Operator's guide to fuel cell bus deployment

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ZERO EMISSION

JIVEs / MEHRLIN projects

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Clean Hydrogen Partnership
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Contents

INTRODUCTION 1

CONTEXT 1
DOCUMENT PURPOSE, SCOPE, AND TARGET AUDIENCE 3
DOCUMENT STRUCTURE 3

PRE-DELIVERY PHASE 5

OVERVIEW 5
MAINTENANCE PLANS 8
PROCUREMENT 9
DEPOT PREPARATION 10
IMPLEMENTATION 11

VEHICLE DELIVERY, RUN-IN, AND OPERATION 15

VEHICLE DELIVERY 15
RUN-IN PERIOD AND BUS OPERATION 15

REFERENCES AND FURTHER INFORMATION 18

APPENDIX – INTRODUCTION TO HYDROGEN REFUELLING INFRASTRUCTURE 19

OVERVIEW 19
HYDROGEN STORAGE 20
HYDROGEN TRANSPORT 21
CASE STUDIES 27

Introduction

Context

The Joint Initiative for Hydrogen Vehicles across Europe programme (JIVE and JIVE 2 projects) introduced new fleets of fuel cell buses (FCBs) and associated hydrogen refuelling infrastructure in cities across Europe. The programme is supporting the deployment and operation of 287 new vehicles in 15 different European cities / regions. The vehicles are being used in regular operation in place of diesel buses.

The overall objectives of the JIVE projects are to:

- Stimulate the market for fuel cell buses in Europe by creating demand for hundreds of vehicles.
- Lower the prices of fuel cell buses using joint procurement and economies of scale.
- Deploy and operate large fleets of fuel cell buses and associated hydrogen refuelling infrastructure, and demonstrate the technology's ability to be a reliable, like-for-like replacement for diesel buses.
- Demonstrate routes to achieve low-cost renewable hydrogen.
- Pave the way for the commercialisation of fuel cell buses in Europe in the 2020s by sharing information and stimulating further uptake.

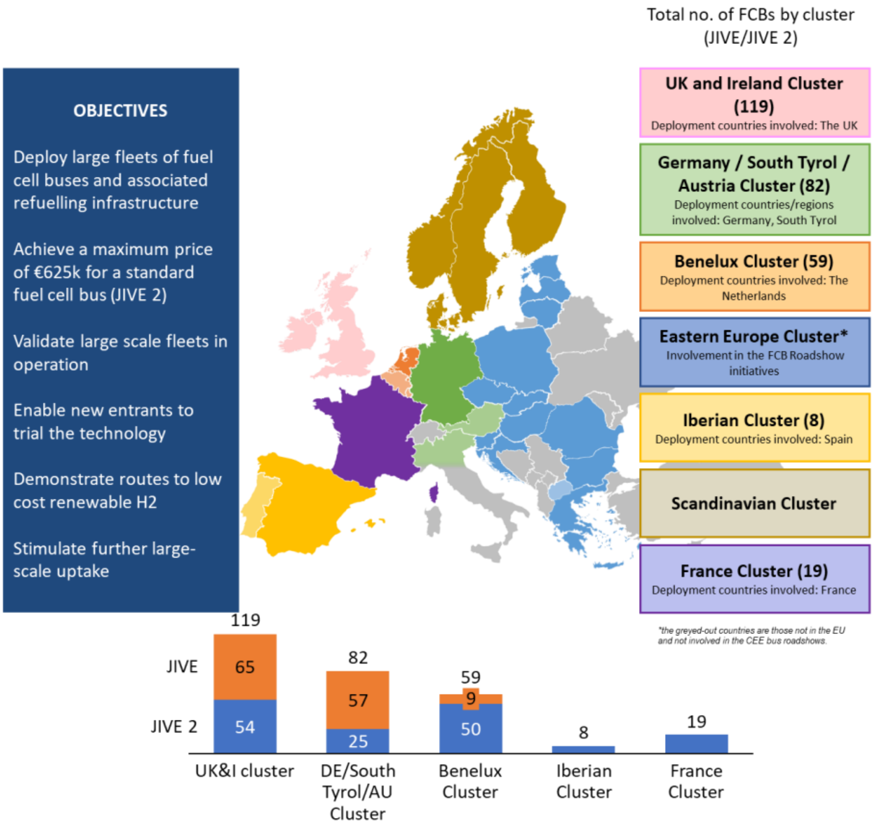


Figure 1: Overview of the JIVE and JIVE 2 projects

The JIVE projects include cities with a range of experiences relating to fuel cell buses, from those that have been operating fleets of such vehicles for many years (e.g., Aberdeen, Bolzano, Cologne, London), to cities / regions with limited prior knowledge of hydrogen buses. JIVE followed and builds on the experience of previous European funded fuel cell bus demonstration projects such as CHIC, HyTransit, and HighV.Lo.City. A key difference is that while the earlier projects typically involved demonstrating small numbers of vehicles (tens in total in the case of CHIC), JIVE is based on deploying larger fleets (many tens in some locations) in a coordinated way to create demand for hundreds of fuel cell buses.

When the JIVE programme was conceived, very few bus manufacturers (OEMs) were offering hydrogen-fuelled vehicles and production costs (hence prices) were high due to the low volumes of vehicle manufacture. By creating demands for hundreds of fuel cell buses, JIVE sought to attract additional OEMs to the market while also creating a scale that unlocked price reductions relative to previous generations. The project has succeeded in these objectives and as of October 2023, a total of 252 fuel cell buses have been delivered to customers under the JIVE programmes.

Another aim of the JIVE initiatives is to stimulate further demand for fuel cell buses as the programme was designed as the stepping stone between technology demonstration and commercialisation of hydrogen buses. Cities from within the programme and beyond are now planning further roll-out of fuel cell buses. The organisations involved in JIVE (and previous demonstration projects) have gained a significant amount of experience relating to planning and delivering hydrogen transport initiatives and by sharing key lessons via documents such as this the partners are seeking to support the successful implementation of hydrogen in public transport fleets across Europe and beyond.

Document purpose, scope, and target audience

This document is a guide for cities / public transport operators seeking to introduce fleets of hydrogen fuel cell buses. The main aim is to summarise the key tasks to be undertaken to deploy and operate new fleets of fuel cell buses and to provide references to further sources of useful information. While the main target audience is cities / operators with limited prior experience of the technology, the information provided is likely to be a useful reference source for any organisation planning or delivering a fuel cell bus project.

The focus of this guide is on the vehicles; however, additional information regarding the hydrogen refuelling infrastructure required to operate a fleet of fuel cell buses and links to further sources of information on this topic are provided in the “Further information” and the document’s appendix.

For an extensive consideration of the JIVE and JIVE 2 experiences of FCB deployment, please refer to the Best Practice Report to be published in 2024. This report contains lessons learned and solutions found by active JIVE and JIVE 2 deployment sites during the period from early 2018 – early 2024. While very extensive, the report has been disaggregated in the Knowledge Base Section under ‘Start to Implement’ of the Fuel Cell Electric Bus website (https://fuelcellbuses.eu/). This allows users to dip into the information (largely in tabular form) relevant to their needs at any time. It will also provide extensive supplementary information to that provided in this document.

Document structure

The following sections provide lists of tasks and insights from hydrogen fuel cell bus demonstration projects structured in chronological order from the preparatory stages, through to vehicle delivery, run-in, and full operation.

A selection of fuel cell buses demonstrated in previous projects by city and bus supplier

London (Wrightbus) ***Cologne (Van Hool)*** ***Hamburg (EvoBus / Daimler)***

Pau (Van Hool)

Aberdeen (Wrightbus)

Barcelona (Caetano)

Groningen (Van Hool)

South Holland (Solaris)

Toulouse (Safra)

A selection of fuel cell buses demonstrated in the JIVE and JIVE 2 projects by city and bus supplier.

Pre-delivery phase

Overview

Various tasks must be undertaken in the initial phase of any project seeking to deploy and operate fuel cell buses. These can be classified into the follow areas:

1. **Budgeting and business case development** – one of the earliest tasks is to develop a comprehensive budget for the project (including cash flows over time), funding strategy, and overall business case. As of 2023, there remains a premium for fuel cell buses relative to diesel vehicles, which means that most projects rely on some form of public subsidy. Securing the necessary funding is clearly a high-priority early action in project development. However, it is worth noting that prices have significantly decreased since the first funded FCB projects, due to the success of the increasing scale of the JIVE deployments and that minimum costs are accessible for vehicles orders of more than 20-30 buses (price varies depending on specifications).

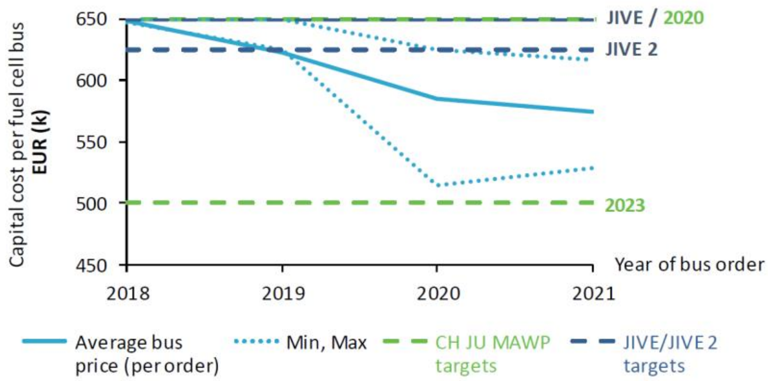


Figure 2: Actual Bus CAPEX - JIVE & JIVE 2

2. **Infrastructure planning** – the bus fleet to be deployed and the hydrogen refuelling station (HRS) have to be planned and realised together in parallel; therefore, the business case must also account for infrastructure and hydrogen supplies. This includes consideration of the funding strategy, procurement strategy, preferred technical solution, etc. Note that the optimal infrastructure solution is likely to depend on a range of factors such as local context (e.g., proximity to existing sources of hydrogen), anticipated demand for hydrogen (affected by fleet size and expected fuel demand per vehicle), available space at the depot, etc.
3. **Procurement** – develop a procurement strategy, carry out early market engagement with potential suppliers, prepare tender documents (technical specifications, draft contracts, etc.), run procurement exercises (noting the risk that if a tender procedure results in no viable offers the exercise may need to be repeated), etc. This needs to cover the vehicles and refuelling infrastructure (hydrogen supplies) and attention must be paid to ensure compatibility of the vehicles with the refuelling infrastructure (including geometry of nozzle / tank connector, refuelling protocol, fill speed, etc.). While most of the projects within the JIVE programme procured buses and hydrogen supplies separately, some suppliers now offer all-inclusive packages in which customers pay per kilometre for zero emission mobility (e.g., Messer's one-stop-shop solution in partnership with Caetano bus and the Toyota Group[1]). Note that the back-to-back performance of the station affects the amount of on-site storage needed and required compression capabilities. It is recommended that engineers from the bus operator visit the bus

[1] See Messer Group Hydrogen One-Stop-Shop.

supplier's factory during the build process to check on progress and to ensure that the vehicles are being built to the agreed specification.

