Zemo Partnership
Accelerating Transport to Zero Emissions

Zero Emission Bus Guide

October 2022
zemo.org.uk

First Edition

Acknowledgements

Zemo Partnership would like to thank members of the Bus Working Group for supporting the development of this guide

Authors:

Daniel Hayes
Programme Manager

Tim Griffen
Project Officer

Reviewed by:

Jason Doran
Head of Marketing

Zemo Partnership
Accelerating Transport to Zero Emissions

Zemo Partnership
3 Birdcage Walk, London, SW1H 9JJ

T: +44 (0)20 3832 6070
E: Hello@Zemo.org.uk
Visit: Zemo.org.uk

@Zemo_org
Zemo
Zemo YouTube Channel

Contents

Contents

Glossary of Terms

AC Alternating Current
BEV Battery Electric Vehicle
COMAH Control of Major Accident Hazards (Regulations)
DC Direct Current
DfT Department for Transport
DNO Distribution Network Operator
FCEV Hydrogen Fuel Cell Electric Vehicle
GHG Greenhouse Gas
IDNO Independent Distribution Network Operator
kW a kilowatt: 1,000 Watts (unit of power)
kWh a kilowatt hour: 1,000,000 Watt hours (unit of energy)
MJ a megajoule (unit of energy, 1kWh = 3.6 MJ)
MW a megawatt: 1,000,000 Watts (unit of power)
MWh a megawatt hour: 1,000,000 Watt hours
SOC State of Charge
SOH State of Health
TfL Transport for London
WTW Well-to-Wheel

1. Introduction

1.1. Aim of this guide

The **Zero Emission Bus Guide** aims to provide bus operators and local authorities with an overview of the benefits of zero emission buses technologies combined with renewable energy that will help improve local air quality and reduce greenhouse gas emissions.

The guide outlines the environmental credentials, funding and incentive schemes, together with operational and total cost of ownership factors that operators should consider when procuring new zero emission buses and supporting infrastructure.

The guide additionally demonstrates the role that "repowering" diesel buses with zero emission powertrains can play in accelerating the shift to a net zero emission bus fleet.

Case studies are included to demonstrate the real-world solutions for both small and large fleets.
The zero emission bus technologies covered in this guide are:

- battery electric with depot-based charging,
- battery electric with opportunity charging & depot-based charging,
- hydrogen fuel cell with depot-based refuelling,
- hydrogen fuel cell with off-site refuelling,
- repowering diesel buses to zero emission.

1.2. Why do we need Zero Emission Buses?

Buses play a critical in reducing carbon emissions, by delivering sustainable transport in our towns and cities and provide rural connectivity to a broad cross section of the UK population. However, existing diesel buses have been a source of air pollution in towns and cities whilst also contributing to greenhouse gas emissions.

Buses are responsible for 3% of total road transport greenhouse gas emissions[1] and 5% of total transport roadside oxides of nitrogen (NOx) emissions[2] and have been identified as a key sector for improving air quality and accelerating decarbonisation.

Why do we need zero emission buses?

- More energy efficient than traditional diesel combustion engines;
- Can use renewable energy to reduce greenhouse gas emissions;
- Produce no harmful tailpipe emissions improving local air quality;
- Reduced noise and vibrations help improve passenger experience.

[1] - DfT, 2021 - 'Transport and Environment Statistics 2021 Annual Report' available at Transport and Environment Statistics: 2021 Annual Report (publishing.service.gov.uk)
[2] - NAEI, 2018 - 'UK Emissions Data Selector' available at UK emissions data selector - NAEI, UK (beis.gov.uk)

