Fuel cell bus deployment in the UK – lessons from JIVE and next steps

JIVEs / MEHRLIN projects

@fuelcellbus www.fuelcellbuses.eu

Clean Hydrogen Partnership

Co-funded by the European Union

Main author(s): Michael Dolman, Gianluca Galeazzi
Contributor(s): Nikhil Eswaran

June 2024

Dissemination status: final
Dissemination level: public

Approval process

Steps	Status
Work Package Leader	Approved
Coordinator	Approved
Clean Hydrogen Partnership	Pending

Disclaimer

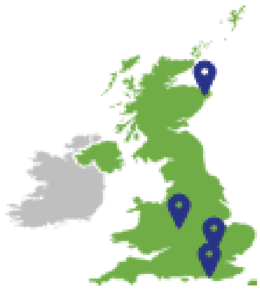
Contents

Executive summary

Introduction

The JIVE programme is Europe's flagship fuel cell bus demonstration initiative. Together, the JIVE and JIVE 2 projects are supporting the deployment of nearly 300 fuel cell buses in 16 sites across six countries. JIVE began in 2017 and concluded at the end of June 2024, with JIVE 2 beginning in 2018 and expected to complete in the summer of 2025. The JIVE projects were designed to demonstrate hydrogen buses and refuelling infrastructure at a scale never previously attempted in Europe, and to prepare the market for larger uptake in the 2020s. In addition to the deployment and operational activities, JIVE supports tasks relating to data analysis, capturing lessons learned and best practice, and dissemination of results to ensure that the impact of the project is maximised. This report summarises the results of a task focused on assessing the performance of the buses deployed in four UK sites under the JIVE and JIVE 2 projects. The work involved input from each of the city representatives and bus operators of the four sites: Aberdeen, Birmingham, Crawley, and London.

Operational experience



As of May 2024, a total of 85 fuel cell buses had been deployed in the UK under the JIVE programme, with a further 34 vehicles due to be delivered by the end of the year. All vehicles are supplied by Wrightbus. Each site has a different approach to sourcing hydrogen, including on-site production using existing assets (Aberdeen), new on-site production at a publicly accessible hydrogen refuelling station (HRS) (Birmingham), delivered gaseous hydrogen for depot-based refuelling (London), and delivered liquid hydrogen for depot-based refuelling (Crawley).[1] The vehicles have performed well in terms of range and fuel efficiency. However, all sites have struggled to achieve consistent, reliable operation of the vehicles and infrastructure over extended periods. There are multiple reasons, many unrelated to the buses. Several sites have experienced issues in securing fuel supplies, despite having long-term fuel supply agreements. The number of sources and suppliers of high-purity, mobility-grade hydrogen in the UK is currently limited, which has led to constraints in fuel supplies available when primary supplies have been interrupted. This is expected to change in the coming years, with the installation of new electrolytic production facilities and several companies investing in additional hydrogen storage and distribution infrastructure.

Despite the challenges faced, the cities and operators involved in the UK deployments recognise the potential for hydrogen in decarbonising public transport for routes / locations that are difficult to electrify. The partners have continued to work together constructively as well as with vehicle and hydrogen suppliers to resolve the issues faced and ensure reliable operation of the fleets needed to demonstrate the viability of fuel cell buses.

Other project achievements

The JIVE projects have led to several first-of-a-kind developments. Notable achievements from the UK projects include:

- Deployment of the world's first fleets of fuel cell double decker buses.

[1] Note that the Crawley HRS using liquid hydrogen has not yet been fully commissioned due to challenges securing the required permits to use the station at full capacity. Work is ongoing to resolve this issue.

- Installation of high-capacity hydrogen refuelling stations designed for expansion with minimal additional CAPEX investment. This includes the HRS in Crawley, which is designed to accept liquid hydrogen and demonstrates a low-footprint solution that can support whole depot conversion to zero emission buses.
- The project unlocked significant investments in modifications to depots required for the safe maintenance of fuel cell buses. Furthermore, the project catalysed activity leading to progress towards guidance for standardised approaches to depot modifications.
- Establishment of a fuel cell bus user group, which offers the opportunity for operators to exchange information on a range of relevant topics and for "follower" sites to learn from those with greater experience.
- Development and delivery of new training for drivers, with a focus on eco-driving, using techniques to maximise fuel efficiency. Adoption of these practices reduces fuel consumption independent of the powertrain technology.
- Raised awareness of hydrogen buses amongst operators and other interested stakeholders. The cities and operators involved in JIVE have communicated information to a wide range of organisations and hosted a large number of depot visits for interested parties from multiple countries.

Next steps

For hydrogen to play a role in decarbonising public transport (and other areas of the transport sector), the issues encountered by the UK-based operators in the JIVE projects must be resolved urgently. Bus operators and others in the sector (e.g., public transport authorities and investors) are adopting and implementing decarbonisation strategies now, hence the need for urgent action if hydrogen is to gain a meaningful share of the market. Greater resilience is required in the supply chains for both vehicle and fuel supplies. The industry must aim for the highest possible levels of availability (>90% of the fleet reliably in service), which will require redundancy and robust back-up options to mitigate the impacts of failures in primary fuel production / supply routes. It is worth noting that other projects within JIVE beyond the UK have not experienced the same level of issues with accessing reliable fuel supplies. For example, in Cologne, where 50 fuel cell buses have been in operation since 2022, the operator has access to multiple hydrogen refuelling stations, each with a different owner / operator.

While this analysis has focused on the UK-based activities in JIVE, the findings are relevant for any sites considering adopting fuel cell buses, and to those with existing fleets considering expansion. The analysis and discussions with cities and operators have led to sets of recommendations for industry (bus and hydrogen / infrastructure providers), bus operators, and governments / policy makers, which if followed should help to unlock the potential of clean hydrogen in decarbonising public transport.

Introduction

Document purpose

The JIVE projects have supported the deployment and operation of fleets of fuel cell buses in four cities / sites in the UK. All the UK buses are from the same manufacturer (Wrightbus), and the same model of vehicle has been operating in Aberdeen, Birmingham, and London (a double decker bus). The cities and operators are now planning further deployment of zero emission buses and agreed to work together under the JIVE programme to share experiences, discuss best practices, and identify the remaining challenges and potential solutions to further adoption of fuel cell buses. This is known as the "UK-specific analysis task" under the JIVE project.

This document summarises the results of this analysis and is intended for a wide audience of interested stakeholders, including public transport operators, public transport authorities, suppliers of zero emission buses and refuelling / recharging infrastructure, funders, and policy makers. The overall aim is to capture and share lessons learned and to highlight the remaining challenges and potential solutions to facilitate wider uptake of fuel cell buses in the UK, elsewhere in Europe and beyond.

JIVE project context

EU policy context

The transition to zero emission buses has been underway across Europe for at least the past decade. The number of cities and in some cases whole countries committing to replacing diesel buses with alternatively fuelled vehicles[2] has been growing, as have the fleets of zero emission buses in operation, as illustrated by the figure below.

[2] Alternatively fuelled refers to vehicles not fuelled by petrol or diesel, including both zero emission options (such as battery electric and fuel cell electric) and other fuels such as compressed natural gas (CNG) and liquefied petroleum gas (LPG).