4. **Maintenance** – as part of the supplier engagement / procurement activity thought should be given to the maintenance strategy for the buses and refuelling infrastructure. This includes ensuring access to spare parts and availability of trained technicians / training of the bus operators' own technicians / engineers to work on the buses / HRS.
5. **Depot preparation** – this includes a range of activities including physical works at the depot in readiness for the HRS installation (assuming depot-based refuelling is the preferred option), risk assessments, installing hydrogen sensors, training, employee engagement, and developing emergency procedures.

Further information on the first three stages outlined above is available from existing publications. For example, the FCH JU's (now Clean Hydrogen Partnership) "*Strategies for joint procurement of fuel cell buses*" study (2018) contains examples of project structures and funding strategies, in addition to case studies on procurement of fuel cell buses.[2] A dedicated report on lessons learnt from joint procurement of fuel cell buses in JIVE has also been produced (deliverable 1.1). Several reports from the CHIC project are also relevant, e.g., "*Recommendations for hydrogen infrastructure in subsequent projects*" (2016) and "*CHIC final public report*" (2017).[3] The FCH JU-funded NewBusFuel study is also a valuable resource for any organisation planning a fuel cell bus project. This study, which concluded in 2017, produced two main public deliverables: a summary report covering the findings of the study into the feasibility and costs of large-scale hydrogen refuelling stations for bus fleets, and a guidance document on large-scale hydrogen bus refuelling. The guidance document includes a proposed framework for planning the installation of hydrogen refuelling infrastructure for bus fleets (see following page). As indicated earlier (in section 'Purpose and Scope'), the Best Practice Report to be published in the first half of 2024 highlights challenges faced and solutions found by JIVE and JIVE 2 deployment sites over the 7 years of the projects.

Given the amount of existing guidance and the status of most local projects within the JIVE programme, the following sub-sections focus on points 4 and 5 from the list above, drawing on experience from JIVE and previous fuel cell bus demonstration projects.

[2] See Strategies For Joint Procurement Of Fuel Cell Electric Buses
[3] See Publications from CHIC Project.

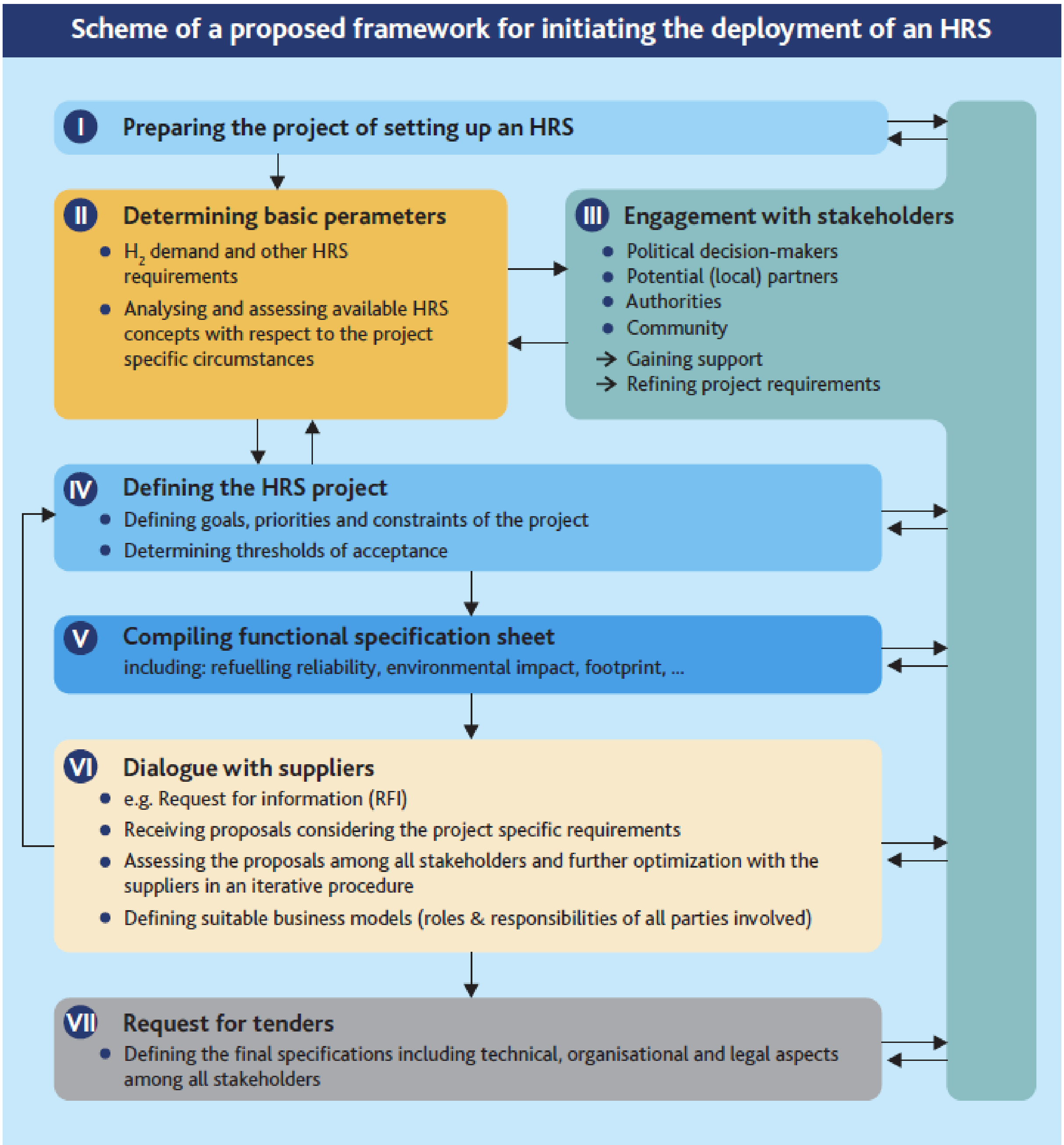


Figure 3: Framework for initiating the deployment of a hydrogen refuelling station (source: NewBusFuel)*

*Regarding specifications, these should be outcome based.

Maintenance plans

Buses[4]

Maintenance responsibilities should be clarified as part of the procurement process. The requirements in terms of maintenance support needed from the supplier(s) will vary by customer. For example, operators with experience with the technology might decide to take on much of the maintenance of the vehicles themselves and only require a parts support package from the bus supplier. At the other end of the spectrum, an operator new to fuel cell buses might prefer to take a more *hands-off* approach to maintenance and seek an all-inclusive support package that involves the bus OEM (or their suppliers) providing personnel to carry out most of the maintenance work on the vehicles. Hybrid approaches are also possible in which the bus operator sub-contracts much of the specialist maintenance of the vehicles for an initial period but then retrains staff to be able to take on more of the maintenance responsibilities as the vehicles age.

Currently, most FCB operators have their own maintenance technicians trained by the bus supplier, who are supported on-site by the supplier's technicians for a certain period. After this initial period, many suppliers provide "flying doctor" support. Manufacturers are increasingly using pre-emptive maintenance to monitor when parts are likely to need replacement. Some sites have chosen to outsource bus maintenance, and as with diesel buses, it is likely that various approaches to maintaining fuel cell buses will be required to suit the needs of individual operators.

Either way, it will be important to ensure that sufficient spare parts (both consumables and strategic spares) are available at (or near) the workshop / depot, and that there are suitably qualified technicians available to carry out scheduled and unscheduled maintenance. In addition, specialist tooling is also required to maintain fuel cell buses, for example hydrogen sensors (sniffers), software for monitoring the vehicle systems and diagnosing issues, etc.

Hydrogen refuelling stations

The maintenance strategy for the HRS will vary depending on the entity responsible for operating the station and the nature of the overall hydrogen supply contract. Given the specialist nature of the equipment needed to store, compress, and dispense hydrogen, all-inclusive contracts with suppliers that include the fuel along with provision and maintenance of the infrastructure (to agreed availability levels) are likely to be attractive to many operators.

This type of arrangement means that maintenance responsibility for the station lies with the experts best placed to diagnose and resolve any issues, and the bus operator can concentrate on providing bus services. Like for the buses, attention must be paid to stocks of strategic spare parts. Keeping an extensive stock of spares for the HRS at the site is not likely to be feasible, in which case a clear understanding of how spares will be sourced, and the time needed to access critical spare parts is needed. Experience suggests that hydrogen compressors are a vulnerable component in terms of maintaining high availability levels (see graph). Some suppliers have developed concepts that remove the need for on-site compression at the depot (using high pressure logistics systems that allow dispensing to 350 bar or storage of liquid hydrogen on site). The other primary means of guaranteeing high availability levels is to include redundancy in the station design. The Air Products liquid hydrogen refuelling station at Crawley is presented in the Appendix.

[4] A dedicated report on FCB Maintenance Workshops will be published in 2024 by the JIVE 2 project (D3.5, Best Practice Guide for Fuel Cell Bus Maintenance Workshops).

