Operators' guide to fuel cell bus deployment

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FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

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Introduction

Context

The Joint Initiative for hydrogen Vehicles across Europe programme (JIVE and JIVE 2 projects) is introducing new fleets of fuel cell buses and associated hydrogen refuelling infrastructure in cities across Europe. In total around 290 new vehicles will be deployed and operated for extended periods in standard commercial operations in over 20 different cities. 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 (up to 30 per site) 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 commercialisation of fuel cell buses in Europe in the 2020s by sharing information and stimulating further uptake.

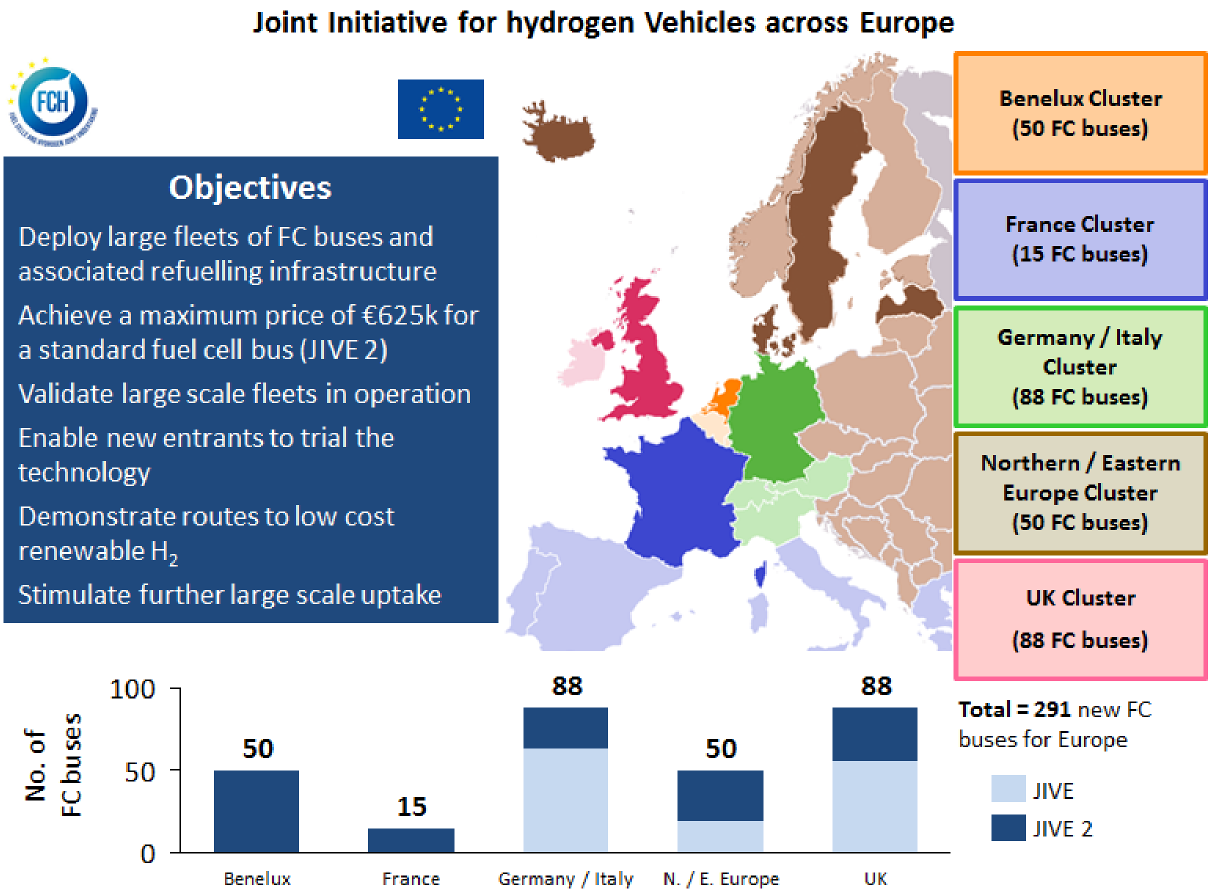

Figure 1: Overview of the JIVE and JIVE 2 projects

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.

Document purpose, scope, and target audience

This document is intended to provide 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 successfully 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 those 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; reference is made to the hydrogen refuelling infrastructure that is also 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" section.