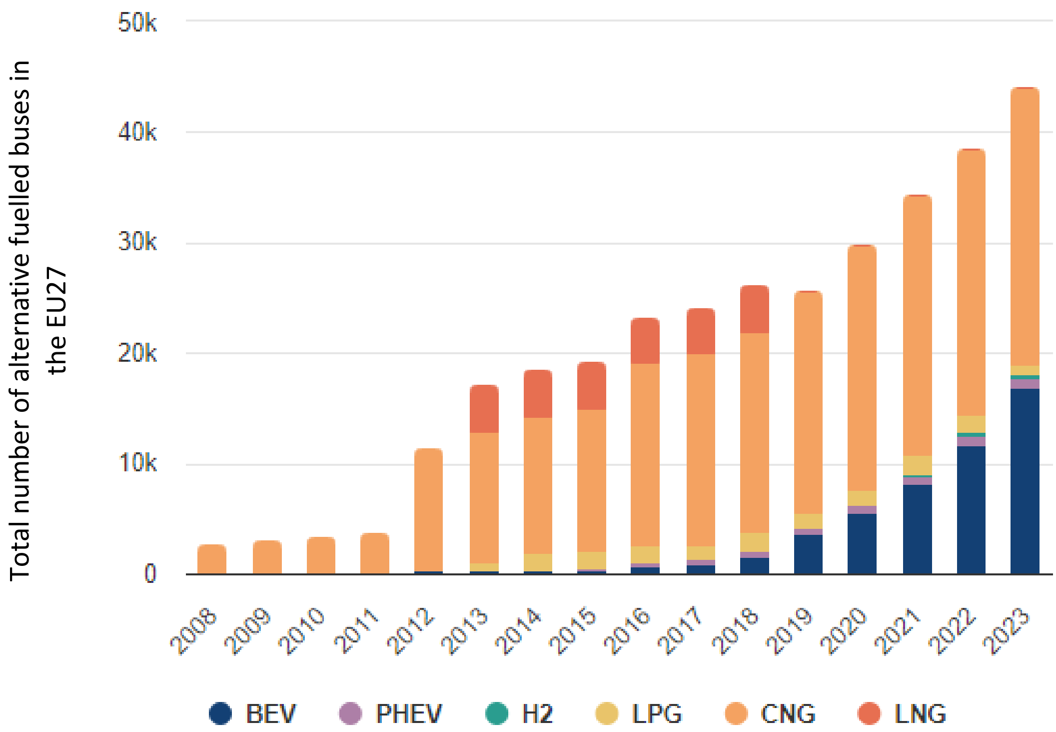


Figure 1: Total number of alternative fuelled buses (M2 and M3) in the EU27 by year[3]

BEV = battery electric vehicle, PHEV = plug-in hybrid electric vehicle, H2 = hydrogen, LPG = liquefied petroleum gas, CNG = compressed natural gas, LNG = liquefied natural gas

The Clean Vehicles Directive, adopted by the European Parliament and Council in June 2019, seeks to promote "clean mobility solutions in public procurement".[4] The Directive applies to cars, vans, trucks and buses (excluding coaches) purchased under public procurement rules, for the provision of passenger road transport services and through service contracts for public road transport services, special-purpose road passenger-transport services, non-scheduled passenger transport, refuse collection services, mail and parcel transport and delivery. The Directive sets national targets for procuring clean vehicles covering the period to 2030.

EU targets to reduce CO_2 emissions from new trucks and urban buses are now in place, and in January 2024 an agreement between the European Parliament and Council on strengthening CO_2 emissions standards for new heavy-duty vehicles (HDVs) entering the EU market from 2030 was announced.[5] The announcement included the following: "*To accelerate the transition to zero-emission public transport across Europe, new urban buses must reduce emissions by 90% as of 2030. All new urban buses will have to be zero-emissions by 2035.*" An even earlier date for all new city buses to be zero emission (of 2030) had previously been discussed.[6]

In addition, representatives of cities from across Europe, along with bus and equipment manufacturers and other transport organisations have signalled their intent to transition to

[3] Category M covers motor vehicles with at least four wheels. M2 and M3 relate to vehicles with more than eight seats in addition to the driver seat. M2 covers vehicles with a mass <5 tonnes. M3 covers vehicles with a mass >5 tonnes. Source : [Vehicles and fleet | European Alternative Fuels Observatory (europa.eu)]
[4] [Clean Vehicles Directive - European Commission (europa.eu)]
[5] [Agreement on strong EU targets to reduce CO2 emissions (europa.eu)]
[6] [EU Commission proposes all new city buses to be zero emission starting in 2030 (sustainable-bus.com)]

zero emission public transport fleets through the European Clean Bus Deployment Initiative.[7] Work on this began in 2016 and the initiative is based on three pillars: (1) a public declaration endorsing an ambition to accelerate deployment of clean buses, (2) a deployment platform to facilitate information exchange and leverage investment action, and (3) creation of an expert group bringing together actors from the demand and supply side.

In the mid-2010s, the market share and total number of fully zero emission buses (battery electric and hydrogen fuel cell electric) in Europe was very low, as shown in Figure 1 and Figure 2. Note that zero emission bus deployments in the UK are ahead of the EU average and the UK currently has the largest fleet of zero emission buses of any country.[8]

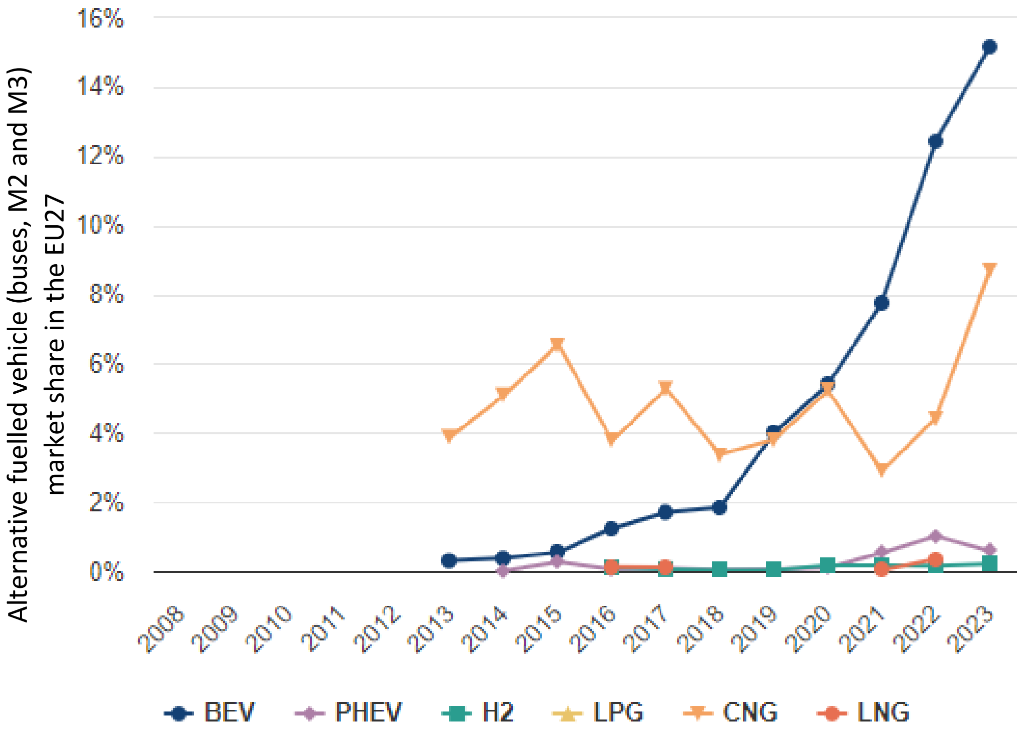


Figure 2: Alternative fuelled vehicle market share relative to total new vehicle registrations in the EU27 (M2 and M3)[9]

