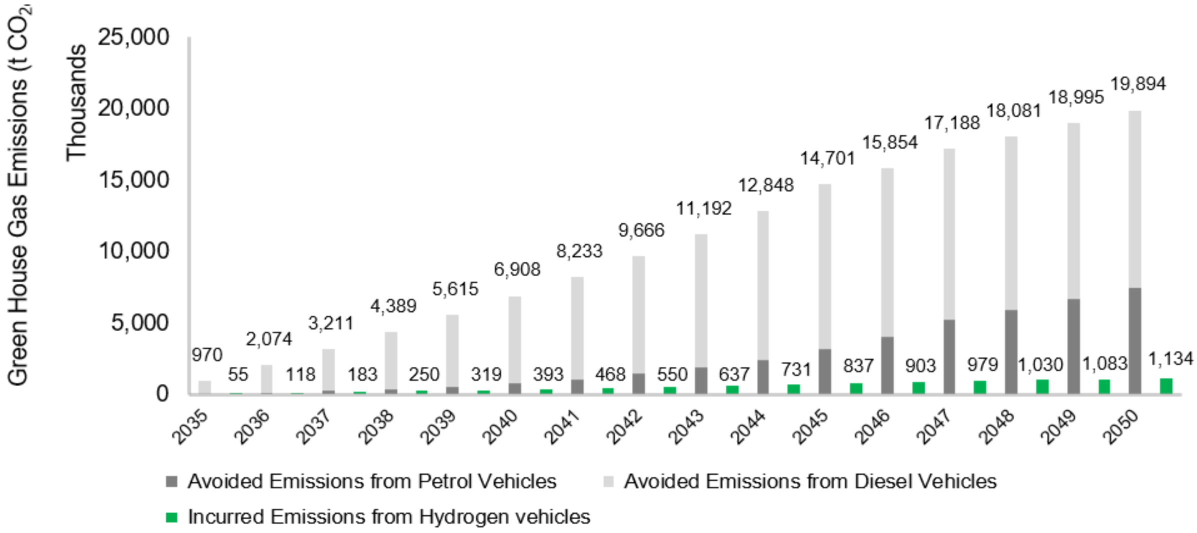


Figure 13 - Comparison of Emissions between continued use of fossil fuelled vehicles and FCEVs

5.6.1 Hydrogen leakage

Some concerns have been expressed publicly about hydrogen leakage rates and how hydrogen could impact global warming as an indirect GHG. It should be noted that this study (Phase 1) did not set out to complete a full lifecycle analysis of GHG emissions for the Hy4Transport concept, nor to measure/estimate hydrogen leakage rates/associated emissions of future wider systems. However, relevant data is beginning to emerge, with one recent study concluding that if hydrogen were to be used and traded in the same way as natural gas is currently – then the associated emissions (from leakage, venting, slippage etc.) would be considerably smaller (around 29 times lower in CO_2eq. across the supply chain from production to pipeline distribution - albeit with a reasonable level of uncertainty) when comparing the two [24]. This is because hydrogen has a significantly smaller GWP and a higher mass energy density, meaning a smaller mass needs to be transferred for the same end-use and any emissions that do occur have a lesser effect. The majority of any hydrogen emissions are expected to occur at the production and liquefaction stages upstream – with downstream emissions in hydrogen transmission, storage and distribution expected to contribute significantly less comparatively. It is reasonable to believe that the purification process would not add any significant losses (consumed in the process) or emissions (directly lost to atmosphere) to the supply chains considered within the reference study. However, it should be further noted that the losses and emissions values used contain a reasonable level of uncertainty. Phase 2 of this project offers the opportunity to take real-world measurements for the losses and emissions relevant to the Hy4Transport concept to feed into a detailed lifecycle assessment (LCA).

5.7 Potential Barriers and Opportunities

The commercial viability of the Hy4Transport concept was evaluated by means of a barrier assessment following the commercial readiness index (CRI) framework published by the IEA. The CRI assessment guidance has been applied to other emerging renewable energy technologies and covers the major route to market considerations. It focusses on three key areas - enablers, financial attractiveness, and capacity to deliver.

Barrier levels were selected from ‘Low, Moderate, High’ (denoted as L, M, H). This is detailed fully in Annex 3, but the ‘high’ factors were identified as:

- **Political Support (Enabler)** - push, pull, and/or enabling policies are required to allow hydrogen in the existing gas grid; current policies favour EVs for smaller vehicles.
- **Risk-Return Profile (Financial)** - the build-out of a large network of grid-connected HRSs to service the projected demand of hydrogen for road transport requires significant capital investment and ongoing operational expenses.

- **Market Opportunities (Financial)** - actual demand will rely on effective policy & market signals in all of production, grid conversion, HRS infrastructure and FCEV deployment.
- **Resource Availability (Capacity)** – the Hy4Transport concept relies on a significant supply of hydrogen. Additional electrical resources could be required if compression requirements are significant - necessitating upgrades to local electricity infrastructure.

6a) Rollout Potential & Scalability

6.1a Overview

This section summarises the rollout of grid-connected HRS sites between 2035-2050, with a closer focus on the contribution of the proposed Hy4Transport purification system to net HRS footprints, and their respective scalability.

6.2a Future Grid-Supplied Refuelling Network

The estimated number, and spread of capacities, of HRSs required to service the predicted hydrogen demand for surface transport is broadly in line with the previous work previously completed as part of HG2V [5]. The indicative locations of the HRSs provided in the HG2V work were largely along the strategic road network (SRN) - 4,300 miles of motorways and major A roads. The SRN carries one third of all traffic, and two-thirds of road freight.