The JIVE projects provide a unique opportunity to share experience between the leading innovators in hydrogen fuel cell buses and to capture new learning through the practical experience gained in delivering the local projects. This guide will be updated during the JIVE projects to take into account the latest lessons and best practice recommendations.

Document structure

The following sections provide lists of tasks and insights from previous 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)

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 2018, there remains a high 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.
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** – carry out early market engagement, run trials of demonstration vehicles (if possible), develop a procurement strategy, 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.). 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 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 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 outline above is available from existing publications. For example, the FCH JU's "*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.[1] 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).[2] 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

[1] See www.fch.europa.eu/publications/study-strategies-joint-procurement-fuel-cell-buses.

[2] See http://chic-project.eu/info-centre/publications.

document on large-scale hydrogen bus refuelling.[3] The guidance document includes a proposed framework for planning the installation of hydrogen refuelling infrastructure for bus fleets (see following page).

Given the amount of existing guidance and the status of most local projects within the JIVE programme, the following sub-sections focus on points 3 and 4 from the list above, drawing on experience from JIVE and previous fuel cell bus demonstration projects.

[3] See http://newbusfuel.eu/publications/.

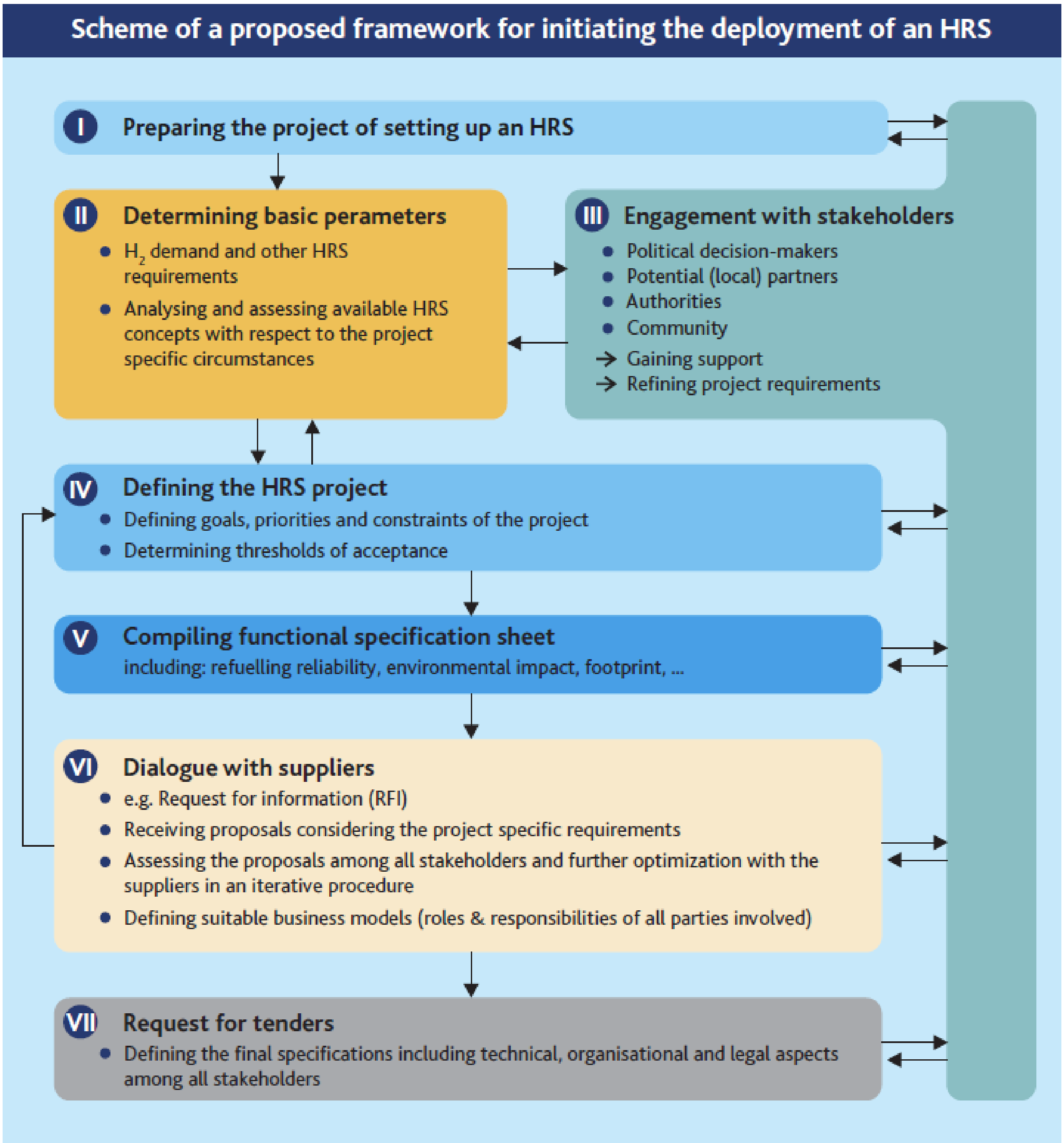

Figure 2: Framework for initiating the deployment of a hydrogen refuelling station (source: NewBusFuel)

Maintenance plans

Buses

Maintenance responsibilities should be clarified as part of the procurement process. The requirements in terms of maintenance supported 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. 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 depend on who has responsibility for operating the station and the form of the overall contract for hydrogen supply. An all-in supply agreement is likely to be attractive to many operators (where the HRS supplier takes responsibility for providing reliable hydrogen supplies, including all maintenance of the station and any other associated equipment (e.g. tube trailers)). 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). The other primary means of guaranteeing high availability levels is to include redundancy in the station design.