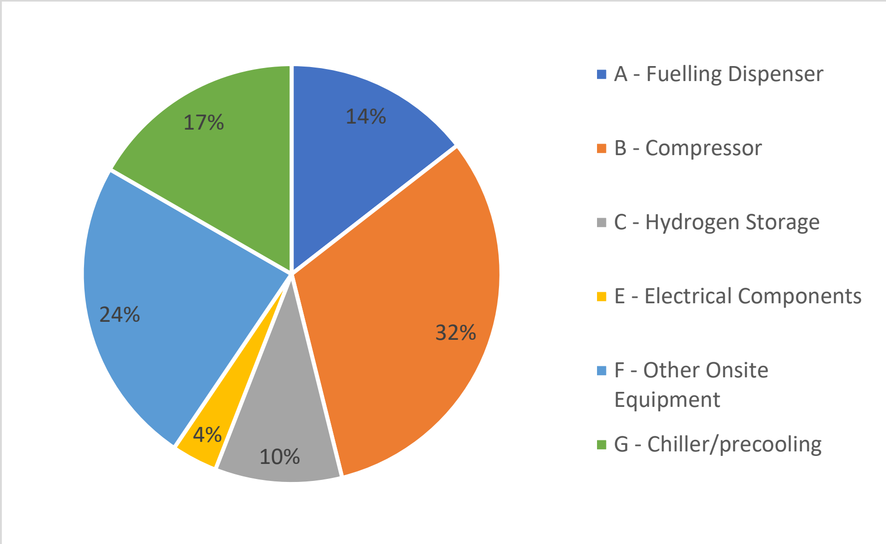


Figure 4: H2ME and ZEFER HRS Downtime by category[5].

Procurement

Collaborative efforts between Public Transport Operators (PTOs) and Public Transport Authorities (PTAs) are crucial to facilitate the procurement of fuel cell buses. Vehicle manufacturers recommend prioritising performance outcomes over technical details in tender documents to allow for flexible solutions.

Simplifying the procurement process involves aligning it with the PTO investment cycles, sourcing information about hydrogen technology. Also, maintaining open communication channels with suppliers throughout the tender process is essential for validating assumptions.

Insufficient competition and responsiveness from manufacturers, particularly for orders involving fewer than ten vehicles, pose a key challenge in selecting a bus supplier in the current market. To overcome these challenges, it's essential to maintain transparent and adaptable communication channels with suppliers during the tender process. Also, be prepared to negotiate add-ons and explore lower prices once manufacturers have submitted bids. In the current market, manufacturers may offer reduced prices when procurement is scaled.

Finally, when developing the contract, negotiation challenges arise in relation to pricing and delivery timelines, addressing technical and legal particulars, and effectively managing risks in joint procurement efforts. To address these challenges, consider the following recommendations:

- Ensure absolute clarity between all parties on desired outcomes and strict compliance with tender and contract details.
- Clearly specify maintenance expectations, timeliness, and expertise requirements in contracts, assigning responsibilities to relevant parties (PTA/PTO/supplier).
- Include a requirement for bus suppliers to collaborate with hydrogen refuelling station (HRS) suppliers when developing contracts.

[5] Source: *H2ME, D6.10/D6.18, Commercial advancements in the hydrogen fuel retailing – final / Recommendations for harmonising the hydrogen refuelling business in Europe – final, Element Energy*

- Investigate "fuel cell as a service" models where bus manufacturers or component suppliers agree to replace fuel cells free of charge in the event of unplanned damage.
- Consider separating the fuel cell warranty from other vehicle components for added flexibility.

Depot preparation

Most of the local projects within JIVE involve integrating fleets of fuel cell buses into existing depots (rather than constructing dedicated new facilities). Preparatory work at the depot in such situations can be classified into the following stages:

- **Design** – involves design work and risk assessments to determine details of the equipment needed for safe operation and maintenance of the vehicles and infrastructure. A plan for training employees and engaging with third parties (e.g., emergency services) should also be developed at this stage.
- **Implementation** – work to prepare the depot needs to occur before delivery of the first fuel cell buses. In this stage the required measures identified at the design stage are implemented, and training / familiarisation tasks are undertaken.

Further details of the types of activities required at these stages are given below.

Design

One of the first tasks required to prepare a depot for the introduction of fuel cell buses is an assessment of the measures needed to allow safe maintenance of all parts of the vehicles. Maintenance work on buses is generally carried out within buildings ("sheds") and the bus operator will need to decide where maintenance of the fuel cell buses will take place (e.g., at certain bays within the facility). The characteristics of hydrogen mean that working on a fuel cell vehicle in enclosed spaces presents different risks from those associated with diesel buses. For example, any leak from the gas elements of the system will lead to hydrogen rising and potentially accumulating in the roof space, thus creating a fire / explosion risk. This risk can be mitigated via several measures (e.g., hydrogen sensors, improved ventilation, installation of ATEX lighting) and the most appropriate requirements will be site-specific.[6] There are also risks associated with the high voltage systems on the vehicles. A "safe" parking area may be required for buses that are awaiting checks for (suspected) hydrogen leaks. Qualified experts should be appointed to carry out risk assessments and provide recommendations on measures that can be taken to mitigate any risks identified. It is important to note that the assessment of risks and appropriate mitigation measures can vary depending on the assessor. In some countries (e.g., the UK), groups of industry and bus operator representatives are collaborating to develop recommended best practice and seeking to achieve a level of standardisation in safety measures (acknowledging that there are differences between different bus depots / workshops).

The bus operator will also need to ensure that all the equipment/tooling needed to work on the vehicles is in place. This is likely to include arrangements for providing safe access to the roof (typically where the hydrogen tanks are placed on single deck buses) and underside of the vehicles – fall prevention systems and mobile platforms may be required (see photo).

Fuel cell buses introduced via previous projects have required access to a power (electricity) supply for plugging in overnight for freeze protection of the fuel cell system during cold weather. The latest generation fuel cell buses

[6] One option for providing well-ventilated indoor maintenance areas for fuel cell buses is adapting an existing paint shop, as these buildings tend to have effective ventilation systems in place.

have integrated freeze protection and therefore do not need to be plugged in overnight (although it is worth checking this requirement with the vehicle supplier).

In addition to consideration of the requirements for maintaining the buses, a significant amount of design work on the hydrogen refuelling station must be undertaken. HRS designs will generally be developed by the infrastructure provider, working closely with the bus operator to understand constraints at the site and other operational priorities. If the refuelling strategy involves using delivered hydrogen (rather than on-site production), thought needs to be given to access requirements for the tube trailer(s), and timing of fuel deliveries to ensure that there is no interference with day-to-day operations at the depot.

Finally, at the design / planning stage, a strategy for training bus operator employees and providing information to other third parties should be developed. Further information on the likely requirements for training is given in the following section.

Implementation

Workshop safety

It is likely that some form of workshop adaptation will be required to allow maintenance of the fuel cell buses in an existing depot. In addition to the physical measures that may be required (see box), safety can be ensured through the definition of procedures for working on the vehicles, and by encouraging a culture of safety (e.g., continuous identification of hazards, empowering all employees to take responsibility for safety). Clearly, some basic rules (e.g., a ban on smoking / introduction of ignition sources) should be implemented and enforced. Experience from past projects suggests that in general fire extinguishing equipment required at hydrogen depots is the same as for regular bus workshops.

Physical measures that may be needed at a hydrogen workshop

- Mobile hydrogen sensors
- Forced (active) ventilation system
- Additional ceiling vents / fans
- Ceiling-mounted hydrogen sensors, linked to alarm / warning system
- Bus grounding wire or dissipative floor on workshop (reducing risk of electrostatic charge build up on vehicle during maintenance)
- Fire doors (if not already present)

Note that some of the equipment installed may require periodic inspection / testing (e.g., hydrogen sensors and alarms).

Other recommendations for preparing for the delivery of fuel cell buses include:

- Risk assessments of delivery, maintenance procedures, refuelling and standard operation should be undertaken.
- Regular sensor and alarm test schedule should be produced.
- Automated emergency procedure implemented – shut down of all standard equipment, action as required from emergency equipment e.g., sprinkler system, ventilation system activate.
- Evacuation plan produced and included in training.
- Emergency procedure drills planned.

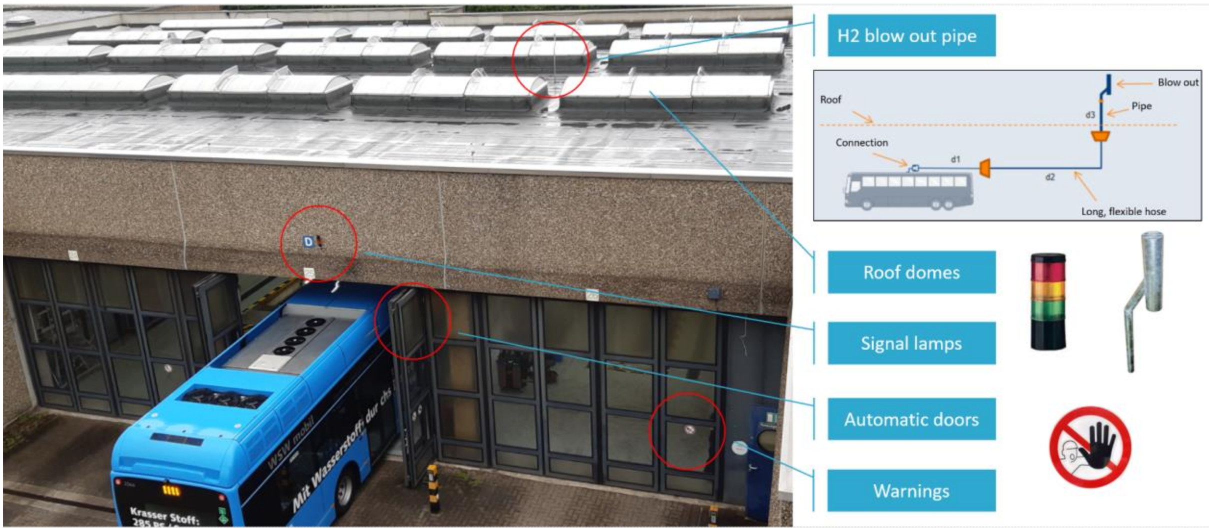


Figure 5: Wuppertal (DE) bus depot - outside (safety equipment)