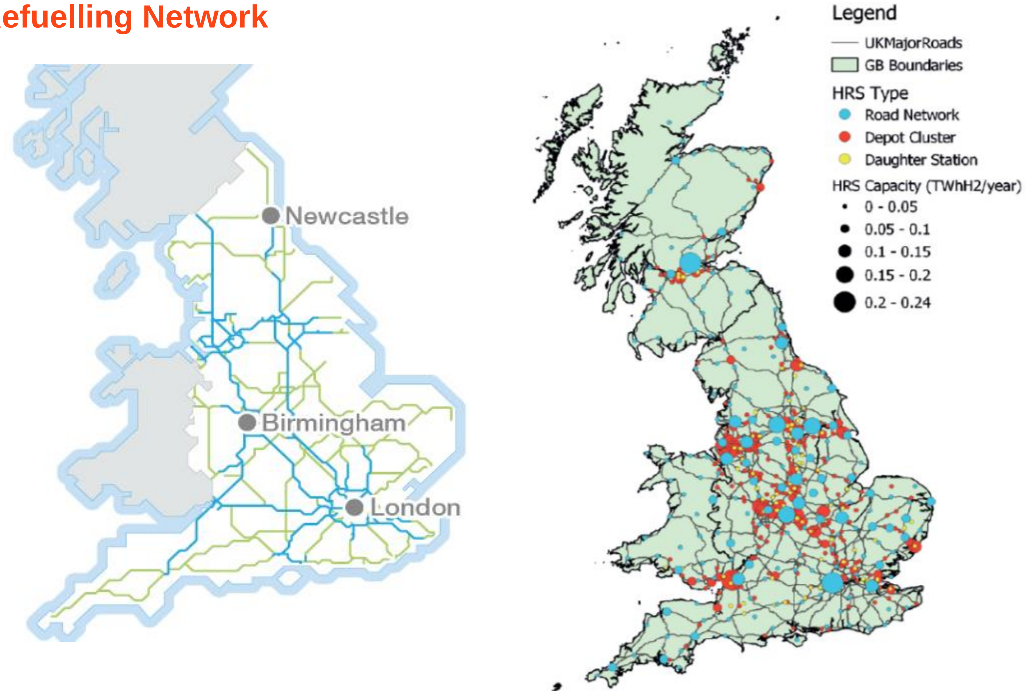


Figure 14 - Indicative HRS Deployment Locations (2050) relative to the existing Strategic Road Network (SRN) [6]

On average, the HRS network presented in this Hy4Transport concept would be the equivalent of one large HRS (≥2 tonnes H_2 demand/day) for every 12.3 miles along the SRN. This rollout can be visualised by the adjacent figures - relating projected future HRS hub locations (from Cadent's GGTP report) to the SRN in England.

In the Hy4Transport scenario, the deployment of surface transport hydrogen vehicles begins in 2035, when it is expected that widescale roll out of this technology is feasible. A split of HRS sizes, based on previous work presented in Cadent's GGTP report, was assumed to represent a network of HRSs ranging from small public forecourts to large industrial hubs [6]. The modelled cumulative deployment of the HRS network from 2035 to 2050 is shown in Figure 15.

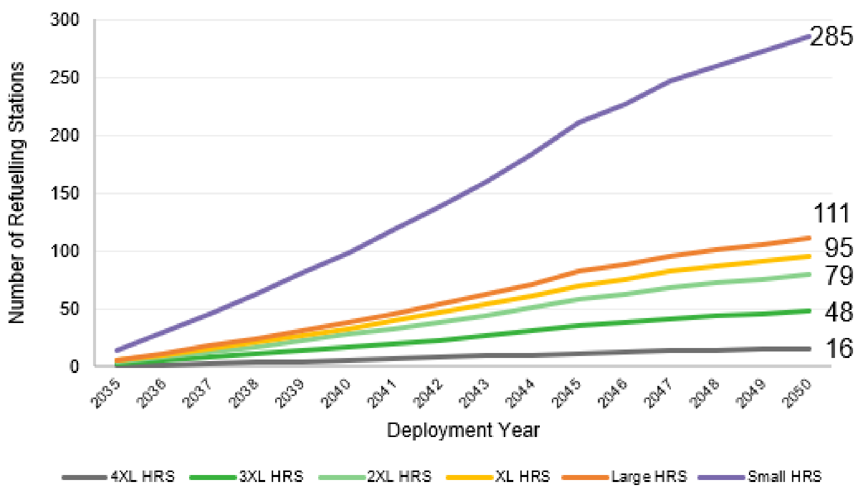


Figure 15 - Deployment of grid-connected HRS stations from 2035-2050 to meet growing road transport demand

The hydrogen refuelling infrastructure particulars were modelled by calculating the number of refuelling stations required to service the annual estimated hydrogen demand across mainland Great Britain. A representative split of HRS sizes, based on the indicative capacities presented in the GGTP report, was assumed in order to achieve a total network capacity which closely aligned with the projected total hydrogen demand for road transport.

6.3a Footprint & Site Applicability

Activated carbon beds appear to provide the most promise for purification on small HRS forecourts due to their high purification throughput per square metre of plant. However, this will need to be proven in the proposed Phase 2 demonstration phase. In addition to this, the proposed life cycle assessment of purification media production could establish the sustainability of its use in a nationwide network (of over 600 HRS sites).

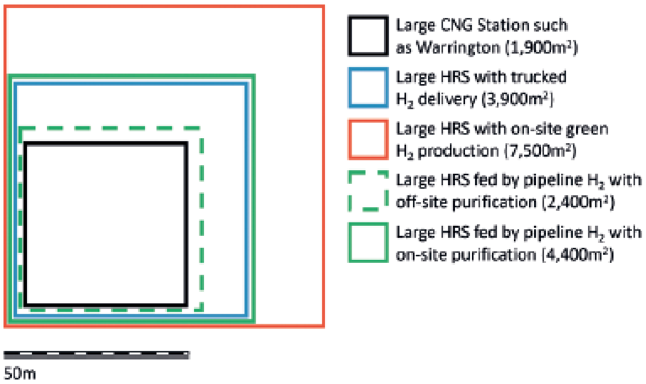


Figure 16 - Footprint comparison of a large CNG and hydrogen (20t/day) station (does not include area for parking, truck turning circles etc. as this is assumed to be constant between station designs) [6]

There is greater confidence in the purification footprints of the traditional PSA and compact PSA processes due to their significant deployments globally, however they have not been used in a grid-connected setting for transport use and do come with a higher cost per kilogram of purified hydrogen. Whereas footprint might be a major concern for the smaller public refuelling stations, it is not expected to be such an issue for depot refuelling sites. Figure 16 shows the footprint comparisons for various refuelling concepts including two options for a networked hydrogen supply, capable of delivering approximately 20 tonnes/day, one with on-site purification (Hy4Transport) and the other off-site purification.