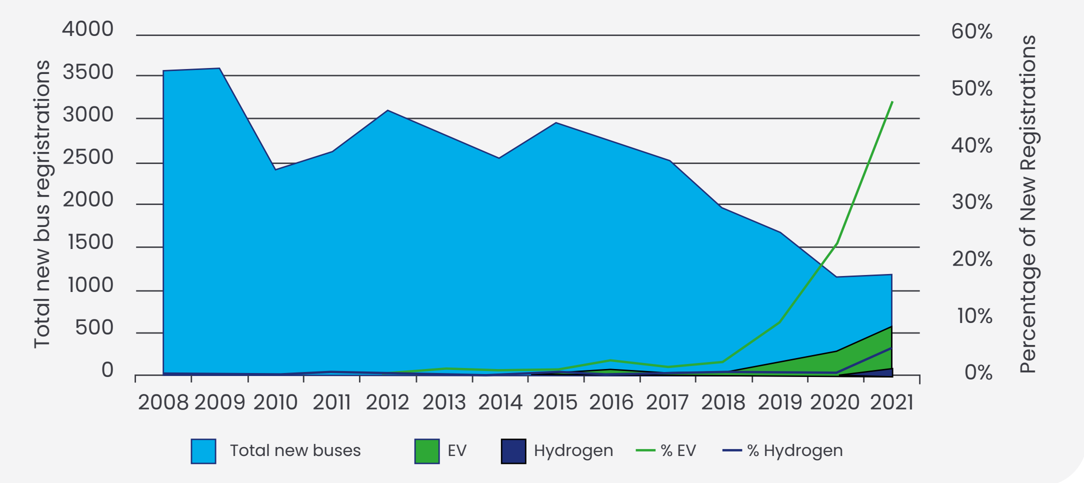
The bus industry has already achieved significant reductions in tailpipe emissions through introducing the latest Euro VI engines, upgrading aftertreatment systems of existing fleets, adopting low carbon biofuel blends and meeting Clean Air Zone requirements.

However, the UK Government's commitment to achieve net zero greenhouse gas (GHG) emissions from transport by 2050 will require the adoption of technologies which are more efficient, take advantage of renewable energy and produce zero harmful emissions from the tailpipe.

To support this transition, the Government has pledged to introduce 4,000 zero emission buses (ZEBs) in England by 2025, supported by £270m of capital grants for new buses and infrastructure through the Zero Emission Bus Regional Areas (ZEBRA) scheme. This is expected to be followed by a further £205m of funding in 2023.

Importantly ZEB technologies have now reached a stage of maturity that enable deployment on commercial bus services. So much so that Transport for London (TfL) has set a goal of having a fully zero emission bus fleet by 2034 or sooner (over 9,000 buses or a one-third of the English bus fleet). Progress is accelerating in London, with an ambition for 10% of the fleet to be zero emission by Spring 2023.

Figure 1: ZEBs represented over 50% of new UK bus registrations in 2021. The growth of zero emission buses in the UK is in the context of a declining bus market further impacted by the COVID-19 pandemic.



Significantly, commercial operators have also matched the net zero ambition with coach operator National Express committing to a fully zero emission bus fleet by 2030, and Go-Ahead Group, First Bus and Stagecoach committing to go fully zero emission by 2035.

Zero emission will one day be the only choice, with the DfT expected to announce an end date to the sale of new, non-zero emission buses soon, having consulted with industry in the summer of 2022.

Alongside adoption of new technologies, both national and local policies will be needed to improve bus priority measures and encourage greater patronage, driving modal shift away from private cars journeys, especially in urban areas.

The government has committed to supporting these measures in the National Bus Strategy, which has allocated £1.1bn of funding through Bus Service Improvement Plans (BSIPs) to focus on faster journey times, reduced fares and improved route and timetable information.

Greater collaboration between all stakeholders will be needed to ensure that the bus industry successfully recovers from the impacts of the COVID-19 pandemic, new emerging patterns of work and travel, alongside offering a new perception of modern bus services that are accessible, affordable and zero emission.

1.3. What is a Zero Emission Bus (ZEB)?

A clear and concise definition of a Zero Emission Bus is crucial to ensure public money supports proven technologies and provides consistent standards to both the market and public.

What is a "Zero Emission Bus"?
A ZEB is defined as:

- no combustion engine(s) on-board (including diesel heaters);
- no regulated emissions from the tailpipe(s);
- achieves a 50% well-to-wheel (WTW) greenhouse gas saving compared to a conventional Euro VI diesel over the UK Bus Cycle.