The JIVE project (see below for further details) was conceived in the mid-2010s, at a time when the zero emission bus sector was in its infancy. There were very few models of fuel cell buses available, and the deployment of battery electric buses in day-to-day operations was only just beginning. As Figure 2 shows, the market share of battery electric buses has increased significantly over the past decade, whereas sales of hydrogen-fuelled buses have remained relatively low. There are many reasons for this, some of which are explored in this report. While most people in the bus industry expect battery electric to be the dominant zero emission technology, many operators remain attracted by the operational flexibility that fuel cell buses can deliver and believe that hydrogen-fuelled vehicles will play a role in the full transition to zero emission public transport systems, principally where direct electrification is not possible.

[7] European Clean Bus deployment Initiative - European Commission (europa.eu)
[8] 42% of the city buses registered in Europe in 2023 are zero emission - Sustainable Bus (sustainable-bus.com)
[9] Source : Vehicles and fleet | European Alternative Fuels Observatory (europa.eu)

UK national policy context

The UK Department for Transport has consulted twice on ending the sale of new, non-zero emission buses, proposing dates between 2025 and 2032. The equivalent date for coach has been proposed as 2040.[10]

As in Europe, concerns have arisen over the difficulty electrifying all interurban routes and the resulting risks to rural bus services. The move by national government towards zero emission mandates for smaller vehicles in 2023 suggests a growing reluctance by the current administration to legislate, although the formal position remains that legislation is imminent.

The UK Government has supported the uptake of zero emission buses through various competitive funding schemes in recent years, such as the Low Emission Bus Scheme, Ultra Low Emission Bus Scheme, and Zero Emission Bus Regional Areas (ZEBRA) Scheme. No further capital support schemes for zero emission buses are expected under the current government, although the state is increasingly supportive through the UK Infrastructure Bank. Zero emission buses, including hydrogen but not other gases, benefit from favourable revenue support rates where services are operated commercially (most notably Bus Service Operators Grant (BSOG) in England).[11]

Overview of JIVE

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 nearly 300 new vehicles are being deployed and operated for extended periods in 16 different cities and regions across six countries. The objectives of the JIVE projects were to:

- Stimulate the market for fuel cell buses in Europe by creating demand for hundreds of vehicles.
- Reduce 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.

The JIVE project began in January 2017 (with JIVE 2 starting one year later), and the funded projects are due to conclude in June 2024 and June 2025 respectively. "JIVE" is a collection of fuel cell bus demonstration projects taking place in multiple cities and regions across Europe. An overview of the deployments supported under the JIVE programme (and associated MEHRLIN project which provided funding for some of the refuelling stations) is given below.

[10] https://assets.publishing.service.gov.uk/media/623dfbfbe90e075f06b37219/non-zero-buses-coaches-minibuses-consultation.pdf
[11] https://www.gov.uk/government/publications/bus-service-operators-grant-guidance-for-community-transport-operators/bus-service-operators-grant-guidance-for-community-transport-operators

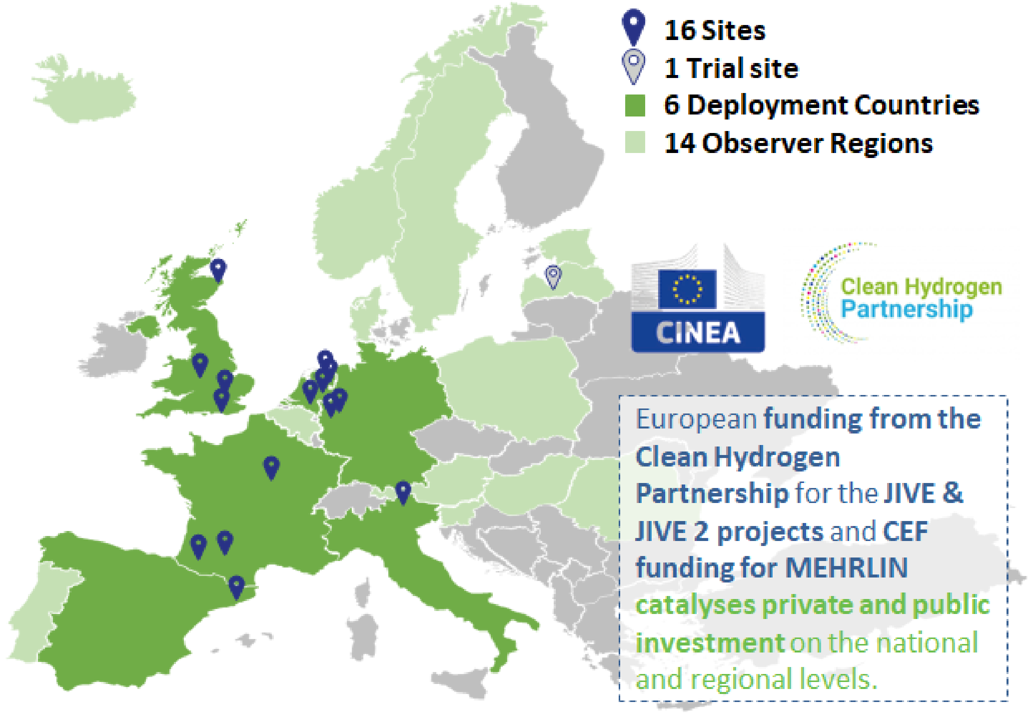


Figure 3: Overview of the locations in which fuel cell buses and hydrogen refuelling stations are being demonstrated in the JIVE projects

The projects included the following broad phases of work:

1) Procurement of hydrogen fuel cell buses and hydrogen supplies (and refuelling infrastructure).
2) Preparation for deployment.
3) Deployment and operation of the fleets of fuel cell buses – including collection, monitoring, and analysis of operational data.

While the original intention was for many of the buses supported under JIVE to be deployed within the first two years of the project (i.e., by early 2019), various factors caused delays across all sites, which meant that most buses did not enter service until the early 2020s. Nevertheless, by early 2024 several years of operational experience had been accumulated. Furthermore, in most sites the intention is to operate the buses in day-to-day service well beyond the conclusion of the funded projects.

Overview of deployment and operation of fuel cell buses in the UK

Summary of fuel cell bus demonstrations in the UK under JIVE and JIVE 2

The JIVE and JIVE 2 projects have supported deployment and operation of fuel cell buses and hydrogen refuelling stations in four locations in the UK, as shown and described below.