The footprint difference between the two options is approximately 2,000m^2, which is effectively the footprint assumed to be needed to purify 20 tonnes/day of hydrogen on-site. This is roughly the same footprint again as that required for the equipment which is common to both concepts - compression, storage and dispensing. Data from the OEMs as part of the Phase 2 tender process revealed a wide range of footprints required to produce 2 tonnes/day of purified hydrogen, however the maximum was far less than 1,000m^2, with the potential to be significantly less than this, at less than 200m^2.

Figure 16 also shows the footprint savings of hydrogen delivery by network in comparison to onsite electrolysis. Without gas network delivery, the potential for mass HRS deployment would be severely limited due to the large footprint requirements of electrolytic fuelling stations – or by the limitations of road delivery of compressed/liquefied hydrogen (as outlined in Section 5.4). While it is apparent that a relatively large footprint is required for grid-supplied hydrogen with on-site purification – the Hy4Transport project will help to confirm/identify ways of further reducing this.

6.4a Scalability

The base-case Hy4Transport concept of grid-connected refuelling stations and with on-site purification significantly reduces the on-site storage requirement of each site, since reliability is achieved through redundancy of key equipment (e.g. compressors, dispensers) and the inventory of the grid (including storage via line-packing). In the event of failure leading to loss of purification plant capability, the station could be serviced by tube trailer deliveries for a short duration until the failure is remedied. Previous studies (such as HG2V) have assumed on-site storage capacity to be as high as 3 days-worth of capacity, but both the ‘base’ HRS footprint and the ‘purification footprints estimated in the GGTP study (in Figure 16) are expected to be overestimates for the more informed Hy4Transport concept, and on-site storage volume is expected to be reduced. This will be confirmed in the proposed Phase 2 project, once the chosen OEMs are actively engaged and purification performance can be more accurately assessed on-site.

The Xebec PSA unit presented promising figures with respective dimensions (L, W, H) of 1.8x1.9x2.9m for the 200kg/day unit and 2.7x6.1x3.8m for the 2 tonnes/day unit - equating to a ~4.82x increase in footprint area for a 10x increase of throughput capacity. The CPL Activated Carbon unit is also promising, with the proposed unit for the Phase 2 demonstrator capable of a gas throughput of 2000 m^3/hour (equivalent of over 4 tonnes H_2/day) with dimensions of 1.3m diameter by 2.9m in height.

6b) Route to Market

6.1b Overview

This section provides a high level, indicative pathway to achieving purification readiness in the appropriate timeframe proposed up to 2050. While it will realistically be approximately a decade before widescale deployment of this technology is possible (aligned with the potential readiness of a '100%' hydrogen network in the UK in the mid-2030s), it is imperative that momentum is maintained as a significant amount of progress is required to transform this novel solution into an optimised and commercialised reality.

6.2b Location

The availability of hydrogen supply is likely to be strongly linked to location in the early stages of the market. This is due to demand anchors and CO_2 storage infrastructure that are expected to develop in the industrial clusters. There will be electrolytic production outside of these clusters, but this is likely to be of more limited capacity - particularly in the early stages of low carbon hydrogen deployment. Due to the higher supply of hydrogen around clusters, the regions near to these will be the first to experience network conversion, and therefore present the best opportunity for early adopter HRS sites to utilise the gas network and the proposed Hy4Transport purification model. Figure 17 shows some potential locations for CCUS-enabled hydrogen projects based on public announcements. As these are likely to be of a much larger scale than initial electrolytic projects, they provide a good indication of where most early UK hydrogen volume could be, before a nationwide network is developed.

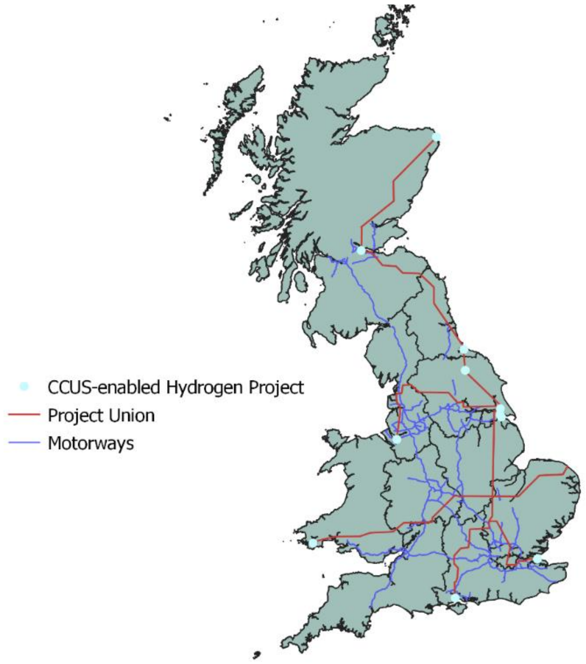


Figure 17 - Locations of Potential Large Scale Hydrogen Production, Motorways & Hydrogen Transmission Lines

Significant work has been undertaken in the UK to develop plans to link the hydrogen production at industrial clusters with a hydrogen transmission network. This project, named 'Project Union', led by National Grid, may present further opportunities for network repurposing in regions that have high heat and transport demand, but are not located near planned hydrogen production. Figure 17 shows an indicative example of where this transmission network repurposing could occur, as well as the motorway network in Great Britain, to show the areas of greatest potential for network-supplied hydrogen for use in FCEVs.

