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PUTTING FUEL CELLS TO WORK

FUEL CELL ELECTRIC BUSES:

AN ATTRACTIVE VALUE PROPOSITION FOR ZERO-EMISSION BUSES IN THE UNITED KINGDOM

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Executive Summary

De-carbonisation of the transportation sector is a necessity to improve air quality and reduce the amount of greenhouse gas (GHG) emissions globally. As several cities in the United Kingdom (UK) are imposing low emission zones in city centers, transit operators are looking for cleaner transit alternatives which can deliver the same the level of service as traditional diesel transit buses. There are several options for low emission buses with only a limited number of zero-emission options. Electric buses offer a quiet, comfortable and efficient solution with zero-emissions at the tailpipe. However, battery electric buses today have operational limitations including limited range, long charging time, and challenging large-scale expansion of the charging infrastructure.

At Ballard Power Systems (Ballard), we believe that fuel cell electric buses will provide operators with an affordable direct replacement of diesel buses with no compromise to service and operation.

In this paper we will highlight some of the key benefits of fuel cell electric buses:

- **GHG Reductions:** Fuel cell electric buses have zero tailpipe emissions. They produce no nitrogen oxides, sulfur dioxides or particulate matter. The production of hydrogen from renewable energy sources provides full carbon neutrality from a well-to-wheel perspective and significantly reduces carbon dioxide (CO2) emissions in cities.
- **Performance:** Fuel cell electric buses are the only zero-emission technology to offer full vehicle performance (e.g. gradeability, highway speeds, and long range) over all types of transit routes.
- **Scalability:** The use of a compressed gas (like compressed natural gas or hydrogen) as a fuel for transit buses has proven to be a fully scalable solution up to hundreds of buses per depot without stressing electrical infrastructures.
- **Flexible Vehicle Integration:** With fuel cell modules in the range of 30 to 100 kilowatts, and a flexible battery hybridization model, bus OEMs can easily integrate fuel cell systems into all sizes of electric vehicle platforms as range extenders or for full propulsion.
- **Robustness:** With continuous technology improvements during the past ten years, fuel cell electric buses now demonstrate engine lifetimes exceeding 20,000 hours and greater than 85% service availability.

We will then look at the current major barriers to a wider adoption of fuel cell electric buses:

- **Cost:** Fuel cell electric bus capital pricing has decreased considerably as volumes have grown. Since the first deployments in the 1990s, purchasing costs for fuel cell electric buses have fallen by more than 75%. Currently, the target price for a 12-meter fuel cell electric bus is €650,000 (£520,000) as part of the next funded European deployment program. We believe that this price could be below €500,000 (£400,000) by 2020 with fuel cell power module reaching £1/watt. In addition, expected efficiency improvements in the fuel cell electric bus will result in a fuel cost per kilometer that is below the price of diesel when using green hydrogen.
- **Hydrogen Fuel:** Deployments around the world have proven fuel cell electric buses can be fueled safely and efficiently in the depot. Hydrogen as an industrial gas is currently produced and distributed throughout the UK for a variety of applications. A range of standard solutions exists today to deliver or produce, store and dispense hydrogen gas at transit bus depots.
- **Technology Perception:** We will present the up-to-date facts about fuel cell electric buses and case studies for London and Aberdeen where fuel cell electric bus fleets are currently in operation.

With nearly 10 millions of kilometers in commercial service and more than ten years on the road in different environments and transit bus duty cycles, fuel cell electric buses have been proven to meet operational requirements of transit agencies and bus operators. Fuel cell electric buses offer a 1:1 replacement to diesel buses without performance compromises.

We believe at Ballard that fuel cell electric buses will be:

- **Affordable:** Offering superior cost of ownership versus an all-battery bus and within 20% of the cost of operating diesel buses. Ballard expects to reach this point of ownership cost parity with electric buses by 2020, working with our bus manufacturing and hydrogen supply partners.
- **Operable:** Offering the same convenience as a diesel bus for bus operators, without requiring any operational compromises (such as limited range, long charging times or on-street charging).
- **Clean Zero-Emission Vehicles:** Virtually silent, with no local emissions of any kind.

Figure 1: Fuel cell electric bus deployed in London, England

1 Introduction

City councils in the United Kingdom (UK) have recognized the urgent need to take action to address poor air quality in their cities and have also made commitments to reduce greenhouse gas emissions from the transportation sector. London is taking the lead globally in tackling these issues. While London's air quality has improved in recent years, an equivalent of 9,400 deaths in the city per year is attributed to air quality related illness.[1] There is a particular impact in disadvantaged communities, often located by busy roads, where people are on average exposed to 25 percent higher levels of harmful nitrogen oxide (NOx) emissions.[2] Diesel vehicles are recognized as a major contributor to pollution and associated health impacts in London.

The Mayor of London, Sadiq Khan, is addressing these issues head-on with a proposal of an Ultra-Low Emission Zone. From September 2020, all cars, motorcycles, vans, minibuses, buses, coaches and heavy goods vehicles (HGVs) will need to meet strict exhaust emission standards (ULEZ standards), or pay a daily charge, when traveling in central London. To support the ULEZ, Transport for London, the city's transit operator, is leading by example and will ensure all double decker buses operating in the ULEZ will be hybrid and all single decker buses will be fully electric or hydrogen fuel cell powered. London is now operating a fleet of eight fuel cell electric buses.