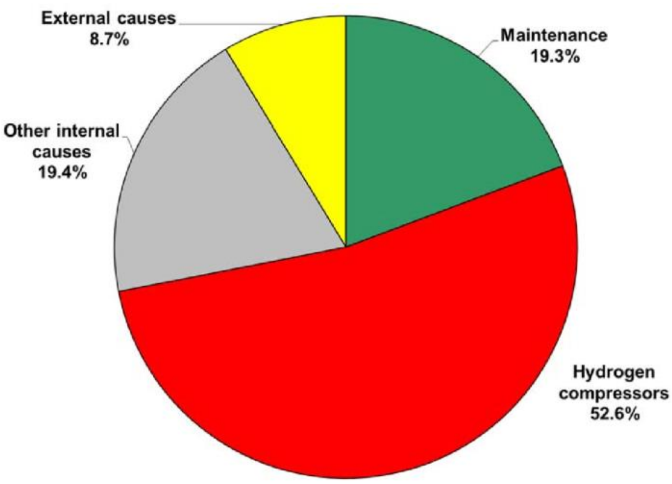

Figure 3: Causes of HRS downtime in the CHIC project[4]

[4] Source: http://chic-project.eu/wp-content/uploads/2015/04/CHIC_D1-5_Public_Summary.pdf.

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.[5] There are also risks associated with the high voltage systems on the vehicles. Suitably qualified experts should be appointed to carry out risk assessments and provide recommendations on measures that can be taken to mitigate any risks identified.

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 are expected to have integrate freeze protection and therefore not expected to 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.

[5] 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.

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.

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 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.).

Vehicle delivery, run-in, and operation

Vehicle delivery

Based on the production schedules of suppliers offering fuel cell buses as of mid-2018, a lead time (period between buses being ordered and first vehicle delivery) of at least six to twelve months is expected. Depending on the supplier and status of their order book, this could be longer until production capacities are increased in response to growing demand for fuel cell buses (e.g. with the creation of addition production lines). 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 HRS (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. 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).

In general, the fuel cell stacks used in buses have proved to be highly reliable. Issues are more often encountered with auxiliary components (e.g. DC/DC converters, cooling pumps, sensors) and software. In some cases newly deployed vehicles have shown warning lights for no reason other than a fault in the warning system. Such issues must be monitored closely, particularly during the early stage of operation, and corrective action taken should problems arise.

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. The ambition in JIVE is for the teething period to be no longer than six months (and ideally considerably shorter for customers taking delivery of vehicles later in the programme given the experience gained from the earlier projects).

Following this initial 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 FCH JU, and the project(s) include organisations dedicated to collection and analysis of the data. In addition to the quantitative information, it is generally 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.