The areas that are most likely to first convert their existing gas grid for hydrogen will also depend on whether there is local large scale storage potential - as gas grid conversion, and therefore switching to hydrogen heating, will require significant storage capacity due to the highly seasonal demand for heat. Studies from the UK CCS Research Centre have indicated regions of potential for salt cavern storage (which is expected to be a leading solution for long duration, large-scale hydrogen storage). This study showed the most suitable onshore regions for salt cavern hydrogen storage in England to be in the South near Bournemouth, North West near Liverpool, and North East between Hull and Middlesbrough.

6.3b Roadmap

For hydrogen to be delivered through the gas network for widespread transport applications, a sequence of steps must be taken to ensure the purification technology is ready for deployment when hydrogen volumes, and the gas network, are ready for this solution. These steps are outlined in the suggested roadmap below (also visualised in Annex 4):

1	**Phase 1 – Feasibility Study:** 2022 This first phase has established the feasibility of Phase 2 - including defining potential contaminants/ allowable levels of contaminants, identifying suitable providers of purification technology and a demonstration site, establishing a costed demonstration plan, quantifying potential socio-economic benefits of widespread deployment, and developing a future roll out plan.
2	**Phase 2 – FOAK Demonstration of Purification Equipment:** 2023-2025 This will provide the first proof of concept that the chosen purification technology systems can accomplish the key objectives of the Hy4Transport project – reaching FCEV grade quality hydrogen and safely disposing of waste in a cost-competitive model when compared to counterfactual modes of delivery. This phase, conducted in an isolated trial, will also allow further identification of any additional technical challenges for integration with refuelling forecourts (such as gas analysis) and provide recommendations to address these.
3	**‘Phase 3’ – Further Purification Trials in Wider HRS Environment:** 2025-2030 This phase intends to test the proven purification systems equipment in real world refuelling operations. Ideally this will involve taking hydrogen from the gas grid, purifying this with the Hy4Transport system, and then supplying FCEVs in a full end-to-end system. This could potentially occur at current commercial refuelling stations – some of which have already been identified. As part of Phase 2, more sites across the UK capable of facilitating a wider trial of these technologies will be identified and reviewed. Such sites would ideally be early adopters of 100% hydrogen pipelines (e.g. located within developing hydrogen clusters, such as the HyNet North West, or East Coast Hydrogen programmes). It is expected that hydrogen will be first distributed through the gas grid from 2025 in one of the proposed hydrogen village trials. A full hydrogen pipeline could be constructed in the wider HyNet programme around 2027. This presents an ambitious opportunity to co-locate the hydrogen trials for both heating and transport. The UK government has also announced plans to run a hydrogen town trial by 2030 - which could present an opportunity for larger scale testing.
4	**‘Phase 4’ – Commercial Deployment of Purification Solution on Live HRS Sites:** 2030 onwards If Phases 2 and 3 are successful, the next step would be the transition to full commercialisation on larger HRS stations. This could occur as early as the early 2030s once regions may begin to be converted to hydrogen.
4^+	**Refinement of Purification Technology:** late 2020s-early 2030s The ‘next generation’ of purification technology will become more refined through commercialisation – and as the nature of contaminants change, likely reducing in extremity over time (as per Section 1.4).

6.4b Business Plan for Future Development

The consortium is confident that the Hy4Transport system concept/purification solution will continue to be developed after the proposed publicly funded pilot programme (Phase 2) ends in February 2025, and that further development will not be dependent on continued public-sector funding, provided that Phase 2 proves to be a successful exercise with promising results.

As outlined in the roadmap in Section 6.3b, following a successful Phase 2 demonstration (in which the purification technologies themselves will be tested & developed in an isolated trial), the consortium intends to then bring the improved and proven purification system into a wider end-to-end boundary, in a ‘Phase 3’ demonstration (likely beginning in 2027/28). This is planned to be situated on an operational hydrogen refuelling station, with real demand from FCEVs, and with hydrogen supplied by a real ‘100%’ hydrogen pipeline. The project team has already engaged with the relevant partners across the supply chain on this – having built positive relationships with hydrogen refuelling station providers/operators, and FCEV vehicle fleet operators. These strategic relationships are growing and will be formalised along with the ever-growing business case for the Hy4Transport concept of grid-supplied high-purity hydrogen. The consortium intends to provide evidence of these relationships via formal letters of support in the upcoming Phase 2 funding bid.

It is likely that Cadent can provide the connection of a full ‘100%’ hydrogen pipeline via integration with the proposed HyNet North-West programme. Construction for HyNet is due to begin from 2025, subject to obtaining planning consent, and pipelines could be operational from 2027. Construction of several hydrogen refuelling stations in the North-West area is also expected in alignment with the HyNet programme, therefore the major ‘components’ required for a future ‘Phase 3’ programme (hydrogen producers, a hydrogen pipeline, developed purification technologies, hydrogen refuelling stations, and FCEV fleets) should be accessible – enabling a natural evolution from Phase 2. The timeline of development for the Hy4Transport concept can be visualised at a high level in Annex 9.

Opportunities to collaborate with other developing hydrogen clusters, such as the East Coast Hydrogen programme, will also be explored. Collaboration with the other similar hydrogen village trials in different areas of the country could also be possible, as these projects will be formed around the framework of local 100% hydrogen networks.

Any public funding opportunities following the completion Phase 2 will be identified and assessed for applicability/eligibility, however if no suitable funding scheme is available, then we could expect the relevant parties across the Hy4Transport supply chain to fund their respective contributions towards Phase 3. At present, we could likely expect a Phase 3 programme to cost between £5m-£15m – however, this must be scoped out further towards the end of Phase 2 (aligned with WP5a), once the purification technologies are more developed and understood.

Dissemination

As the main purpose of Phase 1 was to identify, assess, and select both - suitable hydrogen purification technology suppliers and a suitable host of a demonstration programme, naturally the bulk of project engagement was directed towards relevant parties in these areas.

Public engagement and information sharing has not been the focus during this phase, due to the sensitive nature of supplier IP and site security, and NDAs being established with the assessed parties. However, the Hy4Transport group plans to greatly increase public engagement going forwards throughout Phase 2 once more relevant updates can be shared. As an example of this intent - in July the ‘Hy4Transport.co.uk’ URL domain was purchased by Cadent, and plans have been made to draft this website in parallel with the Phase 2 bid – to act as an online hub for shared learning if the project progresses. Branding workshops have also been held with respective media and communications specialists among the consortia.