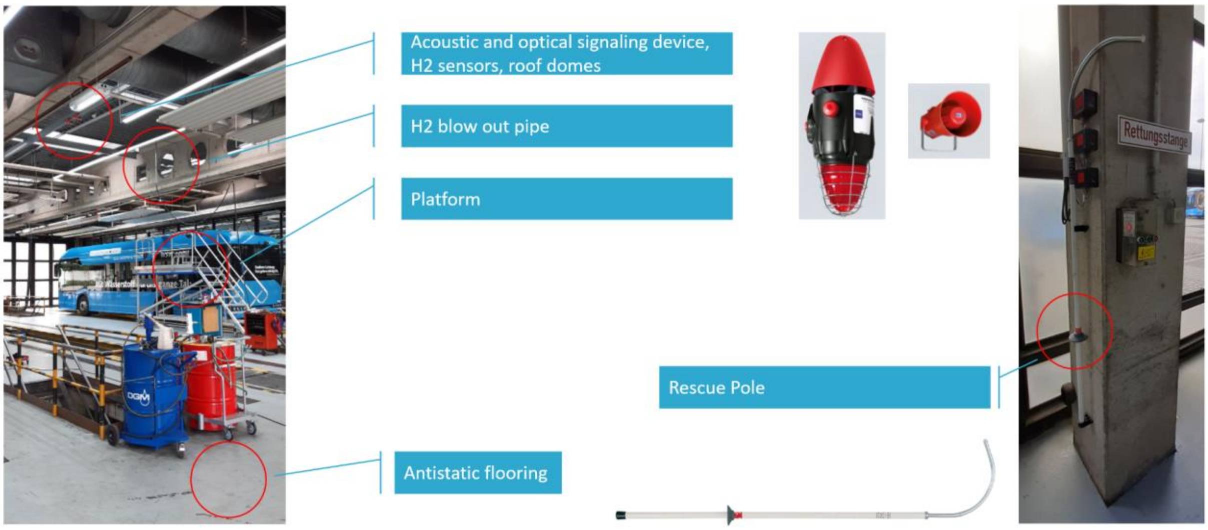


Figure 6: Wuppertal (DE) bus depot - inside (safety equipment)

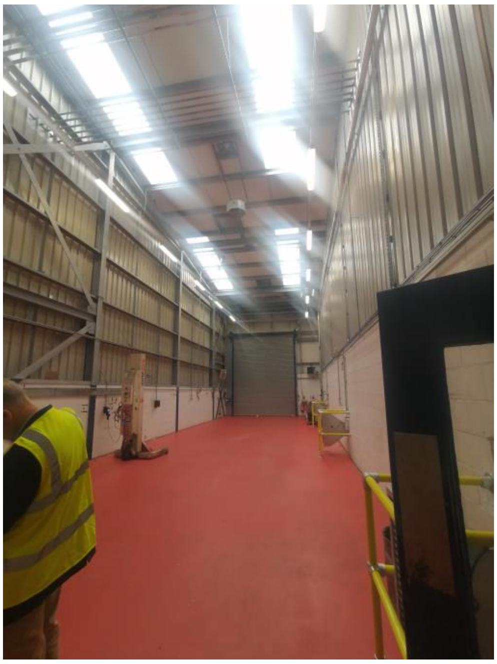


Figure 7: First Bus Hydrogen Maintenance Bay in Aberdeen (UK)

The following upgrades were made to the Aberdeen bus depot to accommodate the fuel cell buses:

- Hydrogen sensors
- Increased ventilation and lighting
- Grounding points

Training

As with the introduction of any new technology, the deployment of fleets of fuel cell buses for the first time necessitates a degree of training and familiarisation. Experience from previous projects suggests that the following factors should be considered:

- Training provided by the PTO with assistance from the bus / HRS suppliers and involving local / regional training institutions to integrate the information into the formal training system.
- Training programmes should be tailored to the local context, accounting for regional safety requirements and variations in design and functionality of the hardware (buses / HRS) between sites. Training should take place before delivery of buses commences.
- Training should be both practical and theoretical – many cities / operators with experience in this area have reported that training on the bus itself better engages employees and increases efficiency.
- Training manuals / written instructions should be provided alongside any hands-on / oral instruction. This includes safety data sheets and information on emergency procedures.
- Refresher courses should occur regularly (e.g., every one to two years).
- Define early who participates and who delivers training, as well as where and when it will occur. Securing availability of qualified trainers is a priority.
- There is value in broad awareness-raising activities across the operator's organisation when introducing a new vehicle technology. I.e., while specialist training should be focused on those who require it (drivers, technicians who will be working on the vehicles), it is worth wider communication about the project to other employees to keep all staff informed and create a positive environment around the technology. Attention should be paid to the potential for "fearmongering" relating to the potential dangers of hydrogen and fuel cell buses. Those leading the programme need to be aware of potential

concerns (e.g., relating to high voltage components and pressurised hydrogen) and provide clear, factual information.

- Expectation management is also an important part of training / information sharing. Fuel cell buses do not have the same level of technical maturity as diesel buses and issues are fairly likely, particularly during the early stages of deployment (see following section).

Group	Type of training / information to be provided and other relevant information
Bus drivers	• Comprehensive basic training is found to be sufficient for bus drivers- suggested length of training from 0.5 to 2 days based on prior experience and knowledge requirements. • An overview of the basic technical characteristics of the vehicles should be given (including reference to potential hazards relative to conventional buses such as high voltage components and hydrogen system). The drivers should also be given information on technical differences in operation of the bus compared to a standard diesel bus. • Bus drivers should be given training on procedures to follow in the event of an emergency. • Training should start immediately upon arrival of buses. • Planning is required to ensure sufficient time is free in bus drivers' schedules. • Generally, bus manufacturers will train bus operator instructors, who will then train the drivers.
Technicians	• Training required in handling of high voltage components, fuel cell technology and pressurised gas systems as well as basic training. • Technicians and other depot staff should be given training on procedures to follow in the event of an emergency. • Training should ideally occur before buses arrive. • Training should generally be provided directly by bus manufacturer.
Others (e.g., first responders)	• First responders (e.g., the local fire service) should be informed of the plans to introduce hydrogen to the depot and given sufficient information to allow them to develop an emergency response plan (e.g., design of the HRS, quantities of hydrogen stored on site, depot layout, safety features of the vehicles and infrastructure, etc.). • All depot staff should be trained with a particular emphasis on safety.

Vehicle delivery, run-in, and operation

Vehicle delivery

Based on the production schedules of fuel cell bus suppliers in 2023, a lead time of at least twelve months should be anticipated, starting from the order placement to the delivery of the first vehicle. During this period the customer (bus operator) is likely to be in regular contact with the supplier, including visits to the factory to ensure that the buses are being built to the agreed specification. It is necessary to agree a delivery date for the vehicles, a decision that will be affected by several factors, including:

- Availability of hydrogen refuelling station (commissioning date of new infrastructure).
- Completion of upgrades to workshop and other preparatory tasks (e.g., training of technicians, availability of drivers for training).
- Completion of other preparatory tasks outlined above (informing first responders, risk assessments, drafting emergency procedures, etc.).
- Delivery schedule – i.e., whether buses will be delivered one-by-one as they are produced or in batches (single / multiple batches depending on fleet size).
- Other considerations – e.g., avoid scheduling delivery on dates that would clash with other major events / activities.

As with the delivery of any vehicle, consideration must be given to insurance for the buses while in transit and the timing of transfer of ownership of (responsibility for) the vehicles. It is also important to clarify responsibilities in terms of registering the buses and obtaining any other certificates needed to operate them (e.g., safe to fill from HRS supplier). Failure to have explicit agreements in place on such topics is likely to delay the start of operations.

Run-in period and bus operation

Experience in previous projects has highlighted the importance of a “run-in” or “teething” period between the buses being delivered and the start of full operations. This implies a soft introduction of the vehicles into commercial service, i.e., with an expectation that availability levels are likely to be lower than equivalent diesel buses for a short period while teething technical issues are resolved and staff gain experience with operating the vehicles, diagnosing and rectifying issues, etc.

Planning for such a phase from the outset (e.g., by ensuring that additional spare vehicles are available so that bus services can continue without interruption in the event of unplanned downtime of the fuel cell buses) is highly recommended for sites deploying fuel cell buses for the first time. It is important to put in place additional resources to monitor the performance of the vehicles and rapidly address any problems that occur. This includes ensuring that sufficient support is available from the bus supplier (and component suppliers as necessary) and that spare parts are readily available (as part of the maintenance plans described above).

As of 2023, within the JIVE projects, 77% of the sites have exceeded the target of 90% vehicle availability, reflecting a significant improvement in the reliability and performance of fuel cell buses compared to earlier generations.

However, new FCB models (manufactured by inexperienced OEMs) often reported issues related to standard bus components or the electrical system rather than the hydrogen/fuel cell-related components. Some common issues include:

- **Coolant System**: Coolant pressure problems.
- **General Bus Components:** Malfunctioning doors and lights.
- **Electrical System:** Drive train wiring issues and incorrect installation of the power distribution unit.

- **Fuel Cell (FC) System:** Water leaks in FC stacks and FC drive system problems, such as battery issues leading to reduced speed, especially on hilly routes.

It is crucial to closely monitor such issues, especially during the initial stages of operation, and take corrective action promptly if any problems arise. Further recommendations relating to managing and rectifying faults with FCBs include:

- Ensure that the testing phase is sufficient to evaluate new technology and its performance under the planned work cycle and routes.
- If possible, conduct bus testing close to the depot to facilitate a quick return to the base in case faults are discovered. Alternatively, some sites choose to test FCBs at the manufacturer's premises but adapt the testing to local conditions, including fully loaded buses with hill starts.
- Arrange delivery timelines so that approximately 10% of the buses are delivered several months ahead of the rest of the order. This allows most of the "teething issues" to be resolved before the remaining buses arrive.
- Establish regular communication channels between onsite technicians, drivers, operators, and the supplier during the early stages of FCB deployment. This open dialogue helps address issues promptly and collaboratively.
- Implement a closed feedback loop by having a technical inspector from the manufacturer present weekly when the first FCBs arrive for testing. This inspector can report any necessary changes to the bus production line in real-time, ensuring continuous improvements in FCB construction.