Other regions in the United Kingdom are following London's lead. The city of Aberdeen, Scotland aspires to be a leading city for low carbon technology. H2 Aberdeen is an initiative working to bring about a hydrogen economy in the Aberdeen City Region. H2 Aberdeen aims to stimulate innovative hydrogen projects, advance the take-up of hydrogen technologies and position Aberdeen as a centre for excellence for hydrogen technology.[3] To this end, the city has deployed Europe's largest fleet of hydrogen fuel cell electric buses.

[1] Transport for London. "Ultra Low Emission Zone." tfl.gov.uk. https://tfl.gov.uk/modes/driving/ultra-low-emission-zone (accessed November 1, 2016).

[2] Mayor of London. "Sadiq Khan proposes early delivery of Ultra-Low Emission Zone." www.london.gov.uk. https://www.london.gov.uk/press-releases/mayoral/mayor-proposes-early-delivery-of-ulez (accessed November 1, 2016).

[3] Invest Aberdeen. "About H2 Aberdeen." www.aberdeeninvestlivevisit.co.uk. http://www.aberdeeninvestlivevisit.co.uk/hydrogen (accessed November 1, 2016).

2 Benefits of Zero-Emission Fuel Cell Electric Buses

City governments are looking to zero-emission buses as a high impact and highly visible means of addressing local environmental issues, in particular, air quality. Transit operators tasked with implementing zero-emission buses are attracted to hydrogen fuel cell solutions due to the operational benefits. Hydrogen fuel cell electric buses offer zero-emission, virtually noise free, and considerably more efficient operation than diesel buses without the compromise in performance or requirements for major electrical upgrades seen from battery electric buses. The buses emit only water vapor, reducing air pollution locally and offering the potential to fully decarbonize public transport.

The deployment of fuel cell electric buses in UK cities has offered the following benefits:

- Fuel cell electric buses play an important role in emission reduction objectives required for ultra-low emission zones.
- Fuel cell electric buses offer a seamless transition from diesel bus operation to zero-emission buses without service compromise; high range, gradability and ability to refuel in a few minutes.
- Maximize availability of the fleet of buses by avoiding the need to plug in the vehicle overnight
- Hydrogen fuel scales better than electric buses. For a large fleet, massive electrical upgrades can be required at the bus depot. In comparison, hydrogen simply needs a slightly larger fueling station.
- Economic opportunities in terms of local production and supply of the hydrogen fuel as well as the development of new highly skilled jobs.
- Hydrogen production tends to be local and uses local energy resources, which means it helps create local economic activity and supports energy security in a way which imported diesel cannot.
- National technology and innovation leadership with UK transit operators and their employees at the forefront of zero emission transit technology

Hydrogen buses also have the advantage of creating a demand for hydrogen on a sufficient scale to allow the initiation of large-scale zero-carbon hydrogen production projects, which can make use of a wide range of sustainable energy sources. Once initiated, these projects offer an alternative route for bringing truly green energy into the city without taxing existing energy delivery infrastructures such as the electrical grid. This alternative source of fuel for electric vehicles reduces demand and constraints on the electric grid infrastructure required by battery electric vehicles.

Figure 2: Fuel cell electric bus deployed in Aberdeen, Scotland

2.1 GHG Reductions

Fuel cell electric buses have zero tailpipe emissions. They produce no nitrogen oxides, sulfur dioxides or particulate matter. While fuel cell electric buses produce no harmful local emissions, some forms of hydrogen fuel production do generate carbon dioxide (CO2). Currently, the majority of hydrogen used in industry is produced by reforming natural gas which when used in buses offers slightly reduced CO2 emissions compared to diesel buses (EURO VI models) on a well to wheel basis (Figure 3). The use of hydrogen produced from natural gas can be an important first step in the early years of deployment from a cost perspective. However, of more interest is the use of low-carbon hydrogen production methods. Of these, the option of electrolysis from renewable energy sources is the most mature. This allows the buses to reach full carbon neutrality from a well to wheel perspective and hence to significantly reduce CO2 emissions of cities in Europe (Figure 3)[4]. This is the option being used for the hydrogen generated for Aberdeen's buses. Low carbon hydrogen can also be generated from biomass, waste, direct from nuclear or solar heat, from fossil hydrocarbons using carbon capture and storage or as a result of using hydrogen which would otherwise be wasted in industrial facilities. The technology for each of these routes is maturing rapidly and each are expected to lead to plentiful low cost, low carbon hydrogen during the 2020s.

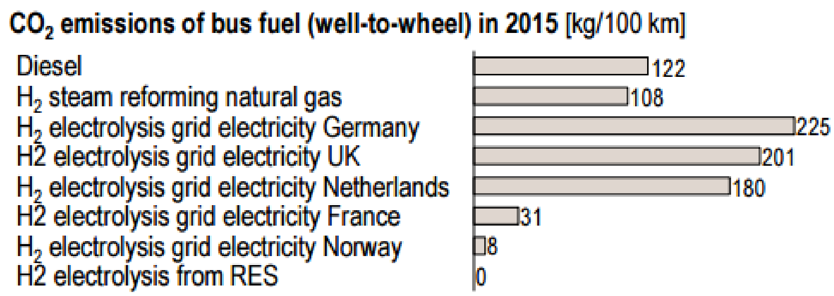

Figure 3: Well-to-wheel CO2 emissions

2.2 Performance

Fuel cell electric buses are the only zero-emission technology to offer full vehicle performance (e.g. gradeability, highway speeds, and long range) over all types of transit routes. Current fuel cell electric buses provide a range of 300-450 kilometers per fill for a tank containing 30-40kg of hydrogen. Refueling fuel cell electric buses typically takes five to ten minutes and occurs once per day. Fuel cell electric buses do a complete day's work even on the most arduous routes and allow for a one-to-one replacement for conventional diesel or compressed natural gas (CNG) technologies. This means that hydrogen fuel cell electric buses are applicable to all urban bus routes without compromise.