If Phase 2 funding is secured, resources will be devoted towards the development of this hub. All stakeholder engagement (anonymised when appropriate) conducted in Phase 1 is summarised in Annex 5.

Conclusions & Recommendations

The feasibility study undertaken between January and September 2022 by the Hy4Transport consortium has captured that a technology demonstration will be a highly valuable exercise for the broader energy transition.

The study built upon previously conducted work in the industry, namely the HG2V study (NIA funded) – which identified that future hydrogen refuelling infrastructure for the decarbonised UK transport sector could be heavily supported by new & repurposed hydrogen pipelines, if purification is addressed.

Through Phase 1 Cadent, with the support of the other Hy4Transport consortium members, have been able to progress understanding of the challenge and lay the groundwork to deliver a physical demonstration. All deliverables outlined in the Project Overview were successfully completed to enable us, BEIS, the wider industry, and broader civil society to have a high level of confidence that a demonstration of purification technologies can successfully be delivered.

The key lessons from Phase 1 include:

- Various contaminants currently exist in the UK natural gas network, and many are likely to remain in the future '100%' hydrogen grid. However, several other factors, including the ongoing replacement of metallic mains with plastic pipes, will influence the long-term purification requirements. Despite this, some form of on-site purification is highly likely to always be necessary for HRS sites to be connected to the gas-grid.
- Numerous purification technologies could potentially provide a viable solution to overcome this purification challenge. The Hy4Transport consortium concluded that a compact PSA unit, and activated carbon bed vessel, (which also provide a potential option to be integrated), currently present the highest chances of success - whilst remaining mindful of the limitations and needs of HRS forecourt environments.
- Several suitable UK locations to host a future demonstration of the chosen technologies exist. The site that was chosen can provide a reliable and dedicated source of hydrogen and enables the opportunity to reuse some of the output hydrogen on-site via the testing of downstream appliances.
- A full 2-year physical demonstration programme (testing the proposed systems against various blends of contaminants) could be successfully delivered within the proposed Phase 2 budget limit of £6m, from February 2023-February 2025. The main demonstration could also be supplemented by various desk-based studies to enable further development of the solution and provide a platform for wider industry engagement and public dissemination activities.
- Socioeconomic models, tailored towards the chosen purification systems, found that grid-supplied hydrogen could enable the cheapest price-at-the-pump for most UK HRS sites (at £6.89-£5.30/kg by 2050). Over 600 UK HRS sites could be grid-supplied by 2050, supplying over 35TWh of annual (maximum) demand for road-transport by 2050. It is estimated that 27,700 cumulative UK jobs could be created with £9.3bn of cumulative GVA, and 160M_tCO_2e being prevented from 2035-2050 - the equivalent of taking nearly 6 million cars off the road.
- The ongoing rapid development of UK hydrogen supply and infrastructure provides a strong platform for further rollout of purification systems following the closure of the Phase 2 trial in 2025. The natural next step would be the completion of a wider trial in a HRS forecourt environment before 2030. This aligns well with the government's UK hydrogen strategy and proposed 'hydrogen cluster' sequencing.

Recommendations

The proposed Phase 2 demonstration could provide opportunities for innovation and discovery in this space which could improve the chosen technologies and drive down costs. Value has already been found in this regard through Phase 1, as interactions by the Hy4Transport project team with OEMs, who are already experienced in gas purification, has identified opportunities to tailor their systems to better suit this specific application.

The development of demonstration projects based on hydrogen delivery through the existing gas network has enabled the likely commencement of physical demonstrations before 2025 (e.g., the HyNet North-West project).

Timely demonstration of the Hy4Transport concept is therefore strongly recommended to fully utilise these developments of network-supplied hydrogen. The critical path for technology development, and the closing window for deployment, in order to meet the UK's increasingly near-term climate targets, necessitates taking action now.

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Assumptions & Notes

The bulk of assumptions made in Phase 1 with any notable influence on outputs naturally relate to the development of the contaminant standard from literature (Section 1.3), the socioeconomic analysis (Section 5), and assessment of rollout potential (Section 6a). The major assumptions are shared in this section for transparency and credibility purposes – however not all are included due to document size constraints.

Contaminant Standard

- Formaldehyde may originate from the feedstock and not from the actual repurposed network.
- Formic acid may originate from the feedstock and any source from the actual repurposed network may be considered negligible based on the available data.
- There is currently no evidence of noticeable fraction of halogenated compounds in a repurposed gas network.
- It was assumed that total heavy hydrocarbons in a repurposed network originate from the previous use. Hence a proposal for the hydrocarbon's representation consists of 66% methane, 20% light hydrocarbons (C_2-C_6) and 14% heavy hydrocarbons (C_7-C_{14}). Heavy hydrocarbons on a methane basis are set at 1400 µmol/mol - which is equivalent to C_7 hydrocarbons at 200 µmol/mol.

FES 2021 – System Transformation Scenario

The 2021 edition of National Grid's Future Energy Scenarios (FES) document and Cadent's Green Gas Transport Pathway report were used as the basis for developing the demand for hydrogen for transport for this Hy4Transport analysis. As these reports focus on Great Britain (GB) the Hy4Transport Scenario was also based on mainland GB. While it is difficult to estimate the deployment that could occur as a result of hydrogen being available from the gas network, the System Transformation (ST) scenario from National Grid is the best aligned with this eventuality, given the assumption within the ST scenario that the gas network is repurposed for hydrogen and there is much higher uptake of hydrogen vehicles than in the other FES scenarios.

In the process of developing this analysis another iteration of National Grid's FES (2022) was published, although due to time constraints the analysis has not been updated with these figures. Updating the analysis would have resulted in a small change in results as the main update to vehicle deployment between FES Scenarios is seen in HGVs (which are based on Cadent's Green Gas Transport Pathway report in the Hy4Transport Scenario).