Aberdeen

FC bus fleet size in JIVE	25
Bus type	Double deck
Date of first bus delivery	October 2020
HRS / H_2 supplier	BOC – on-site production*

Birmingham

FC bus fleet size in JIVE	20
Bus type	Double deck
Date of first bus delivery	July 2021
HRS / H_2 supplier	ITM (Motive) – on-site production**

London

FC bus fleet size in JIVE	20
Bus type	Double deck
Date of first bus delivery	December 2020
HRS / H_2 supplier	Nel / Ryze – delivered gaseous H_2

Crawley

FC bus fleet size in JIVE	20 + 34
Bus type	Single deck / DD
Date of first bus delivery	April 2023
HRS / H_2 supplier	Air Products – delivered liquid H_2

* Buses have been refuelling at Kittybrewster to date. Additional refuelling facilities planned.

** Motive Fuels was sold by ITM Power to HYCAP in October 2023. HYCAP also owns Ryze Hydrogen.

Figure 4: Summary of the UK-based deployments of fuel cell buses under JIVE and JIVE 2

As of May 2024, a total of 85 fuel cell buses have been deployed in the UK under these projects, all supplied by Wrightbus. A further 34 buses have been ordered and are due to be delivered to Crawley before the end of 2024.

In **Aberdeen** an initial deployment of 15 double decker buses began in October 2020. In April 2022, 10 further buses were deployed.[12] The buses are refuelled at the existing Kittybrewster HRS operated by BOC (a Linde company). Additional refuelling facilities are planned in Aberdeen to support expansion of the fuel cell bus fleet, e.g., the Aberdeen Hydrogen Hub.[13]

In **London,** 20 double decker buses were delivered in December 2020. These have been operational since mid-2021 serving routes 7 and 245 on the Transport for London (TfL) network. The HRS for these buses is operated by Nel, and has gaseous hydrogen supplied through tube trailer delivery from Ryze.

In **Birmingham,** 20 double decker buses were initially delivered in July 2021 and began operations in December of that year. The buses are refuelled at a publicly accessible HRS in Tyseley, which is operated by Motive Fuels. The facility includes a 3 MW electrolyser and dispensers for light duty and heavy duty vehicles. Motive Fuels was originally an ITM Power subsidiary but has since been sold to HYCAP in October 2023.

In **Crawley,** 20 single deck fuel cell buses were delivered in May 2023 and a launch event was held in June 2023.[14] A further 34 buses have been ordered and are due to be deployed by the

[12] Note however that the full fleet of 25 buses has not been in operation, partly due to the limited capacity of the existing refuelling infrastructure.

[13] Homepage - Aberdeen (bpaberdeenhydrogenhub.com)

[14] £30 million investment in pioneering hydrogen bus fleet and refuelling station launched for services in and around Gatwick Airport (go-ahead.com)

end of 2024. Furthermore, in March 2024 it was announced[15] that funding has been secured for a further 43 fuel cell buses to be operated by Metrobus.[16] The refuelling strategy is to use a depot-based HRS installed by Air Products. The station, which is based on storing liquid hydrogen delivered to the site, has sufficient capacity to allow the entire depot (>100 buses) to be transitioned to fuel cell buses. The liquid hydrogen is converted into gaseous hydrogen at the site for dispensing into the buses at 350 bar. However, as of May 2024, approval for operating the HRS at full capacity has not been secured. The site requires hazardous substance approval, but the UK's Health and Safety Executive (HSE) has advised the local authority against the application.[17] The various stakeholders involved continue to work with the HSE and other relevant bodies to inform a thorough assessment of the risks and to ensure that appropriate mitigation measures are in place and that the HRS can be commissioned at full capacity. While this process is on-going, the HRS must operate at reduced capacity, which is limiting the operation of the fleet.

All buses deployed across the London, Aberdeen and Birmingham sites are Streetdeck Hydroliner double deckers, manufactured by Wrightbus. This is the world's first hydrogen double decker bus model that has been developed. In the initial phases of the JIVE project, an extensive outreach with bus OEMs was conducted to determine which model bus to use in the trial. Wrightbus was selected given their relevant experience and advanced manufacturing capacity for fuel cell buses at the time.

Fuel cell bus performance to date

The technical performance of the buses is one of several key factors that have been monitored throughout the project to evaluate its success. The trial of fuel cell buses through JIVE had as a main goal the demonstration of fuel cell technology at larger scales, and in the UK, there was specific focus on determining the performance of a double decker bus model. Several different parameters can be analysed to determine bus performance. In this study we focus on the following two metrics: bus usage and fuel consumption.

Bus usage

We have defined bus usage as a metric to describe the number of days per month that a single bus is operational. An operational day is considered to be one where a bus travels a distance of >20 km. Figure 5 below show the bus usage data obtained for all four UK sites across their relative operational periods. The graph shows the average percentage of operational buses in each site for each month. Note that this metric was selected as it could be readily inferred from the data available and provides insights into the overall availablity and level of operation of the fleets. Note that bus operators are focused on delivering reliable services according to defined timetables and contractual requirements and hence are concerned not only with availabilty but also the level of variability in performance of the buses / fleet as a whole.

[15] Fleet of hydrogen powered buses set to launch across parts of Surrey, Sussex and Kent following successful bid for £10 million of government funding | Surrey News (surreycc.gov.uk)

[16] This funding is from the UK Government's ZEBRA 2 scheme and the partnership is between Surrey County Council, Metrobus (Go Ahead), West Sussex County Council, Kent County Council and London Gatwick.

[17] Hydrogen buses: Crawley's fleet hit by fuel plant planning delay - BBC News

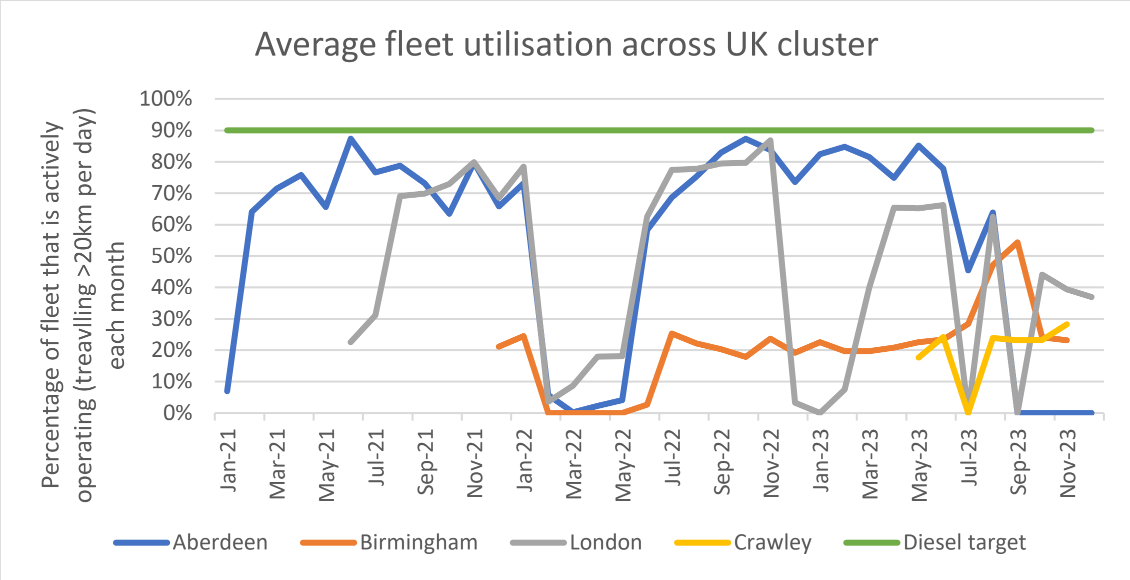


Figure 5: Average fleet utilisation of fuel cell buses by site in the UK (2021–2023)