Fuel cell electric buses running on hydrogen are two to three times more efficient than buses powered by combustion engines. By converting more of the fuel's energy into motive power, fuel cell electric buses offer the potential to reduce overall fuel costs. As Mike Weston, Transport for London's Director of Buses has stated, "We are very pleased with the performance of the fleet of fuel cell buses... We remain committed to the achievement of our clean transportation goals and these buses are an important part of our solution."

[4] Roland Berger GmbH,. "Fuel Cell Electric Buses - Potential For Sustainable Public Transport In Europe." München: The Fuel Cells and Hydrogen Joint Undertaking, 2015. Web. November 1, 2016.

2.3 Scalability

Hydrogen filling stations at transit depots are built to be scalable. The equipment is similar to a CNG station, and a station can increase its capacity from 40 to 400 buses by upgrading the compression and storage equipment and adding dispensers. Like CNG, the cost and footprint for a large fueling station do not scale linearly, so growing the fleet by a factor of ten does not entail a commensurate investment in the required hydrogen infrastructure. Hydrogen stations do not typically need vast electrical utility upgrades to scale up to a commercial level, unlike large battery electric bus fleets.

Figure 4: Fuel cell electric bus fleet deployed in London, England

2.4 Flexible Vehicle Integration

Fuel cell power modules for transit buses are commercially available from 30 to 100 kilowatts, allowing bus manufacturers to offer a range of battery hybrid options to meet their customer requirements, from a range extender configuration to fuel cell dominant buses. Fuel cell power modules can be integrated into any type of bus from 8m to 18m (articulated) including double decker buses. In fact, the light weight and high power density of a fuel cell system make it the ideal zero-emission solution for double decker buses.

2.5 Reliability

Over the years fuel cell electric bus reliability has increased to provide operators with over 85% vehicle availability in commercial service with further improvements expected as the fleets mature. The solid state nature of the fuel cell stack (no moving parts) makes it one of the most robust elements of the powertrain. Ballard fuel cell stacks in service in London have passed the 23,000 hours of operation without a major upgrade. Fuel cell systems are much less susceptible to environmental conditions (temperature) and premature aging than batteries.

3 Cost

3.1 Bus Capital Cost

Fuel cell electric bus capital pricing has decreased considerably as the volumes have grown. Since first deployments in the 1990s, purchasing costs for fuel cell electric buses have fallen significantly by more than 75%, as shown in Figure 5.[5]

Funding provided by the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has contributed significantly to increase deployment volumes. The FCH JU is a unique public-private partnership supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe. Through a series of funded projects, the FCH JU has been instrumental in demonstrating on a large scale the feasibility of fuel cell bus fleets in the United Kingdom. Access presentation to learn more about these projects: http://bit.ly/2eBAD2H

The availability of lower bus prices and government funding has made bus projects economically plausible for operators. Currently, the target price for a 12-meter fuel cell electric bus is €650,000 (£520,000). Funding from the FCH JU contributes €200,000, resulting in a purchase price of €450,000. This compares to a purchase price of approximately €300,000 for a diesel bus and €550,000 for a battery electric bus.

Ballard believes that the price of a 12-meter fuel cell electric bus (without subsidy) could be below €500,000 (£400,000) by 2020.

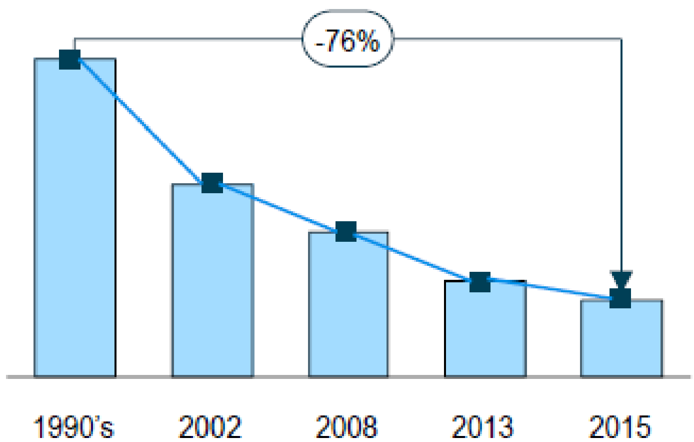

Figure 5: Fuel cell bus purchase cost reduction

Cost reductions are driven by the following factors:

- **Technology Improvement**: Continuous fuel cell technology improvements have led to significant cost reductions over the past decade (including important reductions in precious metal catalyst) and will allow the complete fuel cell "engine" (power module) to reach £1 per watt by 2020.
- **Volume Production:** Demand is primarily driven by strong market interest in China. The new energy vehicle policy launched in China favours fuel cell technology by offering a comprehensive subsidy program at national and regional levels to support commercial deployment of fuel cell electric buses and hydrogen infrastructure. More than 300 fuel cell electric buses will be in service within the next 18 months. This step volume increase will allow cost reductions through strategic purchasing and localization of supply chain.