Socioeconomic Analysis

- This analysis assumes that any HRS deployment that occurs after 2035 is grid connected and therefore additional FCEVs rely on this infrastructure. Any HRS deployment that occurs before 2035 is assumed to not be connected to a repurposed gas grid. This is plausible given the lower cost of grid connected hydrogen distribution and the likely timeframes of grid connected HRSs.
- The transportation distance was set at 150 km (one way) for the no-grid options, representative of large production sites located near to the coast to take advantage of low-cost renewable energy provided by offshore wind.
- Co-location of electrolysers at HRSs was not considered to be feasible due to the significant footprint requirement of the electrolyser and balance of plant equipment. Furthermore, economies of scale favour centralised production of hydrogen, especially relevant given the contribution to the price at the pump that production makes.
- The transportation distance for hub and spoke options was set at 50km (one way). This reflects the shorter travel distance between a repurposed gas transmission network and the

HRS. The relative reduction in transportation distance is in line with detailed geo-spatial analysis conducted for a theoretical hub and spoke network in Germany.

- In the 'Hub and Spoke model, all hydrogen is produced at remote production sites and delivered to a 'backbone' of Purification Hubs by the gas transmission pipelines. Hydrogen is purified at the hubs where it is both dispensed onsite and loaded on to trucks for delivery to 'spoke' HRSs by road - either as gas or liquid as in the 'no grid' scenario.
- The no-grid option uses a swap-and-go model for tube trailer deliveries. Trucks make daily deliveries of filled trailers to each HRS which are left on-site, providing the on-site storage. This avoids the requirement for offloading the trailer's contents into an on-site storage vessel, thus reducing handling time at the HRS; however, the footprint required by the trailers is greater than the equivalent storage vessel & increases total number of trailers required.
- Many previous studies assume 1,000 kg tube trailers for delivery of compressed hydrogen. However, it was noted that these trailers are not expected to be suitable for UK roads due to restrictions and practicalities related to size & weight. The consortia concluded 500kg was the largest possible compressed gas trailer capacity for UK-road use.
- Similarly, numerous studies assume 4,300kg as the trailer capacity for liquified hydrogen. However, this is only applicable to the North American market; in Europe the technical standard is 3,300 kg (HySTOC). This value was used in this study since the UK more closely matches Europe for road characteristics and regulations.
- For the liquid hydrogen delivery modes, a liquefaction plant is required at/near each production site (or hub in the hub and spoke model) to facilitate conversion & loading onto tankers for onward delivery to HRSs by road.
- It was assumed that hydrogen is produced at centralised facilities and connected to large scale storage (i.e., salt caverns). As such, a small cost was assumed for purification of hydrogen being taken from storage and liquefied for distribution to the network of HRSs. Fewer trucks and trailers would be required than the compressed gas tube trailer model due to the significantly larger inventory that can delivered within the same trailer volume. However, the capital cost and associated energy costs for liquefaction and regassification more than offset this saving.

Table 8 – Counterfactual Cost Assessment Inputs & Assumptions Log (for calculations)

Item	Value	Notes
Trailer Capacity (CH_2)	500 kg	Maximum trailer capacity for UK roads (agreed by consortium)
Trailer Capacity (LH_2)	3,300 kg	Maximum trailer capacity for EU (HySTOC)
Average driving speed	50 km/hr	Assumed
CH_2 trailer swap time	1.5 hours	
LH_2 tanker offload time	3 hours	
Hours available per day for trailer swap	8 (min.) 24 (max.)	Modelled two scenarios to reflect two modes of operation: 1- Restricted access, 2- Round-the-clock access
CapEx – truck	£120,000	
Depreciation period	8 years	
O&M	3% of CapEx	
CapEx – trailer (CH_2)	£400,000	
CapEx – trailer (LH_2)	£850,000	
Depreciation period	10 years	

Hydrogen Fuel consumption	6 kg/100 km	As used in the Price Point assessment
Hydrogen price	£6.90/kg	As calculated in the Price Point assessment
Driver salary	£30,000/annum	
CapEx - Liquefaction	Calculated	Average value based on CapEx formula from four sources: HySTOC [25], IEA [26], Reuss et al [27]. and another confidential source.
Plant lifetime	20 years	
O&M	3% (min.), 4% (max.)	Taken from the four sources listed for CapEx
Liquefaction - Electricity requirement	6.1 kWh/kg (min.) 13.4 kWh/kg (max.)	Taken from the four sources listed for CapEx

Uncertainties

Throughout the Socioeconomic Assessment, a number of assumptions were made to address gaps in knowledge or to facilitate calculations at a suitable level for this study. Inevitably, some assumptions may have a significant effect on the results, and, by extension, the conclusions drawn from them. The following assumptions are considered to be potentially significant to the assessment and should be investigated further, either in Phase 2 where possible, or in a future 'Phase 3' during the demonstration of the purification equipment in a forecourt-like setting:

- The previous HG2V work concluded that purification cost, and to a lesser extent footprint, could be a significant barrier to delivering cost-competitive purified hydrogen to a network of grid-connected HRSs. The data provided by OEMs as part of the tender process for Phase 2 of the Hy4Transport project indicated that, with the benefit of cost-down achieved through multiple installed capacity doublings, costs associated with purification could range from £0.06-£0.19/kg by 2050. The Hy4Transport project should engage further with the OEMs to gain more confidence in the likely range for purification cost projections and the associated footprints for the equipment.
- A detailed assessment of the purification media life cycle should be conducted to understand the limitations on waste handling (regeneration) facilities, identify potential uses for the reactivated purification media, and establish the sustainability of purification media production required to service a 2050 hydrogen demand of ~3,000 t/day.
- The siting of the 600+ HRSs that form the 2050 network will necessitate a wide range of lengths of new/upgraded pipeline connections to the nearest accessible point of the repurposed gas grid. The relative location of the HRSs to the LP/MP/IP/HP sections of the LTS/distribution network will also necessitate varying levels of pressure reduction and/or compression to be able to purify the grid sourced hydrogen stream and prepare the purified hydrogen for high-pressure dispensing. The Hy4Transport concept has assumed minimum on-site storage, which brings with it a benefit in terms of reduced CapEx/OpEx relative to previous studies. However, this benefit could be partially or fully offset, or even exceeded by the additional CapEx/OpEx required for new pipelines and compression equipment. A detailed spatial analysis of gas network pipelines relative to HGV depots and major freight routes should be conducted to generate an improved estimate of delivered hydrogen costs.
- A detailed life cycle analysis of the greenhouse gas emissions & primary energy demands for a network of Hy4Transport HRSs is proposed to be conducted in Phase 2. This could cover all relevant scope 1, 2 and 3 emissions and be made against relevant counterfactual delivery options, including tube trailer delivery with FCEV trucks.