Fleets of diesel buses typically have an average availability >90%, i.e., for every ten buses in the fleet, nine would be expected to be available for operation on any given day.[18] The green line on the graph above corresponds to 90% of the fleet being available. While there have been some periods during which some of the fleets of fuel cell buses in the UK have operated well (approaching this level), on average, availability to date has been well below the level required to deliver reliable services to passengers. This is especially evident in Birmingham and Crawley where operations have struggled to achieve fleet utilisation >30%. In both these sites, low utilisation of fuel cell buses was caused primarily by a lack of hydrogen supply. Lower availability levels for new products (as is the case for the vehicles deployed at Crawley) are also to be expected for any new fleet as teething issues are identified and resolved in the initial months of operation. As explained above, the Crawely HRS has not yet been commissioned at full capacity, leading to restrictions on the number of buses that can be operated. Techncial issues with the hydrogen production and dispensing equipment at Tyseley have led to extended periods during which the fleet of buses in Birmingham could not be operated fully. Even in Aberdeen and London, which have had periods during which much higher average availability levels have been achieved, the overall performance has to date been far too variable and inconsistent to deliver reliable services.

In cases where fuel cell buses have been unavailable diesel buses have been used as a replacement to ensure services remained available for passengers. Clearly, the issues causing low availability of the buses (discussed throughout this report) must be resolved for hydrogen fuel cell buses to be adopted at larger scale.

The data presented above show that each site had several periods of downtime. Two main types of downtime have been observed: fleet wide, and isolated. An example of fleet wide downtime is in the months of February to May 2022. In February 2022 an issue with faulty mounting brackets in the hydrogen storage tanks in the buses in Aberdeen was detected. This issue was noted by Wrightbus who determined it safest to recall all buses deployed in the UK for inspection to ensure no other sites would be affected by the same problem. These

[18] This fleet availability figure is not 100% as buses are sometimes off the road for maintenance and repairs.

inspections and resultant modifications were done over the course of several months, and buses were returned to operation in their respective locations in June 2022.

Isolated issues were present across all four sites in the UK. These took the form of a number of different mechanical, electrical and operational faults. In most cases, these faults were only minor and could be resolved rapidly, however operators reported resolution of these issues sometimes took longer than expected. A lack of available support from Wrightbus, as well as a shortage of appropriately trained maintenance personell resulted in buses having longer downtime than expected. Further to this, inexperienced drivers who had not previously operated fuel cell buses were, on multiple occasions, manually resetting buses to eliminate warning lights that appeared. This led to issues not being tackled premptively and causing larger maintenance requirements further down the line. Driver training has since been developed in all UK clusters, and lessons learnt have been shared across operators, but this will need to take place in a more standardised manner to support commercialisation efforts.

Fuel consumption

Fuel consumption is an important metric to monitor and for fuel cell buses this is typically expressed as kilograms of hydrogen consumed per 100 kilometres driven. The fuel consumption of the buses across the four locations to date averages in the range of **5.5-9 kgH_2/100km**. This is a significant improvement compared to previous generations of fuel cell buses that had been monitored in Europe. Differences in terrain and route topography can influence the fuel consumption, however the data from the four sites (Figure 6) indicate that across the UK the results were similar. An interesting observation when comparing the UK data to other clusters in the JIVE project is that the UK buses tend to have lower fuel consumption than those in mainland Europe. This is consistent with results from previous projects.

The fuel consumption in all sites remains relatively constant throughout the year, having only minor fluctuations in an irregular pattern. This suggests that ambient temperature (in different months and seasons) has little effect on the performance of the buses. This is an advantage over battery electric buses as the range of BEBs can be highly sensitive to ambient temperature (and hence heating / cooling demands of the bus). For example, in sub-zero temperatures, a significant proportion of a zero emission bus's energy demands can come from cabin heating to maintain comfort for passengers. Assuming operators need buses to have the same range all year round, this implies that the energy stored on board needs to be designed based on the most extreme day (in terms of heating / cooling demand). Fuel cell buses offer an advantage over battery electric buses in this regard as additional fuel can easily be added on days of extreme weather (compared to the battery electric bus case, where there is a need to carry over-sized batteries for most of the year to cope with days / months of temperature extremes).

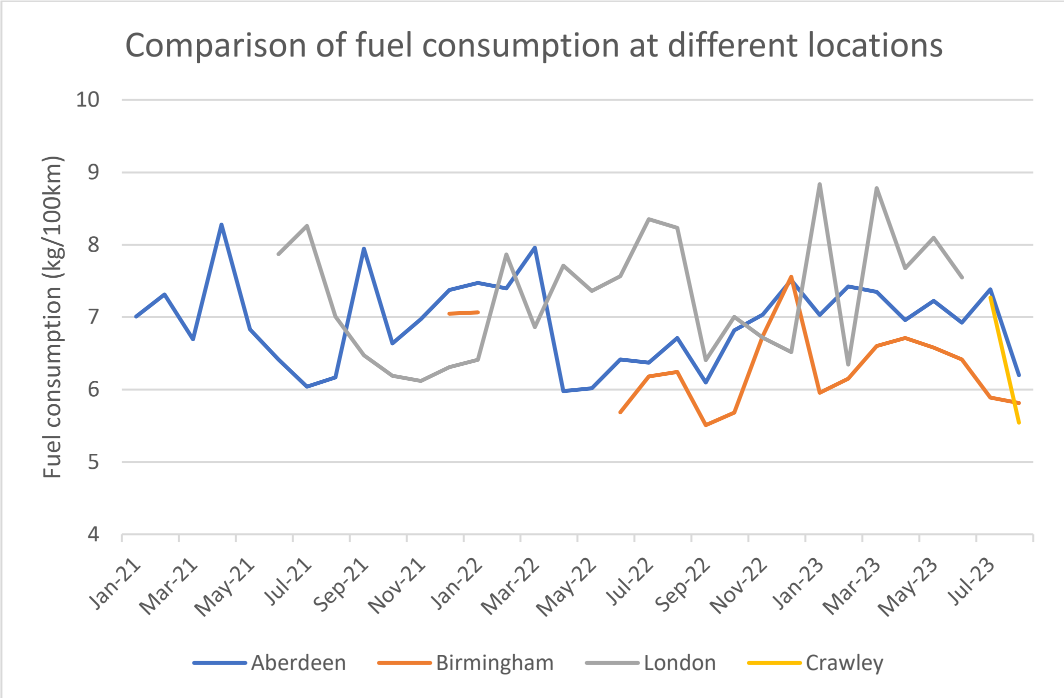


Figure 6: Average fuel consumption of the fuel cell buses across the UK deployment sites

Key achievements

While there have undoubtedly been challenges in terms of achieving consistent, reliable operation of the fuel cell buses in the UK under JIVE, it is important to bear in mind the context. In particular the fact that the use of hydrogen in mobility applications is not widespread in the UK, which means that the market is immature and supply chains are not yet developed. The JIVE project has led to several first-of-a-kind achievements and numerous other positive impacts, some of which are described below.