[5] Roland Berger GmbH,. "Fuel Cell Electric Buses - Potential For Sustainable Public Transport In Europe." München: The Fuel Cells and Hydrogen Joint Undertaking, 2015. Web. November 1, 2016.

- **Hybridization**: Over the past years, battery fuel cell hybridization has reduced the size of the fuel cell stack from several hundred kilowatts to less than 100 kilowatts. The size of the fuel cell power module today ranges from 30 to 100 kilowatts, depending on the hybridization strategy selected by the bus manufacturer.
- **Maturity of Electric Powertrain:** Fuel cell electric buses will continue to benefit from the cost reduction of the electric powertrain in transit buses, including the electric drive, inverters, and batteries. The price for a long life bus battery is expected to reduce further from €655/kWh to near €360/kWh by 2020.[6]
- **Reduction of Integration Cost:** Increased numbers of electric buses being built is driving the reduction in the cost of integrating the systems. Fuel cell electric buses use the same platform as battery electric buses. Furthermore, the cost of hydrogen storage and other components specific to the fuel cell engine are expected to be cost reduced by 40% by 2020 due to increased product volumes. To further drive cost reduction, Ballard is working with bus manufacturers and systems integrators towards an "integrated fuel cell powertrain" concept to reduce redundant elements (e.g. controller, DC/DC converters) and optimize cooling and heating systems in order to further improve bus efficiency. Figure 6 estimates the component cost breakdown of a €500,000 (£400,000) 12-metre fuel cell electric bus with a 60kW fuel cell power module in 2020.

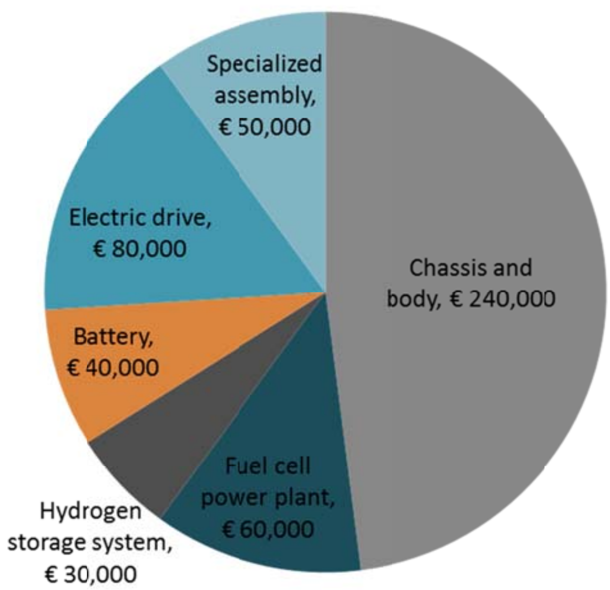

Figure 6: Fuel cell electric bus component cost estimate with 60kW fuel cell power module (2020)

[6] California Air Resource Board. "Advanced Clean Transit Battery Cost for Heavy-Duty Electric Vehicles." California. 2016. Web. November 1, 2016.

- **Competition:** The increased interest in fuel cell electric buses is driving the number of manufacturers developing and selling fuel cell electric buses. Tender processes will generate competition among transit bus OEMs and technology providers.
- **Regional Clusters**: Further cost reduction can be achieved by creating regional "clusters" of fuel cell electric bus fleets, where a number of bus operators and cities agree to work together to procure a large volume of fuel cell electric buses. Increased volumes of fuel cell-powered buses are supporting cost and price reductions through scale of economies, enabling fuel cell solutions to compete more effectively. Regional clusters are starting to work together with a view towards common vehicle specifications and joint procurement options and hence presenting common European and UK industry standards.

3.2 Operating Costs

Maintenance:

For early fleet deployments, the maintenance cost per kilometer has been demonstrated to be comparable to that of diesel buses deployed in comparable environments. A study conducted on behalf of the FCH JU places 2015 maintenance costs for fuel cell electric buses at €0.40 per kilometer and diesel buses at €0.30 per kilometer.[7]

As the technology proliferates and the supply chain matures, a fuel cell electric drivetrain will generate operational savings in comparison to a diesel engine. For an electric drive motor on a bus there is no expected electric motor repair or maintenance needed other than a potential bearing replacement during the typical useful life of a bus. Overall, fuel cell electric buses require less regular maintenance due to its solid state design and the reduction of moving parts. With volume, maintenance costs (including fuel cell stack replacement) will be at or below that of a diesel bus. The forecast for 2025 shows the maintenance cost for fuel cell electric buses aligning with diesel buses at €0.30 per kilometer.[8]

Fuel:

Superior engine efficiency will result in a hydrogen fuel cost per kilometer that is below the price of taxed diesel when using untaxed green hydrogen. It is expected that the total life cycle cost of the fuel cell power system will be less than £0.1/km by 2020.

[7,8] Roland Berger GmbH,. "Fuel Cell Electric Buses - Potential For Sustainable Public Transport In Europe." München: The Fuel Cells and Hydrogen Joint Undertaking, 2015. Web. November 1, 2016.