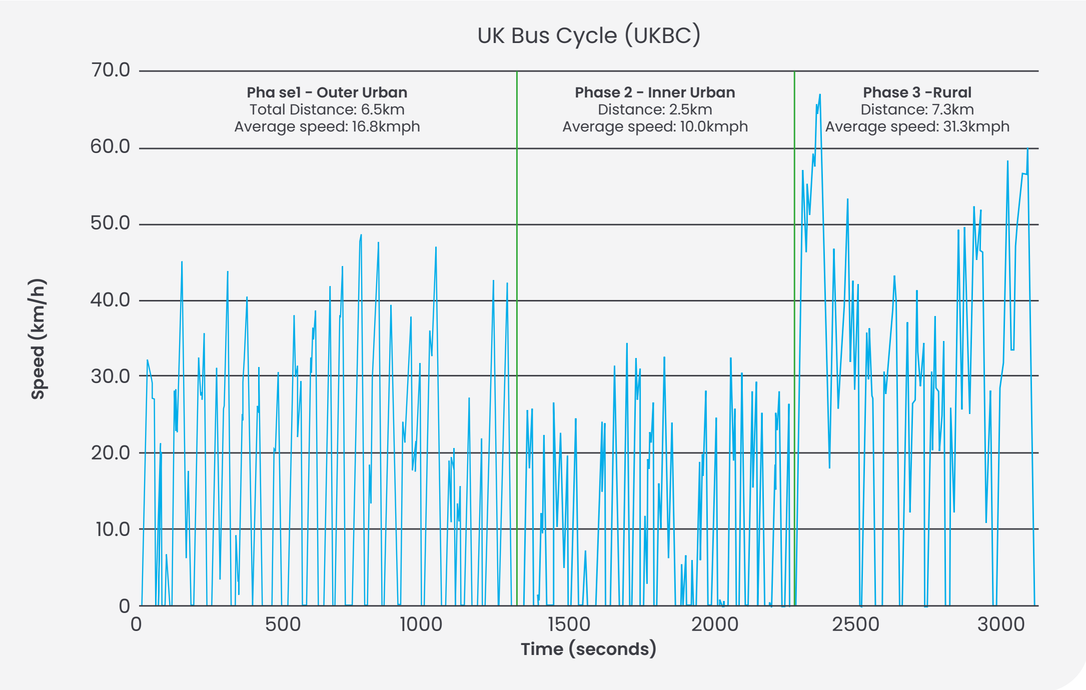
Battery Electric (BEV) and Hydrogen Fuel Cell Electric Vehicles (FCEV) currently meet the ZEB criteria

Zemo Partnership worked with government and industry to define a "Zero Emission Bus", which has been incorporated into the Zero Emission Bus (ZEB) Accreditation Scheme. This scheme builds on the previous Low Emission Bus (LEB) and Ultra Low Emission (ULEB) certification schemes.

The Zero Emission Bus Accreditation Scheme has been adopted by national government capital grant funding schemes and incentives such as DfT's ZEBRA scheme, DfT's BSOG ZEB uplift and Transport Scotland's ScotZEB Challenge Fund.

To meet the ZEB definition, bus models must demonstrate a 50% Well-to-Wheel GHG saving over the UK Bus Cycle (UKBC), a representative test cycle covering inner urban, outer urban and rural operating conditions. The inner and outer phases combined make up the London Bus Cycle (LBC), previously known as the MLTB test.

Figure 2: The three phases of the UK Bus Cycle used to certify Zero Emission Buses, demonstrating energy efficiency performance over three typical operating conditions for UK buses.



Tests are conducted on a rolling road (chassis dynamometer – a treadmill for buses) in a test chamber to ensure consistent conditions providing repeatable and comparable results.

The UKBC also includes conditions to exercise the ancillary loads on the bus, including reaching an internal salon temperature of 17°C from a 10°C chamber start and doors opening and closing at designated "bus stops".

Figure 3: A Yutong TCe12 electric coach being tested over the UK Bus Cycle on a rolling road (chassis dynamometer) under controlled lab conditions to qualify for capital grant funding under Transport Scotland's Scottish ULEB Scheme (Credit Yutong).

Once a manufacturer or vehicle supplier has demonstrated a bus model achieves the ZEB standard over the UK Bus Cycle, Zemo Partnership reviews the results and publishes a ZEB Certificate on its website.

Publicly available certificates enable local authorities and bus operators to understand the expected performance ahead of time and compare different suppliers and technologies.

Operators and local authorities can apply for grant funding and operational incentives in England and Scotland using ZEB certificates.

Table 1: Average energy consumption of certified ZEBs to date, excluding charging efficiency losses. *No Hydrogen Fuel Cell buses have been tested to date, fuel consumption is estimated based on in-service data.

Technology	Average Energy Efficiency/ Fuel Consumption	Average well-to-wheel greenhouse gas saving vs equivalent Euro VI diesel baseline
Single Deck EV	0.98 kWh/km	69%
Double Deck EV	1.05 kWh/km	72%
Hydrogen Fuel Cell (Estimated)	6 - 7.5 kg / 100km*	70-80%

What is "Well-to-Wheel"(WTW) ?