References and further information

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

NewBusFuel project – New Bus Refuelling for European Hydrogen Bus Depots
http://newbusfuel.eu/

CHIC final report
http://chic-project.eu/wp-content/uploads/2017/06/Final-Report_CHIC_28022017_Final_Public.pdf

Report on Hydrogen Infrastructure Operation and Performance
http://chic-project.eu/wp-content/uploads/2015/04/CHIC_D1-5_Public_Summary.pdf

Gaseous Hydrogen Stations IGC Doc 15/06/E, European Industrial Gases Association
https://www.eiga.eu/publications/eiga-documents/

Air Products' hydrogen safety data sheet:
http://www.airproducts.co.uk/~/media/Files/PDF/company/safetygram-4.pdf

BOC hydrogen safety data sheet:
https://www.boconline.co.uk/internet.lg.lg.gbr/en/images/10021694410_39605.pdf?v=6.0

Praxair hydrogen safety data sheet:
http://www.praxair.com/-/media/documents/sds/hydrogen/hydrogen-gas-h2-safety-data-sheet-sds-p4604.pdf?la=en

H2TRUST project final report: *Development of H2 Safety Expert Groups and due diligence tools for public awareness and trust in hydrogen technologies and applications* (2015)
https://cordis.europa.eu/result/rcn/181098_en.html

The UK's Health and Safety Executive has produced several publications on the subject of hydrogen and fuel cell safety – e.g. HSG243: *Fuel cells: understand the hazards, control the risks* (2004)
http://www.hse.gov.uk/pubns/index.htm

HyResponse: European hydrogen emergency response training program for first responders
http://www.hyresponse.eu/links-databases.php

FCH JU recommendations for tender specifications
http://www.fch.europa.eu/sites/default/files/Tender%20specifications%20%28ID%202883324%29.pdf

Strategies for joint procurement of fuel cell buses, Element Energy et al for the FCH JU (2016)
https://www.fch.europa.eu/publications/strategies-joint-procurement-fuel-cell-buses

Strategies for joint procurement of fuel cell buses, Element Energy et al for the FCH JU (2018)
https://www.fch.europa.eu/publications/study-strategies-joint-procurement-fuel-cell-buses

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.[6] 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).

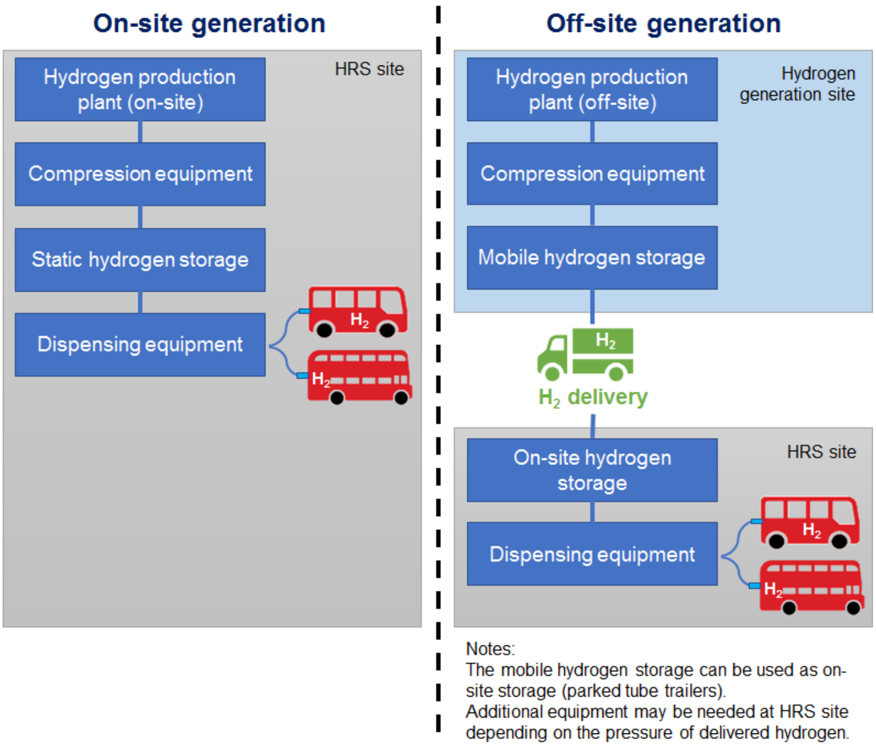

Figure 4: Schematic overview of the principal options for depot-based hydrogen supplies for fuel cell buses

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

[6] 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.[7] 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[8]

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.	175 – 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.	260 – 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.	300 – 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

In general, storing hydrogen at a higher pressure reduces the amount of space needed (and in the case or 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.

[7] Hydrogen can also be stored in liquid form by cooling to –253°C 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.
[8] 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 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. As of 2018 tube trailers typically transport hydrogen at pressures of between 200 bar and 500 bar, with each trailer containing several hundred to up to c.1,000 kilograms of hydrogen respectively.