4 Hydrogen Fueling for Fuel Cell Bus Fleets

Deployments around the world have proven fuel cell buses can be fueled safely and efficiently in the depot. Hydrogen in an industrial gas currently produced and distributed in the UK.

Transit operators can rely on local industrial gas suppliers to design and supply hydrogen filling stations for bus depot using proven and existing solutions. Equipment suppliers will deliver on-site hydrogen production or/and storage as well dispensing equipment customized to meet the bus operator requirements. The footprint of a hydrogen filling station is very similar to a CNG filling station.

Hydrogen is an energy carrier which can be obtained from multiple sources, including natural gas, biogas or other hydrocarbon fuels, as a by-product of chlor-alkali production, or from water through electrolysis. Fuel can either be produced on-site or via centralized production depending on the needs of the Transit agency. In addition to the type of hydrogen fuel production, there are several commercially viable ways the fuel can be distributed, such as including liquid tankers, high and medium pressure tube trailer or even pipeline in targeted regions.

Once on-site, the fuel is compressed, stored and dispensed through a system similar to that of a natural gas fueling system.

Ballard has provided an overview of the different hydrogen fueling options available to guide transit agencies in sourcing the appropriate fueling infrastructure and hydrogen supply for their fuel cell bus fleet. Access this whitepaper now to learn more: http://bit.ly/2fkzKxL

Figure 7: Hydrogen fuelling station in Aberdeen, Scotland

5 Fuel Cell Electric Bus Facts

- Fuel cell electric buses provide a zero-emission solution without range limitations or vehicle performance compromises.

Bus price (12m)	<€650,000
Range	Up to 350 kilometers
Fuel consumption	<10kg/100km
Refueling time	<10 minutes
Fuel cell life time	>20,000 hours
Bus availability	>85%

Figure 8: Fuel cell electric bus performance statistics (2016)

- More than **300** fuel cell electric buses have been deployed around the world and operated millions of miles in revenue service.
- There are currently **65** fuel cell electric buses operating in Europe (18 in the UK) with more than **150** additional buses planned for deployment in the next two years (56 in the UK). The upcoming FCH JU JIVE (Joint Initiative for Hydrogen Vehicles Across Europe) project will support the deployment of fuel cell electric buses across five European regions. The project contemplates the deployment of 142 fuel cell electric buses across nine cities, including 56 buses in the UK.
- Several major transit bus manufacturers are supplying fuel cell electric buses in Europe today including Wrightbus, Van Hool, Solaris, Evobus, and VDL Bus & Coach. Regional manufacturers are currently developing new bus models to meet operator requirements including double decker buses (expected to be available by 2018).
- Most of the hydrogen fuel used in transit bus applications is generated at large scale production facilities, delivered and stored as a liquid on-site. It is dispensed in depot using standard gas dispensing technology for commercial vehicles. Hydrogen fueling infrastructure is widely available and safe to operate. In fact, stations operated by Air Products, a leading global supplier of hydrogen fueling solutions, are fueling at rates of over 1,000,000 hydrogen fills per year.[9]
- Fuel cell technology developed for the transit bus market has started to diffuse into other heavy-duty applications like light rail, drayage trucks, and delivery trucks.

[9] Air Products. "Air Products Providing Hydrogen Fueling Station and Liquid Hydrogen Supply for Stark Area RTA Zero Emission Buses." www.prnewsire.com. http://www.prnewswire.com/news-releases/air-products-providing-hydrogen-fueling-station-and-liquid-hydrogen-supply-for-stark-area-rta-zero-emission-buses-300334253.html. (accessed November 1, 2016).

6 Case Studies

Strong collaboration between transit operators, manufacturers, technology providers and fueling providers has resulted in successful deployments in the UK that are a model for other regions.

6.1 London, England Fuel Cell Electric Bus Fleet

Transport for London first began operation of the first five zero-emission fuel cell electric buses in 2010 as part of its publicly stated goal to reduce CO2 emissions 60% from the 1990 level, by 2025. Three additional zero-emission hydrogen fuel cell electric buses joined the fleet in 2013. All eight buses are powered by Ballard's FCveloCity® fuel cell module.

The fuel cell electric bus fleet in London was made possible through the FCH JU funded CHIC and 3Emotion projects. The buses operate in Central London on a tourist route on a dedicated line: the RV1, which links Tower Gateway Station and Covent Garden. The buses are in operation between 16 and 18 hours per day each and cover a daily distance of 200km. At the end of 2015, one of the fleet's buses achieved its 20,000th hour of fuel cell operation, a significant operating performance milestone.

Air Products provides hydrogen fuel and fueling facilities for the fleet operating in London. The hydrogen is generated in the Netherlands and then shipped across the English Channel as liquid hydrogen and trucked to the transit bus maintenance facility.

To learn more about the fuel cell electric buses operating in London, read Ballard's case study following this paper or on our website at http://bit.ly/2fe8m6z

6.2 Aberdeen, Scotland Fuel Cell Electric Bus Fleet

In support of its ambition to be a world-leading city for low carbon technology, Aberdeen Scotland has deployed Europe's largest fleet of hydrogen fuel cell electric buses.

A consortium of suppliers has come together to design, deploy and support the fleet of ten hydrogen fuel cell electric buses. First Group and Stagecoach operate the buses supplied by bus manufacturer Van Hool and powered by Ballard FCveloCity® power modules. The buses are part of a "whole hydrogen" solution with wind energy supplying power for hydrogen generation through electrolysis.