Zemo use 'Well-to-Wheel' (WTW) to reflect all the GHG emissions involved in the process of extraction/creation, refining and use of an energy/fuel in a vehicle to gauge the total carbon impact of that vehicle in operation. This enables a more accurate comparison of different technologies and promotes awareness of fuel/energy sources.

WTW combines upstream/indirect emissions prior to entering the vehicle's energy storage/fuel tank (Well-to-Tank) with direct vehicle tailpipe emissions generated from vehicle propulsion (Tank-to-Wheel).

Greenhouse Gas (GHG) emissions covered are: carbon dioxide, methane and nitrous oxide. Together these gases are converted into "Carbon Dioxide equivalent" (CO_2e) using a 100yr assessment of the global warming potential (GWP).

For further information on the Zero Emission Bus Accreditation Scheme, including test conditions and guidance, scan the QR code adjacent to visit the Zemo Partnership website.

1.4. Grants and Incentives for Zero Emission Buses

National governments have funded a range of low carbon bus technologies over the last decade. The net-zero commitments have shifted all capital grant schemes to focus on zero emission buses and supporting infrastructure.

Bus funding is devolved to national governments in the U.K., so each regional government has slightly different funding schemes and incentives:

Table 2: Summary of funding schemes available to operators and local authorities in the UK.

	Zero Emission Bus Targets	Grant Funding	Operational Incentives
England	"4,000 zero emission buses in service by 2025" - The ten point plan for a green industrial revolution, 2020.	Department for Transport (DfT) currently awards funding to local authorities via competitive grant schemes. The most recent was the £270m Zero Emission Bus Regional Areas (ZEBRA) scheme, with an expected second round to open in 2022/23 (c. £205m). Local authorities can then choose to procure vehicles and infrastructure or distribute funding to local operators. Zemo Partnership ZEB accreditation required.	Operators in England can apply for £0.22 /km incentive for operating zero emission buses via the Bus Service Operators Grant (BSOG). Requires Zemo Partnership ZEB accreditation. BSOG LCEB £0.06 /km remains in place until full BSOG reform is conducted. Requires Zemo Partnership LEB / ULEB accreditation.
Scotland	"The majority of diesel buses removed from Scotland's roads by end of 2023" – Programme for Government, 2021.	Transport Scotland currently award capital funding to either local authorities or operators via competitive grant schemes. There is currently funding available to support SME operators develop fleet transition plans and assess the potential of zero emission bus repowers via The ZEB Market Transition Scheme (£500K total available). The most recent grant funding scheme was the ScotZEB Challenge Fund Phase 1 (£62m), with Phase 2 expected in 2023 (£58m). Zemo Partnership ZEB accreditation required.	Scotland provides operational support to bus services via the Network Support Grant (NSG), replacing previous versions of the Bus Service Operator Grant. There are currently no operational incentives for running zero emission buses under the NSG.
Wales	"The most polluting 50% of service buses to be replaced by a zero tailpipe emission bus fleet by 2028. The remaining 50% of the service bus fleet to be zero emission by 2035." - Welsh Transport Strategy, 2021.	Welsh Government allocates capital grant funding an ad hoc basis to local authorities for ZEB procurement.	Welsh Government provides operational support to bus services via the Bus Service Support Grant, which is given to local authorities and then distributed to operators. There are currently no direct operational incentives for zero emission buses in Wales.
Northern Ireland	"A zero-emission public transport fleet across Northern Ireland by 2040" – Northern Ireland Assembly, 2021	NI Department for Infrastructure awards capital grant funding on an ad hoc basis to Translink, who operates the bus fleet in NI.	There are currently no direct operational incentives for zero emission buses in Northern Ireland.

For further information on funding schemes in the UK, scan the QR code adjacent to visit the Zemo Partnership website.

1.5. What to consider when purchasing Zero Emission Buses?

The diesel engine has been the workhorse of the bus industry for over 50 years. Business and operational models, skills and training have been based on this one highly flexible, affordable and reliable technology.

New technologies require new thinking and new approaches. There are a range of factors that should to be taken into account when choosing to purchase a particular type of zero emission bus technology, with the most essential parameters highlighted in Table 3.