First of a kind double decker fuel cell buses were successfully built, deployed, and operated in four different cities. This is a world first demonstration of such buses, and thus one of the key milestones for the UK cluster in the JIVE project. The buses operated with low fuel consumption and delivered the quoted mileage. This is a clear advantage compared to the counterfactual battery electric buses that have been deployed thus far which have shown high variability in range across the year, and overall lack of ability to deliver the promised range. Careful planning is required before deploying battery electric buses to check their compatibility for defined routes, and when in service active management of energy consumption is needed. Fuel cell buses offer a higher degree of operational flexibility (closer to that provided by diesel buses). Similarly, the demonstration of rapid refuelling has been successful, with London buses reaching the target of five minutes to refuel; sufficiently rapid to be comparable to diesel.

The demonstration has also helped to set the foundation for a hydrogen network in the UK which will support future commercialisation efforts. The development of depots across the country, including preparation for further roll out and scale up of fleets, has begun to develop the infrastructure for future fuel cell bus projects. The project has also helped to progress towards the development of guidance for a standardized approach to depot modifications to accommodate fuel cell buses. This will help expedite the process for future depots being constructed in the UK, and provide developers with the lessons learnt from the JIVE project.

Strong communication, partnership and knowledge sharing have helped increase the collective learning across the whole sector. Bus operators from across the country have had the opportunity to discuss their learning through initiatives such as the JIVE roundtables held throughout the project. A fuel cell bus user group has been established for UK operators to offer a place beyond the JIVE project where operators can continue to engage. Some of the key achievements include:

- Operators new to fuel cell buses have been introduced to the technology, and interest has grown.
- The project has led to deeper relationships between the bus operators and public bodies (city councils and public transport authority (TfL)), who need to work closely together to deliver the transition to zero emission public transport fleets.
- The project helped catalyse exploration other potential applications for hydrogen such as coaches.
- Learnings on required driver training, and best practices for operating the buses (e.g. using eco-driving to minimise fuel consumption and maximise range) have resulted in increased fuel efficiency not only in the fuel cell buses but also in the battery electric and diesel portions of the fleets.

These discussions have been highly productive and received positive feedback from the operators which have found a place to share their experiences and collectively agree on next steps required for commercialisation of fuel cell buses.

There has also been strong collaboration between bus operators and with the public sector representatives (city councils and TfL), with many discussions focusing on how best to support future fuel cell bus projects at larger scales. Beyond sharing lessons learnt with other operators, consistent engagement with Wrightbus has been maintained to ensure any technical issues have been identified and can be minimised in future generations of the buses. Similarly, conversations with fuel suppliers have been held to try and streamline the hydrogen supply for future deployments. This has been one of the main bottlenecks faced thus far, and persistent conversations are key to ensure operational improvements are seen.

Overall, the JIVE demonstration of fuel cell buses in the UK has had some successes. The interest for future rollout of larger fuel cell bus fleets remains strong from both operators and cities, as well as technology developers. The Aberdeen HRS has hosted over 300 visitors and the London site over 50 in 2023 alone. The variety of interested visitors, and the large number of visit requests across all UK sites show the high interest in hydrogen technologies from government, technology developers, operators, and other key stakeholders. Investments into depots accounting for future expansion of fleets reaffirms the goal of reaching commercial scale. Some scale up has already been planned and received funding – the Crawley fleet is set to almost triple in size to 54 buses from the current 20; a further 43 buses have recently been announced to launch across Sussex, Surrey and Kent having received £10m in funding[19].

Further uptake of fuel cell buses: remaining challenges and proposed solutions

Introduction

JIVE was intended as a stepping stone to larger scale deployment of fuel cell buses on a commercial basis in the context of an increasing shift towards mandating zero emission buses. While much has been achieved and learnt since the project began in 2017, as outlined above,

[19] A fleet of hydrogen powered buses is set to launch across parts of Sussex, Surrey and Kent following successful bid for £10 million of government funding - West Sussex County Council

several barriers to further deployment remain. This section summarises the principal remaining challenges and potential solutions.

Barriers and solutions to further uptake of fuel cell buses

Hydrogen supply and infrastructure

Issue	Potential solutions
Lack of availability of reliable hydrogen supplies	Further investment in facilities to produce, store, distribute, and dispense hydrogen for mobility applications in the UK is needed. Clearly, there needs to be a positive business case for hydrogen suppliers to invest. Programmes are in place in the UK designed to support the deployment and operation of such facilities, such as the Net Zero Hydrogen Fund[20,21] and Hydrogen Business Model.[22] New equipment delivered by projects supported under these programmes is due to be installed from 2025. More infrastructure alone may not be sufficient. The hydrogen supply industry must recognise the need of operators in the mobility sector to have fuel available 100% of the time when it is needed and put in place systems and processes that can allow this target to be met.
Lack of certainty over medium to long-term availability (and price) of hydrogen	As noted above, projects are underway to increase domestic production capacity of renewable hydrogen. Successful delivery of the supported projects will increase availability of hydrogen for various sectors, including mobility. Long-term fuel supply agreements have a role to play in addressing this barrier and can provide mutual benefits for the customer and supplier.
High hydrogen prices and risks of high hydrogen price variability	At scale, hydrogen production costs are dominated by energy costs. Access to low cost, renewable energy sources over long periods is needed (e.g., via long-term power purchase agreements). Hydrogen customers entering into long-term supply agreements with hydrogen suppliers with agreed pricing structures can help give greater certainty over the future demands for fuel. Risks associated with delivering / dispensing the fuel at a cost below the agreed price then sits largely with the hydrogen supplier.
Insufficiently high hydrogen refuelling station reliability	It is important to identify reasons for under-performance / failure of HRS and for suppliers to learn from the experience to improve produce and service offerings. Some progress is being made in this area, for example improvements in HRS reliability have been seen in some sites during the JIVE project. Including redundancy in the design of hydrogen refuelling stations (and the entire hydrogen supply chain) is an important element of achieving the reliable, resilient fuel supplies required to operate

[20] Net Zero Hydrogen Fund strands 1 and 2: summaries of successful applicants round 1 (April 2022) competition - GOV.UK (www.gov.uk)
[21] Net Zero Hydrogen Fund strands 1 and 2: summaries of successful applicants round 2 (April 2023) competition - GOV.UK (www.gov.uk)
[22] Hydrogen Production Business Model / Net Zero Hydrogen Fund: HAR1 successful projects (published December 2023) - GOV.UK (www.gov.uk)

	fuel cell buses on a commercial basis. Redundancy implies higher cost, which is easier to justify / absorb at larger scales. Organisations planning to adopt hydrogen for fleet vehicles should also undertake due diligence on potential suppliers and select those that have a good track record of supplying and operating reliable refuelling stations.