The length of the run-in period required is subject to some uncertainty. In some previous projects, the teething period lasted many months (even years) as technical issues were uncovered and resolved. However, with OEMs gaining more experience in manufacturing FCBs and with the technology maturing, the teething period has in general been steadily decreasing. It is important to note however that full operation of FCBs requires all elements of the "system" to function reliably, i.e. the vehicles, fuel supply and refuelling infrastructure. While in some projects within the JIVE programme, it has been possible to operate FCBs in place of diesel buses, some sites have experienced protracted periods during which back-up fleets of conventional vehicles were required due to issues with availability of hydrogen, HRS, and technical performance of the FCBs.

Following an initial run-in period, the operator is then expected to be in a routine of operating and maintaining the vehicles in accordance with the agreed maintenance strategy. While fuel cell buses can be considered a like-for-like replacement for diesel vehicles (in terms of range and refuelling time), one difference that the operators in the JIVE programme should be aware of is the need to provide operational data (from the vehicles and any infrastructure funded under the project).

Provision of data is a condition of funding from the Clean Hydrogen Partnership, and the project(s) include organisations dedicated to collection and analysis of the data. In addition to the quantitative information, it is expected that bus operators will share feedback on the experience of deploying and operating fleets of fuel cell buses, including lessons learnt, best practice, and recommendations on areas for improvement.

However, data logging and data delivery have posed various challenges across different projects. These challenges include issues such as data collection software not providing necessary operational data, faulty data loggers, and authorization problems with data logging dashboards.

To address these challenges effectively, bus operators should consider the following strategies:

- Clearly define the data collection requirements as part of bus tender documentation – i.e. make data provision part of the contract with the bus supplier(s).

- Aim for a standardised data collection software system that can be used across all buses to avoid complications arising from different systems or dashboards with varying data points provided by individual suppliers.
- Provide comprehensive training for both drivers and technicians to ensure they are comfortable and proficient in using the selected data collection software.

By implementing these strategies, bus operators can enhance the effectiveness of data collection and utilisation. Access to reliable, consistent data on bus operations is important for maximising bus performance and efficiency.

For 350-bar refuelling, there are two primary methods: communicative fills, which involve communication between the bus and the hydrogen refuelling station, and non-communicative fills, where there is no communication between the two. There are internationally established protocols for both procedures, although it's worth noting that non-communicative fills generally result in slower filling speeds.

Additional operation challenges include extended downtimes caused by lengthy spare parts delivery times and issues related to on-site hydrogen production and refuelling unit performance. Therefore, bus operators should consider the following recommendations to address operational difficulties and ensure the smooth functioning of their FCB projects:

1. **Keep a store of conventional spare parts**: To mitigate delays in obtaining spare parts, operators should maintain a stock of conventional spare parts at the project site. This approach ensures the availability of critical components, reducing bus downtime.
2. **Regular fault-finding sessions**: Operators should establish regular fault-finding sessions with hydrogen refuelling station (HRS) suppliers. These sessions are essential for identifying and addressing issues affecting the overall performance of buses and refuelling units. Continuous monitoring and troubleshooting can help maintain optimal system performance.
3. **Back-up hydrogen supplies**: Operators should seek to put in place options for back-up hydrogen supplies (or insist that their hydrogen supplier has robust back-up plans in place), given the critical nature of having reliable fuel supplies.
4. **Plan visits and exchanges with experienced sites:** Cities and operators interested in deploying fuel cell buses should engage with experience sites to gather valuable real life return on experience and insights into how to manage such a project. This approach can be highly beneficial in the strategy defining and technology selection phase.

By implementing these recommendations, bus operators can enhance the reliability and efficiency of their FCB projects, ensuring smoother operations and improved service delivery.

References and further information

Fuel Cell Electric Buses knowledge base
https://www.fuelcellbuses.eu/

New Bus ReFuelling for European Hydrogen Bus Depots report: *Guidance Document on Large Scale Hydrogen Bus Refuelling,* thinkstep AG (now Sphera) (2017)
https://www.fuelcellbuses.eu/sites/default/files/documents/NewBusFuel_D4.3_Guidance-document-for-large-scale-hydrogen-refuelling_final.pdf

CHIC final report
https://www.fuelcellbuses.eu/public-transport-hydrogen/final-report-chic-clean-hydrogen-european-cities

CHIC Project: Report on Hydrogen Infrastructure Operation and Performance
https://www.fuelcellbuses.eu/public-transport-hydrogen/public-executive-summary-report-hydrogen-infrastructure-operation-and

Gaseous Hydrogen Installations EIGA Doc 15/21 (Revision of Doc 15/06), European Industrial Gases Association
https://www.eiga.eu/publications/

Air Products' hydrogen safety data sheet (Safetygram 4: Gaseous Hydrogen; Safetygram 9: Liquid Hydrogen):
https://www.airproducts.com/company/sustainability/safetygrams

BOC hydrogen safety data sheet:
https://www.boconline.co.uk/shop/LINSafetyDataSheetsView?catalogId=3074457345616677919&storeId=715839134&langId=101

Praxair (now Linde plc) hydrogen safety data sheet:
https://us-sds.linde.com/

H2TRUST project
https://cordis.europa.eu/project/id/325357

HyResponder: European Hydrogen Train the Trainer Programme for Responders (the project builds on the successful HyResponse project which completed in 2016)
https://hyresponder.eu/

Strategies for joint procurement of fuel cell buses, Element Energy et al for the FCH JU (2018)
https://www.fuelcellbuses.eu/public-transport-hydrogen/final-report-strategies-joint-procurement-fuel-cell-buses

Upcoming reports to be found on the Fuel Cell Electric Buses knowledge base https://www.fuelcellbuses.eu/
JIVE Final Best Practice and Commercialisation Report (D3.26) and JIVE 2 Final Best Practice Information Bank Report (D3.29)

JIVE 2 Best Practice Guide for Fuel Cell Bus Maintenance Workshops (D3.5)

Appendix – introduction to hydrogen refuelling infrastructure

Overview

Hydrogen refuelling station is a term used to refer to the equipment required to transfer hydrogen from static storage tanks to on-board vehicle storage. The refuelling process involves dispensing gaseous hydrogen into the on-board tanks until a defined maximum pressure is reached. The hydrogen transport sector has adopted two standard pressure levels for vehicles: 350 bar and 700 bar. In general, the higher pressure level is used by smaller vehicles such as passenger cars (where maximising the mass of hydrogen stored per unit volume is a priority), while heavy duty vehicles in Europe (buses, trucks, trains) generally use 350 bar storage.[7] The main advantage of the lower pressure option is financial: the costs of the storage vessels and HRS required for 350 bar fuelling is significantly lower than those associated with 700 bar fuelling.

Since hydrogen is not available in its elemental form naturally, some form of hydrogen generation plant is required within an overall hydrogen delivery system. For the purpose of considering hydrogen refuelling stations, we can classify them into two main categories according to whether the fuel is produced on site (on-site generation) or elsewhere and delivered to the station (off-site generation).

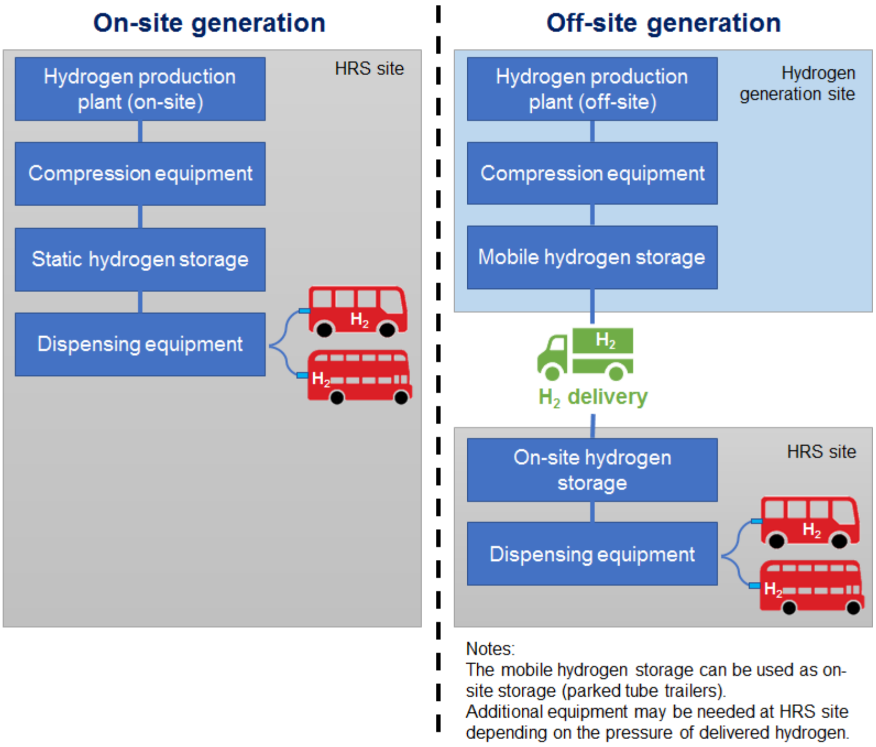


Figure 8: Schematic overview of the principal options for depot-based hydrogen supplies for fuel cell buses

The following sections provide an overview of each of the main elements of the system outlined above.

[7] Note that there are exceptions. For example, small vehicles being developed by companies such as Riversimple and Microcab use 350 bar hydrogen tanks, while the Toyota SORA fuel cell bus has 700 bar on-board storage.