The Aberdeen Hydrogen Bus Project is made up of two separate FCH JU funded projects, High V.LO-City and HyTransit. Aberdeen not only has Europe's largest fleet of hydrogen fuel cell electric buses, but also the UK's first and largest hydrogen production and bus refueling station. The facility has three electrolyzers to produce hydrogen on-site from water, ready for dispensing to the buses on demand.

After one complete year of operation, the buses had traveled more than 730.000 kilometers and carried an average of 36,700 passengers per month, operating six days a week.

To learn more about the fuel cell electric buses operating in Aberdeen, read Ballard's case study following this paper or on our website at http://bit.ly/2f1WmV7

7 Conclusion

With millions of kilometers in commercial services and more than ten years on the road in different environments, fuel cell electric buses have proven to meet operational requirements of transit agencies and bus operators. Fuel cell electric buses offer a 1:1 replacement to diesel buses without performance compromises.

Ballard is currently working with a number of British and European bus manufacturers in programs which are in varying stages of development, all aiming to bring attractive fuel cell electric buses to European operators.

We believe that fuel cell electric buses will be:

- **Affordable** – offering superior cost of ownership versus an all-battery bus and within 20% of the cost of operating diesel buses. Ballard expects to reach this point of ownership cost parity with electric buses by 2020, working with our bus manufacturing and hydrogen supply partners.
- **Operable** – offering the same convenience as a diesel bus for bus operators, without requiring any operational compromises (such as limited range, long charging times or on-street charging).
- **Clean zero-emission vehicles** – virtually silent, with no emissions of any air pollutant and with no tailpipe emissions of carbon dioxide.

Ballard would like to recommend the following actions in order eliminate the current adoptions barriers:

- **Information dissemination**: Call for our industry to share current cost roadmaps and performance data of fuel cell electric buses to transit agencies and major stakeholders in the UK.
- **Reduce further the cost of fuel cell electric buses:** work with bus manufacturers and component suppliers to more efficiently integrate fuel cell powertrains.
- **Provide affordable hydrogen supply and scalable infrastructure:** Call for gas and station equipment suppliers to work closely with bus operator and local authorities to deliver affordable "turnkey packaged "refueling solutions.
- **Working together to achieve large-scale projects:** Call for bus operators and transit authorities to start planning for larger scale hydrogen bus deployments (20 buses+) which provide the economies of scale required to make hydrogen fuel cell technology available at lower ownership costs than all-electric fleets and approaching the ownership cost of a conventional diesel bus.

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Case Study – Fuel Cell Zero-Emission Transit for the City of London

SITUATION

Like many cities around the globe, London has recognized the need to cut greenhouse gas emissions to limit climate change. The Mayor has set a target to reduce London's carbon dioxide emissions by 60% of their 1990 level by 2025. Currently, approximately 20% of London's carbon dioxide emissions are generated by transportation, making it an ideal industry of focus for reductions. Transport for London (TfL), the city's transit agency, is actively working to cut energy use from transit and use new alternatives to diesel buses to reduce emissions.

SOLUTION

Fuel cell buses emit only water vapor, eliminating air pollutants such as nitrogen oxides, sulfur oxides and particulate matter. Robust fuel cell buses deliver the route flexibility, range, gradeability and top speeds demanded by transit operators.

TfL has led the way in adopting these ultra-low emission vehicles, most notably with their fuel cell bus fleet. Originally, TfL operated three fuel cell buses between 2003 and 2006, under the EU and UK government funded CUTE and HyFleet: CUTE programs. Based on this success, TfL took delivery of five next generation fuel cell buses in 2010. Three additional zero-emission hydrogen fuel cell buses then joined the fleet in 2013. All of the fuel cell buses have been powered by Ballard's FCvelocity® fuel cell module.

The eight current buses are operated as part of CHIC, the Clean Hydrogen in European Cities project, which is the essential next step leading to the full market commercialization of fuel cell hydrogen powered buses. The project involves integrating 26 buses in daily public transport operations and bus routes in five locations across Europe. The CHIC project is supported by the European Union's Fuel Cells and Hydrogen Joint Undertaking (FCH JU), and has 23 partners from eight countries across Europe, which includes industrial partners for vehicle supply and refueling infrastructure.

As a next step, London will expand their fleet with two additional fuel cell buses produced by bus manufacturer Van Hool. The project, which has been given the name 3Emotion (Environmentally Friendly, Efficient, Electric Motion), will run for five years (2015 – 2019) and oversee the deployment of twenty-one new fuel cell buses throughout Europe. 3Emotion is also funded by the EU through FCH JU.

FUELING

Air Products provides hydrogen fuel and fueling facilities for the fleet operating in London. The hydrogen is generated in the Netherlands and then shipped across the English Channel as liquid hydrogen and trucked to the transit bus maintenance facility. As of July 2015, more than 5,600 fillings had taken place, with over 96,000 kilograms of hydrogen supplied. London operators are able to fill a bus from empty in less than ten minutes on average.

Today, the majority of hydrogen for transit bus fleets is produced by large-scale steam methane reforming (SMR). This is currently the most cost-effective method of hydrogen production. Longer term, hydrogen can be produced from renewable sources, such as excess wind or solar power, making the vehicle truly zero-emission on a well-to-wheel basis.