Vehicle-related barriers

Issue	Potential solutions
Limited choice of fuel cell buses and coaches	There has been good progress in terms of choice of fuel cell buses since the start of the JIVE project. While there were very few options available in the mid-2010s, many more suppliers have since developed hydrogen-fuelled options. For example, there were at least ten different models of fuel cell buses and coaches on display at the Busworld Exhibition held in Brussels in October 2023. Nevertheless, the UK-based operators involved in the JIVE project would welcome the opportunity to procure fuel cell buses from a wider range of suppliers. Fuel cell coaches are at an earlier stage of development compared to city buses and coach operators need to work with vehicle OEMs to inform the development (and testing) of suitable products.
High fuel cell bus CAPEX	Fuel cell buses come with a significant price premium over traditional (diesel) buses. However, the organisations involved in the UK-specific analysis task believed that prices of fuel cell buses are (and are expected to be) similar to those of battery electric buses, which are becoming the default choice for new vehicles. The total costs of delivering bus services comprise multiple elements: driver costs, fuel, bus repair and maintenance, bus CAPEX, etc. Typically, CAPEX is not the dominant factor (typically 10% of the total cost of ownership for diesel buses, circa 20% for zero emission buses) and therefore hydrogen bus price was not deemed to be a major barrier to further uptake. Although battery electric buses cost around twice the price of diesel buses, they typically lead to OPEX savings. Thus, if solutions to finance the additional CAPEX can be found, there is a business case for battery electric buses. Fuel cell buses do not, in general, offer OPEX savings relative to diesel, which makes the economic case more challenging. Clearly, reducing the prices of fuel cell buses (whilst maintaining quality) is likely to improve the business case for adopting the technology and bus OEMs and key component suppliers have a role to play here. If the other barriers described in this report can be addressed, leading to larger, more consistent orders for fuel cell buses, there is potential for further efficiencies in the supply chain that could lead to reduced costs (and hence prices). If fuel cell bus prices fall below those of battery electric buses, the hydrogen option may become more attractive to some operators sensitive to up-front costs (even if OPEX is higher for fuel cell buses).

High fuel cell bus maintenance costs	Offers from bus suppliers such as parts assurance packages (essentially providing insurance against failure of key components) and/or contracted maintenance services can provide bus operators with more certainty over the lifecycle costs of running fuel cell buses. As experience with and confidence in the technology grows, operators may find a more cost-effective approach involves retraining technicians to allow an increasing amount of maintenance tasks to be carried out by their employees. It is important to note that rapid access to spare parts for repair and maintenance of fuel cell buses is also needed, and bus OEMs need to work with their supply chains to ensure this.
Lack of expertise within bus operators to operate and maintain fuel cell buses	Recruit, train, and retain technicians / other staff to ensure a suitably qualified workforce is in place. Opportunities exist for sending staff on specialist training courses run by the fuel cell supplier, for example.
Lack of expertise within supplier organisations to resolve technical issues	Suppliers need to recruit, train, and retain sufficient staff to be able to support their products in service. A general theme that arose in discussions with the UK bus operators in JIVE was a need for suppliers (of buses and hydrogen / refuelling infrastructure) to focus more on aftersales support. Educational institutions have a role to play in providing suitable courses and training programmes for people to (re)train with the requisite skills. On-the-job experience is also critical, which suggests suppliers should give staff on-going learning and development opportunities and seek to retain employees with specialist expertise. It is worth noting that the barrier relating to too few people with sufficient training and experience to maintain / repair vehicles (both within the supplier organisations and the bus operators) is not a hydrogen-specific issue. There is a need for workforces to retrain and upskill in new areas (e.g., working with high voltage systems) as part of the broader shift towards zero emission mobility solutions.
Uncertainty over fuel cell bus / key component lifetimes	Vehicle OEMs and component suppliers should provide sufficiently long-term guarantees of the performance of their products and potentially introduce new commercial models that reduce/remove the residual value risk for bus operators (e.g., working with leasing companies).

Figure 7: Fuel cell buses and coaches on display at the Busworld Exhibition (October 2023)

Other topics

Several other topics with the potential to delay or hinder the uptake of fuel cell buses were identified and discussed by the UK-based operators, as summarised below.

- **Refuelling speeds** – one of the principal advantages of fuel cell buses is the potential to refuel the vehicles rapidly, so that from an operational perspective they can be used in a similar way to diesel vehicles. The time required to refuel hydrogen buses depends on several factors, and although fill rates varied between sites, the project demonstrated refuelling times of below five minutes per bus. While this is slightly longer than it typically takes to refuel a diesel bus, such fill rates were considered adequate for most operations. Due to the way that HRS operate, care must be given to the specification of new stations considering the quantity of hydrogen to be dispensed within a given window, number of consecutive refuelling events needed (back-to-back capability), target refuelling time per bus, etc.
- **Insurance** – securing insurance for the fuel cell buses deployed in the UK under the JIVE programme was straightforward. Some operators self-insure their vehicles and took this approach with the fuel cell buses.
- **Awareness of hydrogen as an option for decarbonising public transport** – the JIVE projects have been successful in raising awareness of hydrogen buses, and interest in the technology from operators beyond the projects (both in the UK and elsewhere in Europe) remains strong. As the JIVE projects enter their final phases, it is important to ensure that the lessons learned are captured and shared with other interested parties.

Conclusions

Based on an evaluation of the experiences of the companies operating the fuel cell buses deployed under JIVE and JIVE 2 in the UK in early 2024, the following conclusions can be drawn.

Experiences in the JIVE projects in the UK

- The original objectives of JIVE have been partially met by the demonstrations in the UK. The project has demonstrated the benefits of fuel cell buses in terms of range, rapid refuelling, limited decline in range throughout the year, etc. The buses also showed excellent fuel efficiency, a significant improvement on previous generations. The sites that ran competitive procurement exercises for hydrogen supplies secured refuelling infrastructure and long-term hydrogen supply agreements at prices that allow sustained, on-going operation for many years (one site contracted for hydrogen supplies for the buses over ten years). However, the ambition of JIVE to act as a catalyst to stimulate further, large-scale deployment of fuel cell buses on a more commercial basis has not yet been achieved in the UK in full, for reasons outlined below.
- Operations of the vehicles and refuelling infrastructure have not been without challenges. All four sites have to date struggled to maintain consistent, reliable operation of the fuel cell buses. While the fuel cell systems have performed well, a range of other issues (some relating to the buses, and others concerning hydrogen supplies and refuelling infrastructure) have prevented the fleets of vehicles delivering reliable services for extended periods. Although there have been periods within the project when some of the fleets operated reliably, the average downtime and numbers of vehicles off the road have been relatively high. The cyclical nature of the performance of vehicles has meant that the operators have had to use other (diesel) vehicles as a back up to maintain service levels.
- Hydrogen supply has been a major challenge in some of the sites. Clearly, having access to fuel is fundamental to being able to operate the buses. Most of the UK sites have experienced periods during which a lack of hydrogen has restricted the ability to operate the buses. The reasons differ by site (as outlined above, each site had a different hydrogen supply / refuelling solution). Despite extensive efforts of the cities and operators to secure alternative hydrogen supplies, interruptions to fuel supplies have negatively impacted operations. Improvements have been made during the project, including new investments from hydrogen suppliers, and work is underway to provide more robust, resilient hydrogen supplies.
- The challenges faced in achieving consistent, reliable operations of the fleets of fuel cell buses in the UK under JIVE have delayed further uptake. There were opportunities to order additional fuel cell buses in some sites during the project (e.g. in London, where the HRS has capacity to refuel a larger fleet), but commitments to expanding fleets can only be made with greater confidence in the robustness and resilience of the operations. It is worth noting that these issues have not impacted sites in countries elsewhere in Europe to the same extent. For example, since the start of JIVE the bus manufacturer Solaris has deployed over 200 fuel cell buses in Europe and has orders for a further 600 vehicles for delivery between 2024 and 2025.[23] Solaris (like Wrightbus) uses fuel cells from Ballard, and the company announced in April 2024 an

[23] Solaris at Next Mobility Exhibition with the Urbino 12 hydrogen bus (600 units in order book) - Sustainable Bus (sustainable-bus.com)

order for 1,000 fuel cell “engines” by Solaris for 12m and 18m buses to be delivered over the period to 2027.[24]

- Many lessons have been learned throughout the project, and the JIVE programme has led to numerous other positive developments for the zero emission bus sector (as described above). There is interest from the cities and operator involved in JIVE to expand the fleets of fuel cell buses, indeed plans for deployment of >100 additional vehicles were developed during the project. However, the operational performance of the overall system required for fuel cell buses (hydrogen supplies, refuelling infrastructure, and the vehicles) has not yet been sufficiently reliable to allow further commitments to procure more vehicles in all sites.