Hydrogen storage

In general, hydrogen for transport applications is stored as a compressed gas in pressurised vessels, though liquid hydrogen can also be used.[8] Compression is needed to contain the gas in manageable volumes and is required for both archetypes described above (on-site production and delivered hydrogen). Hydrogen can be stored at a range of pressures, from low tens to many hundreds of bar, with different tank types required depending on the pressure level (see Table 1).

Table 1: Pressure vessel classifications[9]

Type	Features	Maximum pressure
Type I	• All-metal construction, typically steel (or aluminium). • Widely available, relatively low cost. • Relatively high mass per unit storage volume. • Commonly used in CNG vehicles.	200 bar
Type II	• Mostly steel or aluminium with a glass-fibre composite overwrap. • Structural loads shared between metal vessel and composite materials. • Higher cost than Type I but lighter weight.	300 bar
Type III	• Tanks made from a metal liner with full composite overwrap (e.g., aluminium with a carbon fibre composite. • The composite materials carry the structural loads.	700 bar
Type IV	• All-composite construction using a polymer liner with carbon fibre or hybrid carbon/glass fibre composite. • Relatively expensive but lower tank mass per unit volume.	700 bar
Type V	• All-composite construction, liner-less construction. • Currently under research.	Estimated pressure 1,000 bar
Cryogenic-compressed H_2	• Types III-IV-V, super insulated. • Temperature: -253°C.	350 bar

In general, storing hydrogen at a higher pressure reduces the amount of space needed (and in the case of transporting the gas by road higher pressure systems allow greater quantities per truck), but the tanks required for high-pressure storage are more expensive than those needed to contain the gas below 200 bar.

[8] Hydrogen can also be stored in liquid form by cooling to –253ºC at ambient pressure (this reduces the amount of space needed but comes with an energy cost). Other forms of storage are also possible, e.g., binding hydrogen on to various carrier molecules.

[9] Source: based on www.compositesworld.com/articles/pressure-vessel-tank-types.

The hydrogen storage options at the bus depot will depend on site-specific factors, including the area available. Hydrogen generated on site is typically stored in pressurised static tanks, at variable pressures. Cascade storage systems are often used at vehicle refuelling sites, where most of the hydrogen is stored at a lower pressure, such as 200 bar and a smaller quantity of hydrogen is stored at a pressure higher than the hydrogen vehicle's tank (350 bar for fuel cell buses).

Hydrogen produced off-site and delivered to the HRS is transported and stored in metallic cylinders transported by trailer. These *tube trailers* can be connected to the hydrogen dispensers and serve as a form of mobile storage. Tube trailers typically transport hydrogen at pressures of between 200 bar and 500 bar, with each trailer containing several hundred to 1,000+ kilograms of hydrogen respectively. Based on current technology, tanks designed to store hydrogen at 350 bar, at which a single tube trailer can hold more than 700 kgH_2, offer the most economical option in terms of cost per kilogram of hydrogen stored.

Hydrogen transport

Hydrogen refuelling can adopt a similar model to current diesel refuelling, with off-site processing of the fuel and delivery to the bus depot. There are advantages to producing hydrogen off-site with savings possible via the economies of scale. Large, centralised hydrogen production facilities can be sited to access low-cost and/or clean energy supplies. Hydrogen can either be delivered to the bus depots in compressed tube trailers, or liquified tankers.

Road transport: compressed gaseous hydrogen (CH_2)

Road transport of hydrogen stored in pressurised tubes is the most common delivery option currently used in Europe as it is the most economical storage and distribution option at small scales, and over relatively short distances (circa 500km).

Once produced, the hydrogen is compressed and stored in pressure vessels attached to trailers and carried by trucks. The development of composite materials for gas cylinders has improved the efficiency of transporting compressed hydrogen in tube trailers. Composite gas canisters are lighter and therefore able to hold greater hydrogen pressures than equivalent steel gas canisters. This allows for a greater quantity of hydrogen to be transported per truck, and therefore lower number of truck deliveries. The current hydrogen supply to London's bus HRS uses delivered hydrogen at 500 bar (with c. one tonne of hydrogen capacity per truck), with vertically stacked canisters, shown below.

Figure 9: Ryze Hydrogen trailer at Perivale station (2021)

One advantage of this approach is that no production facilities are needed on-site. The hydrogen can be produced outside the city where space is at less of a premium and at sites where centralising production provides economies of scale. Furthermore, delivering hydrogen at 500 bar provides the opportunity to eliminate the need for further compression at the HRS when refuelling at 350 bar, leading to reliability benefits as the single biggest source of failure in many stations is the compressor.

However, the low carrying capacity of individual trailers limits the suitability of compressed gas distribution to applications with high hydrogen demands (high hundreds of kilograms per day and above).

Road transport: liquid hydrogen (LH_2)

Liquified hydrogen trailers can transport greater quantities of hydrogen (approximately 4,000 kg per delivery) than compressed hydrogen trailers. Hydrogen can be liquified by reducing the temperature to –253°C (at ambient pressure) using liquid nitrogen and compression and expansion steps. The high investment costs for liquefaction plants can only be justified at large throughputs of hydrogen, with commercial plants built in recent years in the order of 5–10 tonnes per day[10]; in fact, there are currently only four[11] such plants operational in Europe.[12] However, additional liquefaction plants are planned.[13]

The transportation of liquid hydrogen requires insulated cryogenic storage tanks. These, with a carrying capacity of up-to 4 tonnes, offer a more cost-competitive distribution solution than compressed hydrogen for high-

[10] Integrated design for demonstration of efficient liquefaction of hydrogen, report on the Schedule for Demonstration Plant Including Options for Location, (IDEALHY project partners, 2013).
[11] The Hydrogen Economy: Opportunities and Challenges, CUP, 2009.
[12] Two operated by Linde in Germany (Ingolstadt, Leuna), one operated by Air Liquide in France (Waziers), and one operated by Air Products in the Netherlands (Rotterdam). While liquefaction allows a significant increase in the volumetric energy density of hydrogen relative to storage as a compressed gas, there is an energy cost associated with liquefying hydrogen which is of the order 25–40% of the chemical energy of the hydrogen.
[13] For example, Air Products has announced plans to build a second liquid hydrogen plant in Rotterdam and to build a large-scale liquid HRS for trucks in the port of Zeebrugge.
https://www.airproducts.co.uk/campaigns/hydrogen-fueling-for-mobility/projects

demand applications (>1tpd), particularly over long distances. However, maintaining the low temperature required to keep hydrogen in liquid form during the unloading of hydrogen from the hydrogen tanker to the cryogenic storage is a challenging process, with boil-off losses occurring.

New strategies have been proposed to recover and minimize these boil-off losses during liquid hydrogen storage[14]. For example, a pioneering approach proposes solid air (nitrogen or oxygen) as a medium for recycling cooling energy across the hydrogen liquefaction supply chain[15].

The liquid hydrogen, dispensed to delivery trucks, is transported to distribution sites where it is vaporised to a high-pressure gaseous product for dispensing. Given the investments required at each part of the chain (production / processing / storage / transport / dispensing), liquid hydrogen solutions are best suited to relatively high demands (many hundreds of kilograms per day and above per site) and long-term supply contracts. Liquid hydrogen facilities are not as sensitive to increasing distribution distance as compressed hydrogen or pipeline solutions. This allows for liquefaction plants to be strategically placed at large-scale, low-cost sources of hydrogen, and distribute to demand over a wide radius (>300km).

Other advantages of liquid hydrogen include lower cost hydrogen refuelling stations (per unit of dispensing capacity) compared to gaseous hydrogen, lower footprint storage, and the ability to guarantee fuel cell grade purity. However, experience with generating and handling liquid hydrogen is generally limited to large industrial gas companies.

Figure 10: An Air Liquide truck delivering liquid hydrogen[16]

Hydrogen pipelines

Pipelines are an efficient means of transporting large quantities of hydrogen. Pipelines also offer the advantage of some level of inherent storage (storage by line-pack) that is required to manage variations between supply and demand. Dedicated hydrogen pipelines use proven technology and have been operated in various countries throughout the world for many years. They are typically owned by gas companies and co-located with large

[14] EconPapers: Strategies to recover and minimize boil-off losses during liquid hydrogen storage (repec.org)
[15] How solid air can spur sustainable development | IIASA
[16] http://www.hydrogencarsnow.com/index.php/hydrogenforklifts/air-liquide-high-on-hydrogen-fuel-cell-forklifts/

hydrogen users such as petroleum refineries or chemical plants. [17] Hydrogen pipelines offer the lowest OPEX solution of all distribution technologies.

Apart from constructing new pipelines, the utilisation of hydrogen within existing pipeline infrastructure can be accomplished through various methods. These methods include repurposing natural gas pipelines for hydrogen transport or blending hydrogen with natural gas directly within the existing network.

1. Repurposing Gas Pipelines for Hydrogen:

- Repurposing involves retrofitting existing natural gas pipeline infrastructure to transport hydrogen, resulting in lower initial capital expenditure (CAPEX), especially for smaller-scale projects.
- Cost savings can be substantial, with repurposing costs estimated to be only 10-35% of the expenses associated with new pipeline construction.
- Challenges include:
  - Addressing pipeline transmission issues, particularly related to materials. Steel and iron pipelines are susceptible to hydrogen embrittlement, making polyethylene pipelines a preferred choice for hydrogen transport. High-strength steel used in many existing gas transmission networks complicates repurposing efforts.
  - Managing hydrogen permeation and potential leakage.
  - Mitigating the risk of contamination from impurities and odorants, which may necessitate additional purification steps.
  - Adapting existing pipeline operation approaches to accommodate hydrogen.

2. Blending Hydrogen in Gas Pipelines:

- Hydrogen can be blended into the existing natural gas network at concentrations of up to 2% without requiring significant modifications to the current infrastructure.
- De-blending technologies, still under development, could separate hydrogen from gas mixtures after transmission, making blending/de-blending viable for applications requiring pure hydrogen.

These methods provide flexibility in integrating hydrogen into existing energy infrastructure while addressing specific challenges associated with each approach.