Table 3: Key factors when considering procurement of zero emission buses and infrastructure

Vehicle performance	Route characteristics
• Energy consumption / efficiency • Energy storage • Estimated range • Heating/cooling requirements	• Topography • Average speed • Peak power requirements • Average daily distance
Total Cost of Ownership (TCO)	**Funding**
• Lower operating costs • Lower maintenance costs • Higher upfront vehicle cost • New infrastructure costs	• Capital grant schemes • In-service operational incentives • Green financing options
Maintenance requirements	**New Infrastructure**
• Reduced servicing frequency • Battery warranty packages • Staff training / practices	• Fleet planning and optimization • Energy demand profiling • Smart charging / refuelling strategies
Grid Connection	**Data & Telematics**
• Grid upgrade & engaging DNO • Civils and parking arrangements • Installation lead times	• Vehicle and infrastructure telematics • Data analysis and visulisation • Using data to optimise operations

This guide is intended to equip bus operators and local authorities with relevant information to aid planning, market research, procurement and encourage the most appropriate zero emission bus technology for a particular route and application.

There are multiple stakeholders involved in establishing and operating a zero emission bus fleet which can vary depending on the technology chosen. Stakeholders could include:

- bus manufacturers / suppliers
- bus operators
- local transport authority
- infrastructure suppliers
- energy and fuel suppliers
- local electricity network operators
- civil works contractors;
- other technology providers

Introducing new technologies and business practices are challenging and time consuming. ZEBs are certainly not a "plug-and-play" technology that will mimic existing diesel operations and require diligent management when in-service.

Many operators to date have trialled vehicles to understand what solution will work best for their services in their local area. There is no one-size fits all.

ZEB projects take at least a year from concept to deployment and typically take a lot longer. Costs and delivery times and technology can change quite rapidly, especially in a post-Covid-19 world, so extensive market research and contingency is advised when starting from scratch.

There are strengths and weaknesses to starting small and incrementally converting a fleet, compared to replacing a whole depot or towns worth of buses with ZEBs. Cost savings could be found through improved scheduling tools, sharing infrastructure or skills with others in the local area.

On-going partnership work will be crucial in ensuring effective operation and maintenance. Operators and local authorities should identify relevant partners early on in the procurement process and ensure advice is obtained on zero emission buses and accompanying infrastructure options.

2. Battery Electric Buses

Battery Electric Buses (BEVs) are the most popular zero emission bus technology in the UK today, with over 1,500 buses in service. Over 560 BEVs were registered in 2021, representing 48% of new bus registrations. BEVs represent over 3% of the total UK bus fleet today, with over 12 different manufacturers offering solutions.

BEVs have become more efficient in recent years as battery and motor technology has developed, alongside integration of efficient ancillary systems such as heat pumps. While the up front cost of BEVs remain challenging, improved battery warranties and smart charging have supported a reduction in the total cost of ownership, alongside new business models.

Table 4: Key factors for consideration for BEV deployment

Operations	Infrastructure	Maintenance
• Route length and topography • Battery capacity, vehicle efficiency and range • Scheduling and operating timings (run-in and run-out times) • Using telematics data effectively • Driver training to optimise energy efficiency and range	• Engagement with the DNO at an earlier stage • Peak power requirement and grid upgrade • Number, type and locations of chargers • Peak vehicle requirement • Optimising route scheduling • Maintenance contract for infrastructure and telemetry	• Staff training for high voltage components • Component upkeep (battery pack, traction motor, power electronics) • Vehicle warranty • Telematics data to optimise maintenance

2.1. Technology Overview

Battery Electric vehicles (BEVs) operate using an electric motor powered by an onboard battery for propulsion rather than a diesel internal combustion engine. Electricity from the grid is used to charge the battery via cable, overhead pantograph or inductive wireless chargers depending on charging strategy.

Battery electric buses are designed with regenerative braking, enabling a proportion of the energy that would otherwise have been lost when the vehicle is decelerating to be recovered back to the batteries, typically 20-30% of total daily energy consumption.

Battery electric buses are ideally suited for city centre routes and zero tailpipe emission operation. Most battery electric buses are charged overnight in a depot and some take advantage of opportunity or top-up charging in-service to extend their daily range.

Original Equipment Manufacturers (OEMs) supplying battery electric buses to the UK Market are:

- Alexander-Dennis
- BYD
- Caetano
- Equipmake
- EvoBus (Mercedes-Benz)
- EVM
- Irizar e-Mobility
- Mellor
- Switch Mobility
- Scania
- Volvo
- Wrightbus
- Yutong

Electric buses produce zero tailpipe air pollution emissions, making them ideal for city operation where air quality is of particular concern. Electric buses are also quiet and very smooth in operation, offering benefits to noise reduction in city centres and passenger comfort.