Role of hydrogen in decarbonising buses in the UK

- Despite the challenges encountered in the JIVE projects, the UK-based operators have persevered with the trials and remain interested in hydrogen as a fuel for public transport decarbonisation. Like most bus operators, those involved in the UK demonstration under JIVE are taking an “electrification first” approach to transitioning to zero emission buses, i.e., replacing diesel buses with battery electric buses where possible as this solution is typically the lowest cost way of delivering zero emission services. However, there was consensus amongst the group of UK operators that battery electric buses are unlikely to provide a like-for-like zero emission solution for all routes and depots, and that to realise a transition to fully zero emission fleets, there is a role for hydrogen fuel cell buses.
- One of the principal advantages of fuel cell buses over battery electric vehicles is the potential to offer higher and more consistent range. Coupled with rapid refuelling, this means fuel cell buses can provide better operational flexibility. Battery electric buses available today offer a real-world range at the start of their lives of around 170 – 220 miles (range declines over the life of the bus as batteries degrade). While this is sufficient for many routes, some require vehicles that can travel further between recharging / refuelling (without increasing the fleet size), which creates an opportunity for fuel cell buses. However, the view amongst UK bus operators in JIVE was that if battery electric buses could offer a guaranteed real-world range of 300 miles, this technology would likely be capable of serving all routes covered by non-interurban buses in the UK (leaving very little market for fuel cell buses).
- It is important to note that while in theory battery electric buses with longer ranges could replace most diesel buses, various practical considerations must also be considered when planning the transition to zero emission. For example, the ability to secure adequate power supplies at depots to recharge all buses. In some cases, the costs of providing a sufficiently high capacity grid connection may be prohibitively expensive (it may be more cost effective to relocate the entire depot), and securing additional power supplies can take many years.
- The operators in the JIVE project therefore believe that a portfolio of technologies is needed for a complete transition to zero emission bus fleets.
- In addition to urban buses, there is a potential role for hydrogen fuel cell solutions in the coach sector, as the duty cycles of coaches make it challenging to replace diesel with battery electric solutions. However, several challenges still need to be overcome for uptake of hydrogen in the coach sector (e.g. provision of reliable, cost-effective hydrogen supplies in locations suitable for coaches, development and demonstration of fuel cell coaches, an economically viable total cost of ownership, etc.). Work on

[24] Ballard announces largest order in company history - 1,000 engines to power Solaris buses across Europe

developing and demonstrating hydrogen-based solutions for coaches is on-going, for example via the EU-funded CoacHyfied project, which is exploring both new build fuel cell coaches and retrofit solutions.[25]

Recommendations

Recommendations for industry (bus and hydrogen / infrastructure providers)

- The experiences in the JIVE projects show the importance of reliable, robust hydrogen supplies for fleets of fuel cell buses. For the existing fleets of fuel cell buses to be used to their full potential there is an urgent need to resolve the issues with hydrogen supplies at all sites.
- If fuel cell buses (and coaches) are to play a significant role in decarbonising public transport, greater access to affordable, resilient, low-carbon hydrogen supplies suitable for mobility applications is needed. The requirements of customers in the mobility sector should be taken into account by developers of new hydrogen production and delivery systems (e.g., those being supported under the UK's Hydrogen Business Model). For example, it is critical for suppliers of fuel to bus operators to understand that there is no inherent temporal redundancy in the system; i.e., if fuel is not available when needed, buses cannot operate and in the limit operators lose their licences and businesses fail. This is different from hydrogen supplies to industrial markets, where typically there is more flexibility in the system.
- Continue to build expertise and capacity (i.e., numbers of suitably trained, experienced employees) to support vehicles and infrastructure in service. Given the nature of bus operations, support from suppliers needs to be available on a 24/7 basis.
- Investigate options for reducing the lead times of spare parts related to fuel cell buses and hydrogen refuelling stations. If hydrogen buses are to be deployed on a commercial basis at larger scale, extended downtime of vehicles / infrastructure cannot be tolerated.
- Consider developing new commercial models that reduce risks to bus operators. For example, all-inclusive solutions covering bus supply and maintenance and fuel, whereby responsibility for providing vehicles that can operate zero emission services reliably sits with one organisation, leaving bus suppliers to concentrate on delivering services to passengers.

Recommendations for bus operators

- If planning to introduce fuel cell buses into fleets for the first time, bus operators are advised to learn from the extensive experience accumulated via pre-commercial demonstration projects such as JIVE. There is a significant amount of guidance available which should be consulted.[26] Discussions with the cities / operators involved in the JIVE projects, and site visits where possible, are also recommended as a way of increasing knowledge and avoiding repeating past mistakes.
- Existing operators of fuel cell buses should seek to continue to collaborate with each other to share experiences and best practice. Continued engagement with suppliers and a willingness to work constructively to resolve outstanding issues is also recommended.
- Continue to invest in training staff to maintain the buses and seek opportunities to learn from the bus supplier's employees while the vehicles are in warranty or covered by service agreements.

[25] Homepage - CoacHyfied
[26] See for example information available on Fuel Cell Electric Buses | Knowledge base (fuelcellbuses.eu).

Recommendations for government / policy makers

- Continue to recognise the potential role of hydrogen fuel cell buses in the transition to zero emission public transport fleets and ensure that any new support schemes to assist operators with the additional costs of adopting zero emission buses are technology neutral.
- Increase the expertise and capacity of the Health and Safety Executive (HSE) to reduce the time required for approving new hydrogen infrastructure so that strategic decisions can be taken with reasonable confidence that solutions can be implemented and operated.
- Work with industry (via the HSE) to resolve the permitting issues currently restricting the use of the refuelling infrastructure at the Crawley depot.
- Ensure sufficient training centres / resources are available for upskilling workforces in preparation for the transition to fully zero emission bus fleets. Staff from bus suppliers and bus operators need training on topics such as dealing with high voltage batteries and hydrogen safety.

Project coordination:

ERM

Project dissemination:

Hydrogen Europe

The **JIVE and JIVE2 projects** have received funding from the Clean Hydrogen Partnership (formerly known as FCH JU) under Grant Agreement No 735582 and 779563.

This Joint Undertaking receives support from the **European Union's Horizon 2020** research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

The **MEHRLIN project** is co-financed by the **European Union's Connecting Europe Facility.**

@fuelcellbus
www.fuelcellbuses.eu

Clean Hydrogen Partnership

Co-funded by the European Union