[17] Robinius et al, Comparative Analysis of Infrastructures: Hydrogen Fuelling and Electric Charging of Vehicles, Energy & Environment, Volume 408, 2018

Other hydrogen logistics options

There are various methods of conditioning, storing, and transporting hydrogen, as summarised in the figure below.

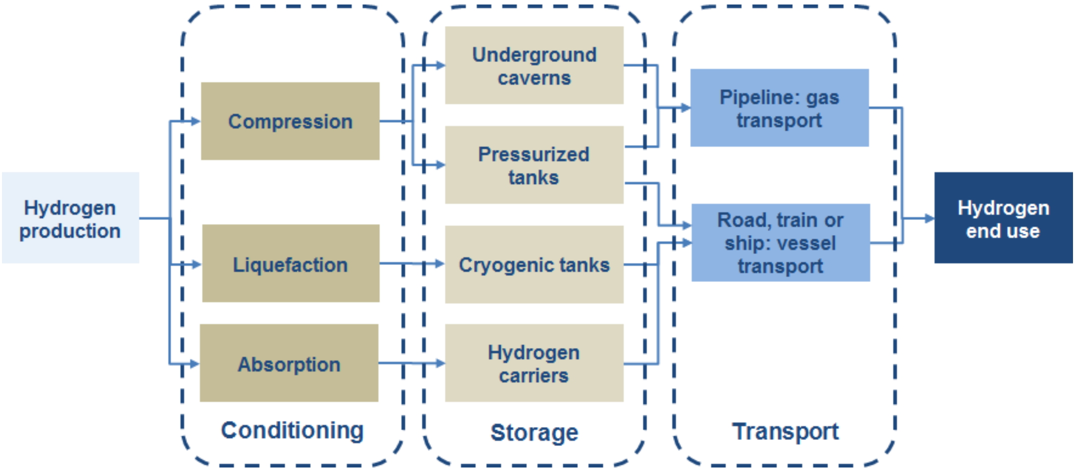


Figure 11: Overview of options for hydrogen conditioning, storage, and transport[18]

In addition to being stored and transported in its pure form, hydrogen can be bonded on to a carrier material before being released for use. Examples include:

- **Liquid phase carriers** – hydrogen can be stored in a liquid state without cryogenic cooling by using liquid organic hydrogen carriers. Hydrogen is stored in / released from the carrier via catalytic hydrogenation (exothermic) and dehydrogenation (endothermic) processes. A major advantage of liquid phase carriers is the ability to transport and distribute the material using infrastructure familiar to mineral oil-based fuel industries. One company developing solutions in this area is Hydrogenious, whose technology allows hydrogenation in a container module which could be located on a refuelling station site.

- **Hydrides** – for example, metal hydrides are materials that store hydrogen reversibly by absorption and desorption of hydrogen at certain temperatures and pressures. Hydrogen is either stored interstitially in the metal matrix, or bonded to metal atoms depending on the material used.[19] The materials used tend to be heavy (e.g., 100kg of storage system per kilogram of hydrogen[20]), which suggests metal hydrides are best suited to niche applications.

- **Reformed liquid fuels** – another way of storing and transporting hydrogen is as part of a liquid fuel. For example, hydrogen can be reacted with carbon monoxide to produce methanol, or with nitrogen to produce ammonia. These liquids tend to be easier to store and transport compared to handling molecular hydrogen. Depending on the end use, hydrogen can be recovered from the liquid fuel (which adds an additional processing step and therefore incurs an efficiency penalty), or the fuel can be used directly.[21] Shipping costs are subsequently low, meaning imports from low-cost production sources

[18] Based on Fig 61, Hydrogen based energy conversion (SBC Energy Institute, 2014).
[19] *Technology and Manufacturing readiness of early market motive and non-motive hydrogen storage technologies for fuel cell applications*, Rönnebro (2012).
[20] http://energy.gov/eere/fuelcells/materials-based-hydrogen-storage.
[21] See for example http://www.theengineer.co.uk/issues/june-2014-online/hydrogen-breakthrough-paves-way-for-ammonia-fuelled-cars/.

overseas could become a practical solution if the cost differential between overseas and locally produced hydrogen is larger than the equipment cost and efficiency penalty of the carriers. The individual processes involved in making reformed liquid fuels are mature; research is currently underway into how to optimise the processes and improve the overall system efficiency.

Hydrogen dispensing

The hydrogen dispenser typically includes a nozzle that connects to the vehicle and a user interface for initiating fuelling (including emergency shutdown controls). The dispenser is usually the only part of the station with which the end users of the fuel interact (the rest of the HRS is typically within a secure compound area).

Details of the connection device (nozzle) are defined by international standards such as ISO 17268:2012 and SAE J2600. The hydrogen refuelling process is also standardised: SAE J2601-2[22] is the standard relating to heavy duty vehicles and differentiates between slow / normal / fast-fulling, with the latter allowing refuelling rates of up to 120 g/s (7.2 kg/minute). This standardisation in hydrogen refuelling ensures a high degree of interoperability and vehicle compatibility – i.e. any hydrogen-fuelled vehicle designed to comply with the agreed standards can refuel at any HRS also designed according to the internationally agreed standards.

Currently, H35 and H70 are pressure measurements used to distinguish between various hydrogen refuelling options. H70 corresponds to roughly 70 Mpa (700 bar), primarily employed for light-duty vehicles.H35 corresponds to around 35 Mpa (350 bar) and is predominantly used for heavy-duty vehicles such as buses and coaches.

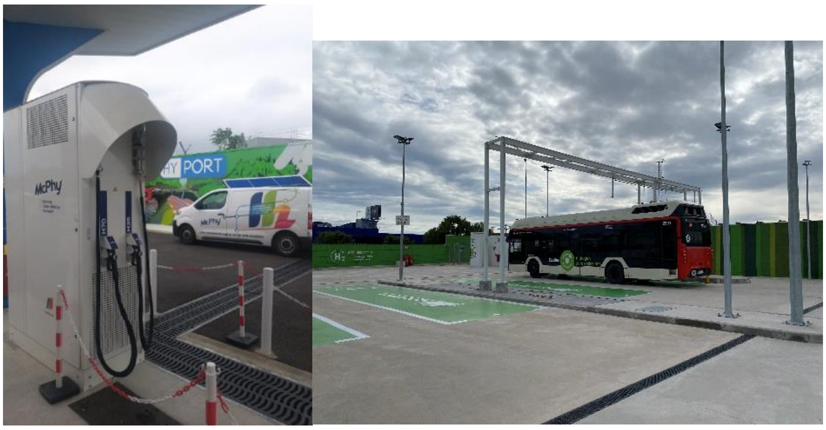


Figure 12: Hydrogen dispensers at the Hyport HRS in Toulouse, France (left) and at the Iberdrola HRS in Barcelona, Spain (right)

[22] Fuelling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles J2601/2_201409. Standards for hydrogen quality for fuel cell transport applications also exist, for example Hydrogen Fuel Quality for Fuel Cell Vehicles J2719_201511.

Case studies

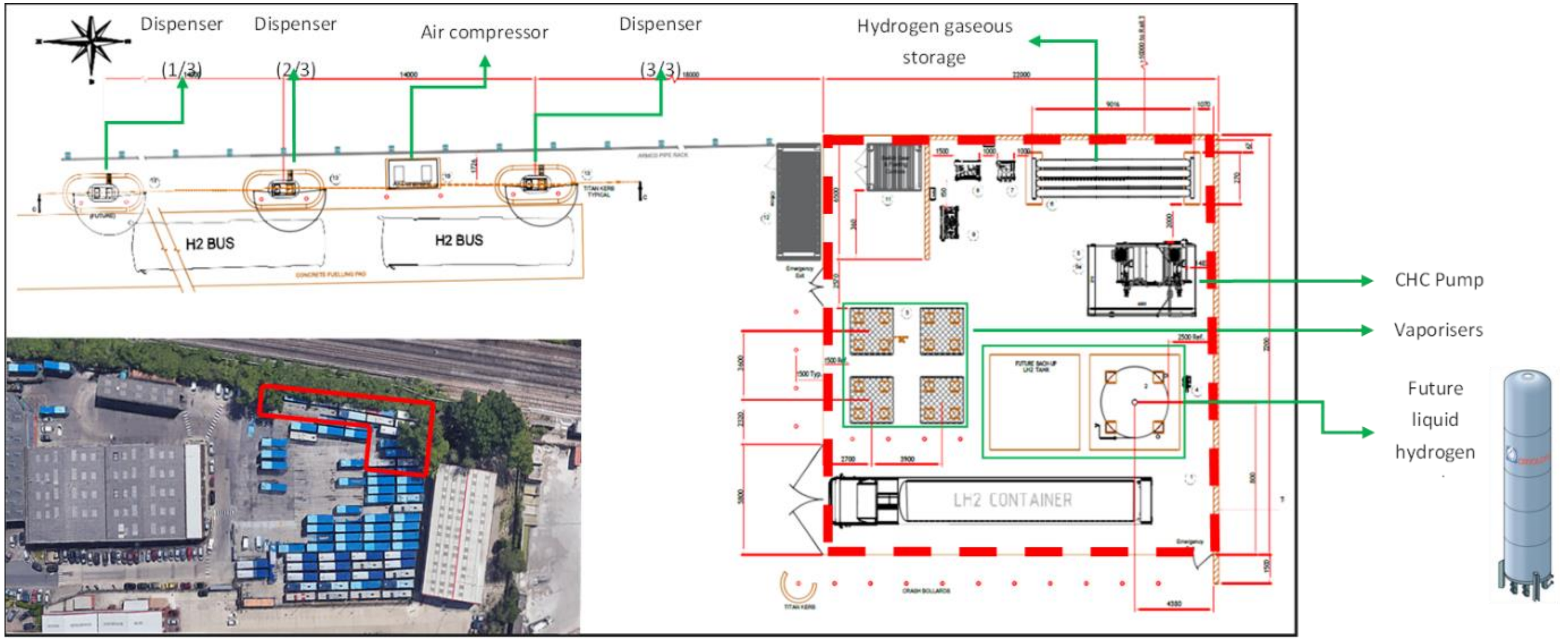
Air Product Liquid Hydrogen Refuelling Station (Crawley)

HRS Overview

- The station is located at the Metrobus Crawley bus depot at Wheatstone.
- 20 hydrogen buses (funded by JIVE II) were introduced on the 29th of June 2023; 34 more are expected to complete the fleet over the next 18 months.
- The hydrogen is stored in liquid form at the Metrobus Crawley depot and later converted to gas stored in roof-mounted tanks on the vehicles.
- This fleet will ultimately comprise 54 hydrogen-powered vehicles (single-decker GB Kite Hydroliner buses, manufactured by Wrightbus), making it one of the largest hydrogen bus fleets in the UK, featuring a liquid hydrogen refuelling station – the largest in Europe.
- Operated by Air Products, it will be the largest in Europe when fully operational, capable of fuelling over 100 buses daily.