SUMMARY

Sites: London, UK

Application: Eight zero-emission hybrid fuel cell buses, with two additional buses planned.

System: FCveloCity ®-HD power module integrated onto Wrightbus chassis

Fuel: Hydrogen provided by Air Products
>5,600 refueling events
>96,000 kg hydrogen supplied

Objective: To support London's publicly stated goal to reduce CO2 emissions by 60% from the 1990 level by 2025.

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RESULT

Transport for London (via their contractor Tower Transit) has been running zero emission hydrogen fuel cell buses on route RV1 between Covent Garden and Tower Gateway since 2011. This is the first time a whole route has been fully operated by hydrogen powered buses in the UK.

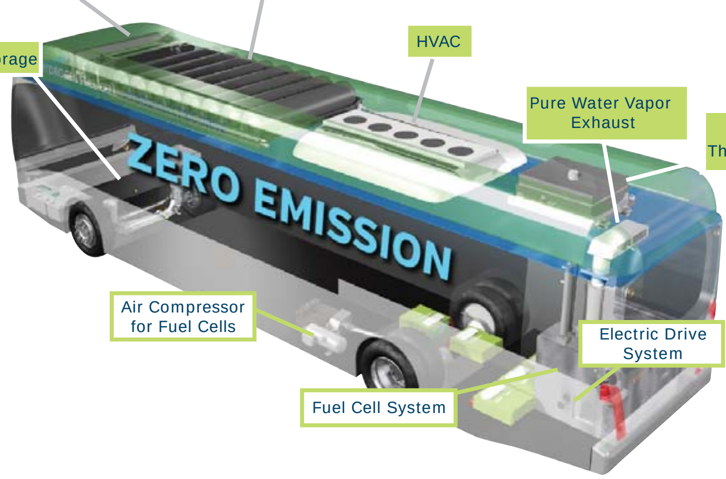
Together, the eight buses have logged more than 132,000 hours of service, covering over 1.3 million kilometers. A single FCveloCity® power module installed in a TfL bus recently set an important milestone of 20,000 hours of continuous operation without replacement or repairs. This performance milestone demonstrates the viability of fuel cell systems as a strong competitor for diesel buses, in terms of fuel efficiency and reliability, with the added benefit of reduced greenhouse gas emissions. One of the most significant results of the trial program is the improvement in the fuel economy. On average, CHIC program buses consume approximately nine kilograms of hydrogen per 100 kilometers, which is more energy efficient than a diesel bus.

As Mike Weston, Transport for London's Director of Buses has stated, "We are very pleased with the performance of the fleet of fuel cell buses, as well as with the ongoing service and support that Ballard is providing. We remain committed to the achievement of our clean transportation goals and these buses are an important part of our solution."

Tower Transit, the agency operating the buses has trained several technicians to look after the preventive and corrective maintenance of the fuel cell buses. Recently, TfL signed an agreement with Ballard to extend operation of the fuel cell bus fleet for a further five years.

FUEL CELL BUS TECHNOLOGY

A fuel cell bus is an electric vehicle that uses compressed hydrogen as the fuel, rather than storing energy in large batteries. Fuel cell power modules onboard the bus generate electricity through an electro-chemical process, producing only water and heat as by-products. The electricity generated by the fuel cells powers the hybrid electric motors and charges the energy storage system. Regenerative braking on the buses increases the fuel economy. High pressure tanks located on the roof of the bus store hydrogen fuel, providing sufficient range for a full day of operation, over 16 to 18 hours. This compares well with the previous generation of fuel cell buses, whose range was less than 200 km, where buses were forced to operate in half day shifts before fuelling.



PERFORMANCE STATISTICS

Run Time:
132,000 hours of service

Distance Travelled:
1.3 million kilometers of service

Stack Hours:
20,000 hours of continuous operation

Bus Range:
250 – 300 km

Daily Operation:
16 to 18 hours

Refueling Time:
<10 minutes

ABOUT BALLARD

Ballard designs and manufactures high performance and easy to integrate FCveloCity® fuel cell modules for use in hybrid electric buses. Ballard's leading-edge fuel cell technology combined with our customer's advanced hybrid system designs deliver zero emissions at the tailpipe with no compromise in vehicle performance compared to other zero emission technologies.

Contact us:
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BALLARD®
PUTTING FUEL CELLS TO WORK

FCveloCity®

Case Study – Fuel Cell Zero-Emission Buses for Aberdeen, Scotland

SITUATION

The City of Aberdeen, Scotland has a world-wide reputation in the energy industry. With the discovery of significant oil deposits in the North Sea, Aberdeen became the centre of Europe's petroleum industry. However, downturns in the oil and gas sector have impacted the economy and city leaders are repositioning the city as the "Energy Capital of Europe," with a focus on the development of new energy sources. The launch of the Strategy Framework "A Hydrogen Economy for Aberdeen City Region" in 2013 reflects Aberdeen's ambitions to become a leading European region in the early deployment of hydrogen technologies.

SOLUTION

City Council implemented the Aberdeen Hydrogen Bus Project to deploy Europe's largest fleet of hydrogen fuel cell buses, replacing ten polluting diesel buses on the city's streets with zero-emission buses.