Annexes

Annex 1 - Summary of Technology Selection Criteria

Assessment Area	Unit Requirements/Desired Capability
Skills & Expertise	Strong previous experience with gas/hydrogen purification processes. (Ideally familiar with the removal of the contaminants in question and reaching FCEV-grade purity hydrogen).
Project Delivery & Management	Established organisational structure, management plans, QMS, and clear evidenced approach to deliver the scope of work aligned with the proposed 2-year demonstration (Phase 2).
Technical Approach	Presentation of a purification technology capable of reaching the required purity of hydrogen (ISO 14687, Grade D) from the contaminated input feed defined by the Hy4Transport 'contaminant standard. Ideally a technology with low power/utility requirements, non-intensive operating conditions, and a high hydrogen recovery rate.
Functional Specifications	Clear outline of unit dimensions/footprint requirements for both demo scale (~200kg output H_2/day) and future commercial scale (~2000 kg/day). Outline of maintenance requirements, labour/training required, unit lifetime, safety measures, and waste/by-product collection and disposal methods. Ideally a compact and highly scalable system, remotely operated, with long design lifetimes and a simple, environmentally conscious, and cost-effective method of contaminant collection & disposal. A system that can realistically integrate with future HRS forecourts.
Commercialisation & Costs	High confidence in all CapEx and OpEx figures (including O&M costs), and in the proposed/existing supply chain. Ideally units are low in capital purchase cost, also with low operating costs due to minimal energy/utility consumption and labour/maintenance requirements, small footprints, and simple/non-intensive means of waste disposal.

Annex 2 - Summary of Site Selection Criteria

Assessment Area	Site Requirements/Desired Characteristics
Hydrogen Supply/Storage	Reliable supply of ≥200 kg/day of >98% purity hydrogen, ideally with some hydrogen storage capacity on site for some flexibility and security of supply. (Ideally hydrogen source is 'low carbon').
Availability of Infrastructure (utilities/ contaminant supply/ equipment connections)	Over 25kW of electrical connection available to the Hy4Transport system, including any required air and water utilities. Clear outline of how the Hy4Transport system would be integrated with existing infrastructure (e.g., BFD with connections, pressure management, flowrates etc). (Ideal – but not essential – if site is experienced with the management and handling of relevant contaminants for testing, with an established supply).
Output Management (on-site demand for purified hydrogen, analysis equipment, waste disposal)	Description of any downstream appliances/users on-site or nearby that could utilise the range of potential hydrogen outputs from the system (possible 98-99.97% purity). Outline of how any system waste/contaminants would be handled and disposed of on-site. Highlight any relevant pre-existing gas analysis equipment or facilities on-site.
Location (space available, accessibility, security, permits)	Description of immediate local area and transport links – outlining accessibility for equipment deliveries and maintenance. Site map highlighting land available (≥7.5x7.5m). Details of existing/required permits, and security plans in place. (Ideal – but not essential – if site is located in mainland GB for consortium access).
Costs (price/kg of hydrogen supply, land & facility rental)	Clear outline of all costs that would be incurred for the Phase 2 demonstrator (hydrogen price, land rental, utilities, ancillary equipment, installations, facility usage, security fees, waste disposal, etc). Effort must be shown to drive costs down as low as possible – to provide best value for money for both the project and funders.

Annex 3 - Detailed Hierarchy of Potential Market Barriers & Opportunities

A hierarchy was applied to identify whether each indicator is specific to the Hy4Transport concept, the hydrogen purification process, the purification technology itself or the OEM/supplier. Please note the barrier levels shown below are somewhat subjective and reflect the project team's current understanding.

ENABLERS

Indicator	Hierarchy	Rat.	Notes
Infrastructure	Hy4 Transport	M	Large sections of the distribution grid are already hydrogen ready; with significant on-going work to prove the suitability of the transmission grid & plans for the initial hydrogen backbone to be ready by the early 2030's.
Planning & Permitting			Planning & permitting regime already in place for HRSs - not likely to be impacted by additional purification equipment. If hydrogen storage volume exceeds 2 tonnes (unlikely for a HRS) then consent is needed from the Hazardous Substances Authority through COMAH. GS(M)R requires amendment to allow hydrogen to be distributed in the existing gas grid.
Stakeholder Acceptance			Hydrogen is largely accepted as a key component of decarbonisation. Industry has not yet made a clear choice/signal as to which propulsion technology(s) will dominate in future for large vehicles. TCO parity is only one aspect of selection criteria - user experience is also critical.
Political Support		H	Push, pull, and/or enabling policies are required to allow hydrogen in the existing gas grid; current policies favour EVs for smaller vehicles.