Figure 13: View of the HRS secure compound; vaporiser in the foreground (right picture) – LH2 tank (tall white structure), with a gaseous hydrogen tube trailer in front (lower left picture) – dispenser unit (upper left picture)

Crawley (Metrobus) – Top view fuelling station (liquid hydrogen)



- For liquid hydrogen stations, four vaporiser units are in place. They play a key role in converting liquid hydrogen to gaseous before being stored in the tube tanks
- A liquid HRS has a smaller footprint when compared to gaseous HRS, explaining the large capacity of the Crawley HRS relative to its footprint. Also, hydrogen compressors are not needed/available on site.
- Potential back-up LH2 tanks could be installed in the future.

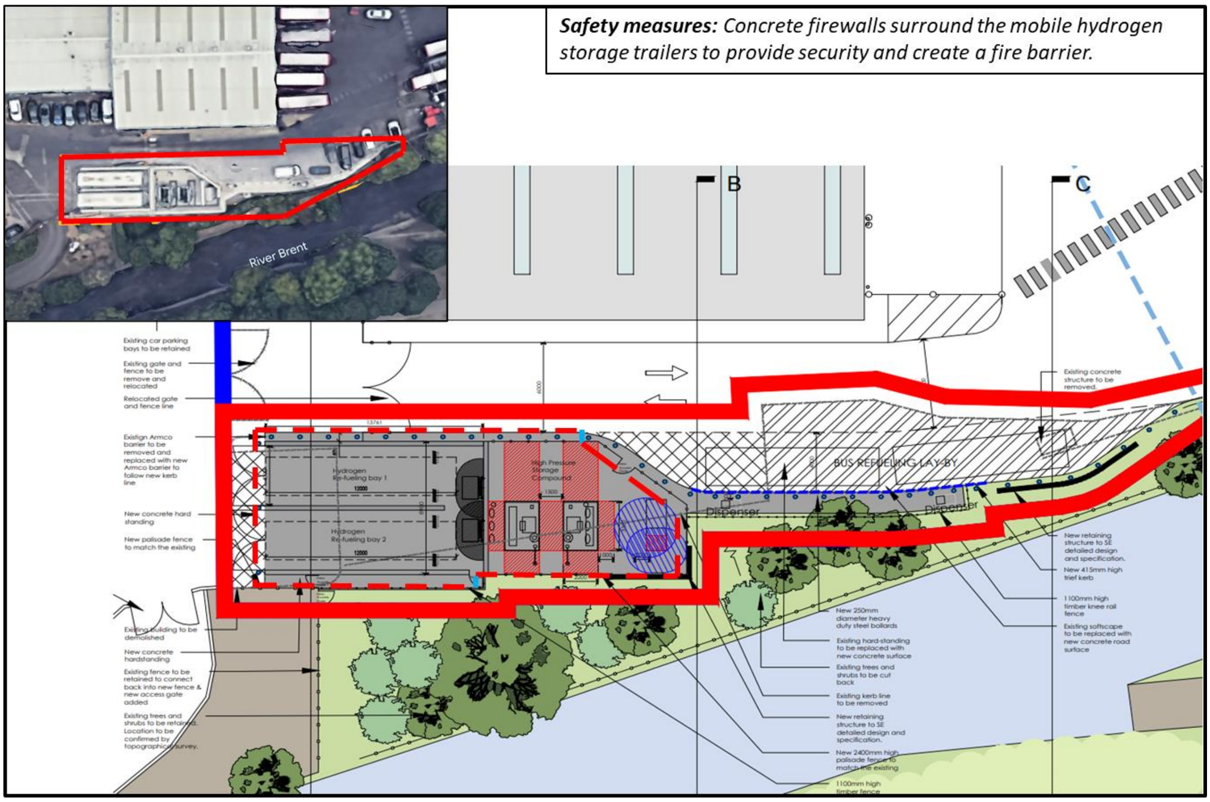
Perivale (Metroline - Nel Hydrogen)

HRS OVERVIEW

- The Perivale Metroline HRS, located in the Metroline's Perivale depot in West London, is designed to refuel 20 buses (double decker buses manufactured by Wrightbus). The station's CAPEX was co-founded under MEHRLIN and the HRS is used by JIVE buses.
- The hydrogen for the buses is currently being produced at an industrial site in Runcorn (north-west England) – by-product hydrogen from an industrial chlor-alkali plant. Plans are in place to transition to a supply of hydrogen from renewables.
- Oxford-based Ryze Hydrogen is responsible for transporting the fuel to the fuelling station.

Figure 14: Bus HRS at the Perivale depot and hydrogen transportation to HRS, London

Perivale (Metroline - Nel Hydrogen) – Top view complete layout (gaseous hydrogen)



- The HRS has a total storage capacity of c. 1,500 kgH2 (with two full tube trailers on site + some fixed storage).
- The station currently fuels 20 buses but has capacity for at least double this number.
- Hydrogen production is done offsite, transported to site via trucks trailers.

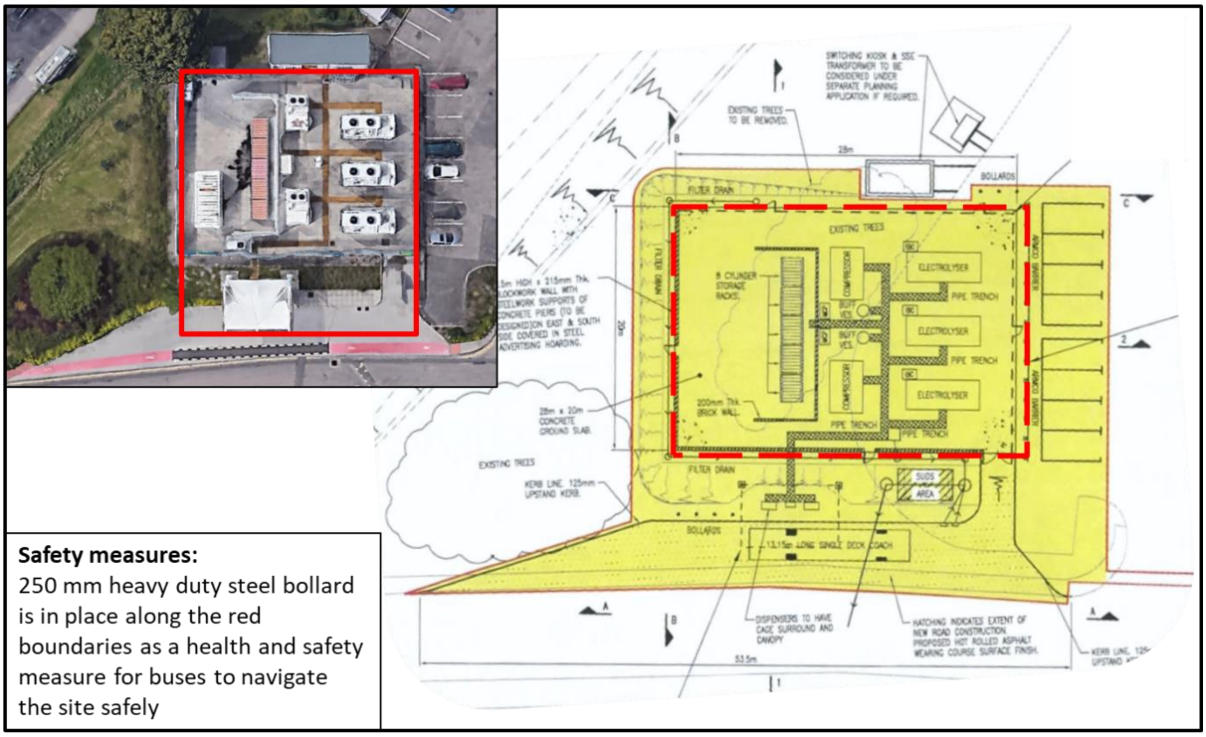
Aberdeen Kittybrewster (BOC)

HRS overview:

- BOC worked with Aberdeen City Council to develop and install a hydrogen refuelling station at the Kittybrewster bus depot. JIVE buses currently use this station to refuel.
- The facility produces green hydrogen from electrolysis on site and stores it as a compressed gas.
- The station opened in 2015 and was originally designed to refuel single-deck buses. In 2018 it was scaled up to offer public refuelling of cars and vans with 700 bar refuelling, and in 2019 it was upgraded again to accommodate double decker buses.
- The site has the capacity to produce 360 kg of hydrogen daily and has the capacity to store 420 kg of hydrogen on site.
- The current fleet of buses travel up to 350 km daily.

Figure 15: FC bus and hydrogen storage at the Kittybrewster HRS

Case study 2: BOC (Kittybrewster) – Top view fuelling station (gaseous hydrogen)



- Hydrogen production is on-site with three electrolyser units.
- As the station produces, stores, and distributes gaseous hydrogen, two hydrogen compressor units are available.
- 8 gaseous storage racks covering a total footprint of 25 m^2.
- Two 350-bar dual dispensers (4 nozzles in total) are present at the station.
- A 13.15 m long single deck coach can refill at the station.

Project coordination:

ERM

Project dissemination:

Hydrogen Europe

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Clean Hydrogen Partnership

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