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 produce 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. 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 5: Air Products high pressure 500 bar tube trailer[9]

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

[9] http://www.renewableenergyfocus.com/view/36777/air-products-launches-hydrogen-high-pressure-tube-trailers-for-european-hydrogen-infrastructure-deployment/

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.

Road transport: liquid hydrogen (LH_2)

Liquified hydrogen trailers can transport greater quantities of hydrogen (approximately 4,000 kg) 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]

The process of liquefaction is more energy intensive than compression and therefore more expensive. Theoretical liquefaction energy demand for hydrogen is 3.9 kWh/kg, although actual plants require 10–15 kWh/kg H_2, at approximately three times the cost of hydrogen compression. 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.

After liquefaction, the liquid hydrogen is dispensed to delivery trucks and transported to distribution sites where it is vaporized to a high-pressure gaseous product for dispensing. A high upstream investment in liquefaction plants is needed. The infrastructure down the supply chain is also expensive and may only pay off if hydrogen is delivered in large quantities and over large distances.

Figure 6: An Air Liquide truck delivering liquid hydrogen[13]

[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, one operated by Air Liquide in France, and one operated by Air Products in the Netherlands. 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] http://www.hydrogencarsnow.com/index.php/hydrogenforklifts/air-liquide-high-on-hydrogen-fuel-cell-forklifts/

Hydrogen pipelines

Pipelines are an efficient means of transporting large quantities of hydrogen and are the only known viable large-scale hydrogen logistics solution from an economic and practical perspective. Pipelines also offer the advantage of some level of inherent storage 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 hydrogen users such as petroleum refineries or chemical plants. [14]

Other hydrogen logistics options

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

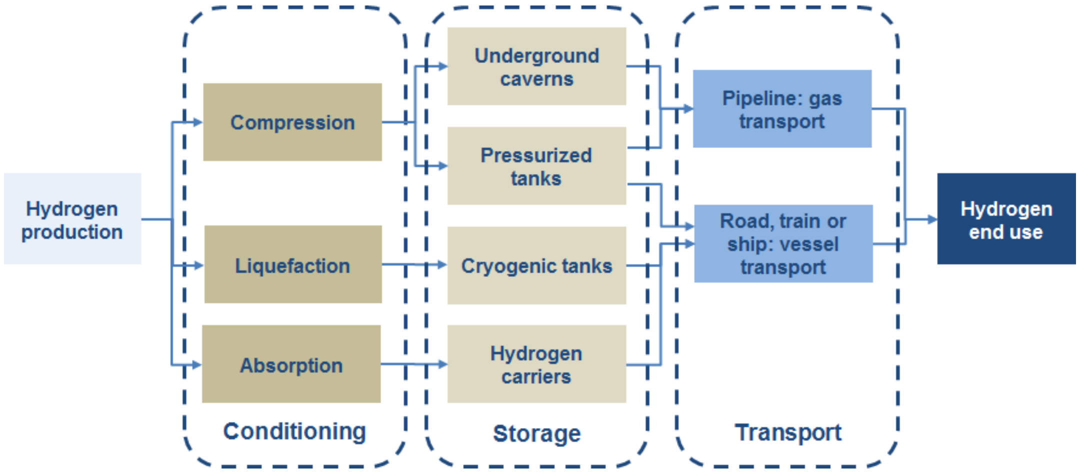

Figure 7: Overview of options for hydrogen conditioning, storage, and transport[15]

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.[16] The materials used

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

[15] Based on Fig 61, Hydrogen based energy conversion (SBC Energy Institute, 2014).

[16] *Technology and Manufacturing readiness of early market motive and non-motive hydrogen storage technologies for fuel cell applications*, Rönnebro (2012).

tend to be heavy (e.g. 100kg of storage system per kilogram of hydrogen[17]), 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.[18] 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[19] 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.

Figure 8: Hydrogen dispensers (at the Lea Interchange depot in London (left) and at the Kittybrewster HRS in Aberdeen (right))

[17] http://energy.gov/eere/fuelcells/materials-based-hydrogen-storage.

[18] See for example http://www.theengineer.co.uk/issues/june-2014-online/hydrogen-breakthrough-paves-way-for-ammonia-fuelled-cars/.

[19] 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.

ZERO EMISSION

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