FINANCIAL ATTRACTIVENESS

Indicator	Hierarchy	Rat.	Notes
Availability of funding	Hy4 Transport	M	Funding for many Net Zero technologies will initially rely on government support schemes to help achieve cost reductions quickly.
Society's willingness to pay			TCO analysis shows cost parity is expected for HGVs and buses. Evidence of bus & HGV fleets willing to pay a premium for decarbonised fuel. TCO parity is only one aspect of selection criteria, user experience is also critical.
Risk-return profile		H	Build-out of a large network of grid-connected HRSs to service the projected demand of hydrogen for road transport requires significant capital investment and ongoing operational expenses. Fuel for transport is a commodity which is likely to have small margins.
Costs	OEM/ Supplier	M	Wide range of costs for purification technologies, hydrogen production methods and other components. Cost reduction potential identified for major cost contributors.
Revenue			Hydrogen demand for transport projected to increase out to 2050, with delivered hydrogen price estimate below that required for TCO parity for some vehicle types, enabling a suitable profit to be achieved. Additional revenue streams could be achieved via grid flexibility services - if significant on-site storage is utilised.
Market opportunities	Hy4 Transport	H	Actual demand will rely on effective policy & market signals in all of production, grid conversion, HRS infrastructure and FCEV deployment.

CAPACITY TO DELIVER

Indicator	Hierarchy	Rat.	Notes
Resource availability	Hy4 Transport	H	Hy4Transport relies on a significant supply of hydrogen. Additional electrical resources could be required if compression requirements are significant - necessitating upgrades to local electricity infrastructure.
Technical performance	Technology	M	PSA technologies proven for hydrogen, but not connected to repurposed grid; other technologies require demonstration (active carbon bed, electrochemical separation).
Supply chain		L	Established supply chains, minimum geopolitical risk, climate physical risk; minimal rare earth minerals in use.
Skills	Hy4 Transport	M	Skills shortage expected across full supply chain, in common with all 'net zero' technologies.
Company maturity	OEM/ Supplier	L	Diversity of OEMs/suppliers for technology options creates resilience; several large multinational companies with purification experience.

Annex 4 - Future Rollout Timeline

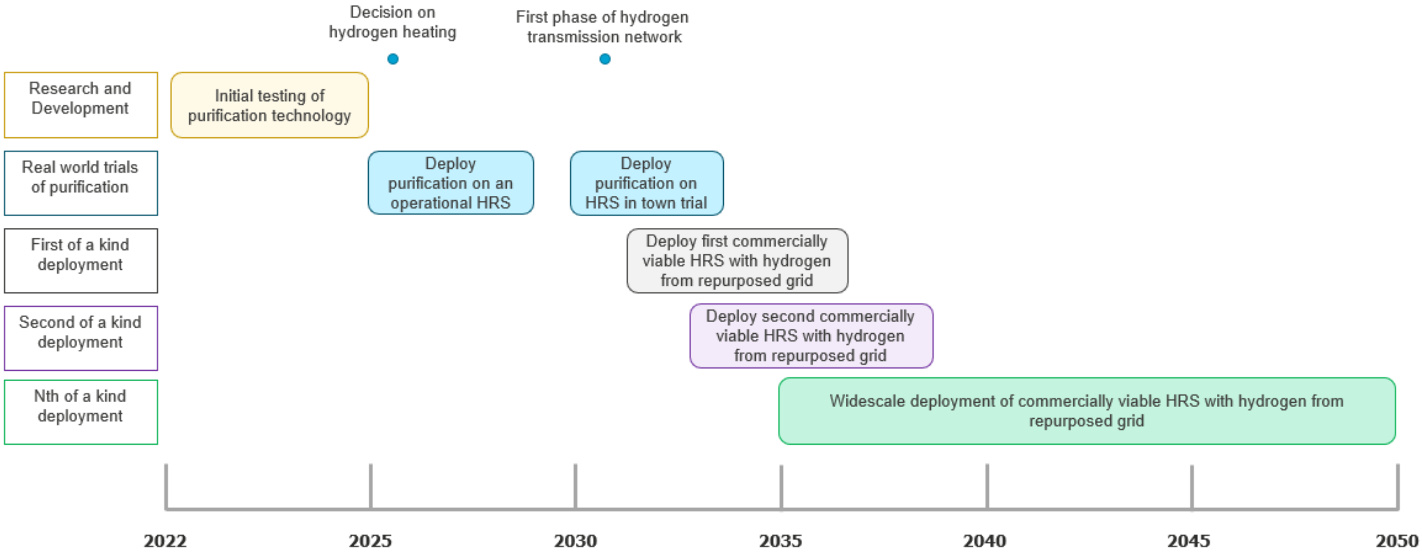

Figure 18 - Potential Timeline of Hydrogen Delivery through a Repurposed Gas Network for Transport

Annex 5 - Summary of Phase 1 Dissemination Activities Undertaken

Stakeholder Type	Summary of Engagement
Purification Technology Suppliers/OEMs	Over 10 suppliers of potential purification solutions were engaged with, including globally recognised industry leaders. This resulted in two partners being selected for future progression (Xebec and CPL). The consortium will continue to monitor disruptive and emerging technologies providing innovative solutions going forward.
Hydrogen Testing/ Demonstration Sites	Four potential demonstration site hosts across England were engaged with, and considered as potential hosts for the Phase 2 demonstration. All four sites were visited in person by representatives across the Hy4Transport consortium. While Kiwa's site in Cheltenham was deemed the preferred choice for Phase 2, positive relationships have been maintained with all parties, and some have been identified as ideal hosts for a potential 'Phase 3' extension beyond 2025.
UK GDNs & NTS Operators	The project team has remained engaged with the UK NTS operator - National Grid - and NGN to share the Hy4Transport vision & identify opportunities for collaboration. Cadent are supporting two relevant SIF-funded projects.
HRS Operators (Current/ Future)	Cadent have engaged with a large-scale future HRS operator, to gauge their needs from a 'customer' perspective, as useful input for the project. This engagement will increase going forward as the project nears to wider system use.
Green Clusters/ Industry Bodies	The Cadent PM presented on the project vision to various cross-industry stakeholders in the Pipeline Industries Guild. Cadent Regional Development Managers have also engaged with a statutory sub-national transport body.
Industry Events	The Cadent PM attended the 'Hydrogen Transport Innovation Conference' (by Foresight) in June, speaking on the project in a panel session to a broad range of stakeholders across the hydrogen supply chain.
UK Universities	Two UK universities, aligned with potential demonstration sites, were engaged with to share the Hy4Transport vision and identify collaborative opportunities.