The Aberdeen Hydrogen Bus Project is designed to test the economic and environmental benefits of hydrogen fuel cell transit technologies and aims to drive the development of hydrogen technologies. It is part of the larger H2 Aberdeen initiative, which provides the opportunity to create a new industry and greater choice in energy production and usage.

Implementation of the fleet of hydrogen fuel cell buses in Aberdeen was co-financed through two projects funded by the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU): High V.LO-City and HyTransit. Other Scottish, UK and European partners came together to co-fund the balance of the project, including the UK's innovation agency, Innovate UK; the Scottish Government; Scottish Enterprise; Aberdeen City Council; transit operators First and Stagecoach; Scottish Hydro Electric Power Distribution; and Scotland Gas Network. BOC, a member of Linde Group, has invested in the hydrogen production and refueling station.

FUELING

The hydrogen bus refueling station, based at Aberdeen City Council's Kittybrewster depot, is the first fully integrated

hydrogen production and bus refueling station in Scotland. The commercial-scale hydrogen station is owned and operated by BOC, a member of the Linde Group. The facility has three electrolysers to produce the hydrogen on site from water, with extremely low emissions. The hydrogen is then compressed to 500bar and stored ready for dispensing at 350bar when required. A purpose-built hydrogen fuel cell bus maintenance facility is co-located at the depot.

SUMMARY

Sites: Aberdeen, Scotland

Application: Ten zero-emission hydrogen fuel cell buses, Europe's largest fleet

System: 150kW FCveloCity ®-HD power modules integrated onto Van Hool chassis

Fuel: Hydrogen provided by BOC, a member of the Linde Group

Objective: To support Aberdeen's goal to remain a world-class energy hub, leading a low carbon economy.

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RESULT

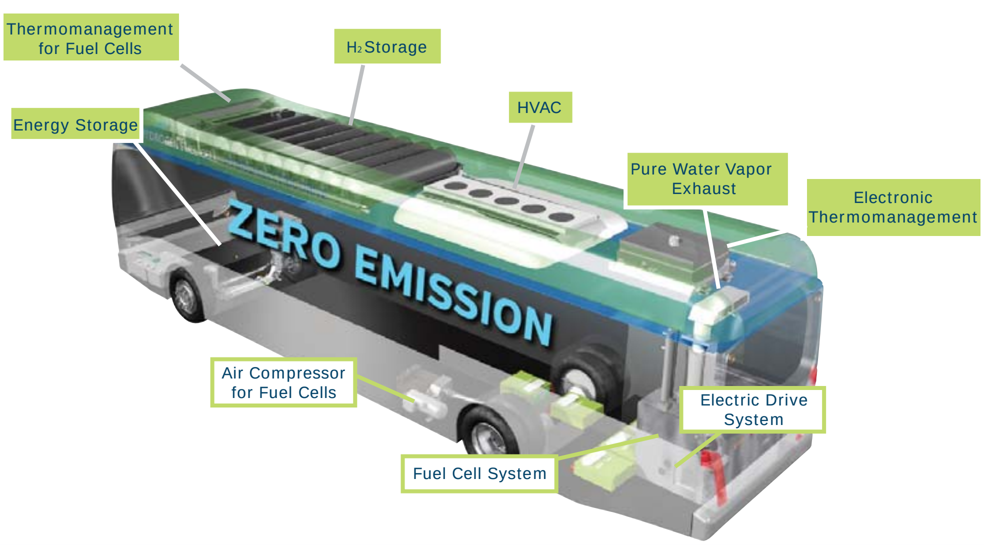
Ten Van Hool hydrogen fuel cell buses, powered by Ballard fuel cells, have now been deployed. Six buses are operated by Stagecoach on the X17 Aberdeen city centre to Westhill route, while First operates four buses on the X40 Kingswells to Bridge of Don park-and-ride route. The buses emit only water vapour, reducing carbon emissions and air pollution, as well as being quieter and smoother to run than diesel vehicles.

The buses had travelled more than 730,000 kilometers and carried an average of 36,700 passengers per month, operating six days a week at 90 percent availability. More than 1,600 refueling events had taken place at the hydrogen station, each taking just five to seven minutes per refueling. With more than 35,000 kilograms of hydrogen dispensed in the first year, the hydrogen refueling station has been extremely reliable, demonstrating 99.99% availability.

Aberdeen City Council has received accolades commending the success of the project, including the 2016 Low Carbon Championship award for the transport initiative of the year. Recently The Aberdeen Hydrogen Bus Project has been so successful, city planners are now considering expansion of the fleet through participation in the European-wide Fuel Cell Bus Commercialisation Project.

FUEL CELL BUS TECHNOLOGY

A fuel cell bus is an electric vehicle that uses compressed hydrogen as the fuel, rather than storing energy in large batteries. Fuel cell power modules onboard the bus generate electricity through an electro-chemical process, producing only water and heat as by-products. The electricity generated by the fuel cells powers the hybrid electric motors and charges the energy storage system. Regenerative braking on the buses increases the fuel economy. High pressure tanks located on the roof of the bus store hydrogen fuel, providing sufficient range for a full day of operation, over 16 to 18 hours. This compares well with the previous generation of fuel cell buses, whose range was less than 200 km, where buses were forced to operate in half day shifts before fuelling.



PERFORMANCE STATISTICS

Distance Travelled: >730,000 kilometers in the first year

Refueling Events: >1,600 in the first year

Refueling Time: 5 to 7 minutes

Availability: 90%

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