Although an electric bus eliminates tailpipe greenhouse emissions, the well-to-tank (WTW) GHG emissions of the electricity used to charge the battery needs to be taken into consideration. This will take into account the carbon footprint of electricity production, transmission and the efficiency of the charging infrastructure. The WTW GHG emission savings for electric buses using current UK grid electricity, certified under the ZEB accreditation, range from 62% - 84% compared to an equivalent Euro VI diesel bus.

In the UK electricity is produced using both fossil fuels and renewable energy. Operators may be able to select a 'green' tariff from their electricity supplier to ensure maximum use of low carbon energy sources or if possible, generate renewable electricity on site.

2.1.1. Range & Energy Consumption

The daily operating range of a BEV is primarily determined by battery capacity and vehicle efficiency on a route i.e. the amount of energy stored in the batteries (kilowatt hours = kWh) and the amount of energy used per kilometre driven (kWh/ km).

For BEVs, the route topography, temperature, road conditions and driving style can all have a material impact on energy consumption and range. BEVs are affected by the seasons, achieving greater ranges in summer when heating requirements are reduced.

Manufacturers (OEMs) choose battery capacities that compromise between daily range, weight and space, which in turn affect the total passenger capacity. OEMs in the UK are currently offering electric buses with battery capacities of up to 500kWh for a single-deck and up to 450kWh for a double-deck.

Energy consumption of BEVs varies from 0.6 – 2.0 kWh/km, providing daily ranges of 200-400km, depending on time of year, age of the batteries and driving style.

Understanding the existing requirements of a diesel fleet in terms of mileage and fuel consumption can help inform procurement and charging solutions. Once in service, data logging telematics systems enable real time monitoring of electricity consumption and range, allowing operators to manage fleets effectively.

OEMs can simulate energy consumption and predict battery degradation based on route profiles, allowing for appropriate battery sizing, management and cost-effective total cost of ownership models.

These improvements with in-service experience has enabled many operators to replace diesels fleets on a like-for-like basis with BEVs, removing the need for additional vehicles to make up for historic range limitations.

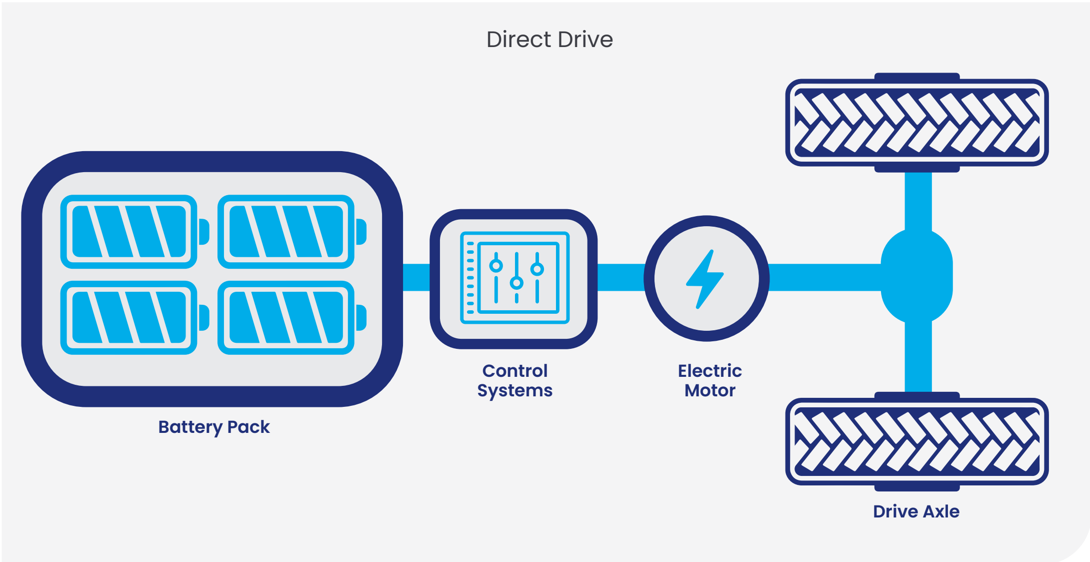
The UK legal weight limit for two-axle buses has recently been increased from 18000kg to 19500kg for alternative fuel vehicles. This has enabled battery electric buses to carry larger battery packs, with little or no loss of passenger capacity compared to diesel buses, except on routes with local weight limits (such as weight limited bridges).

2.1.2. Electric Motors

The key elements that make up a BEV powertrain are the electric motor(s) and batteries, along with the battery management system, control units and inverters.

Electric buses are driven using a motor, which converts electric energy into mechanical energy and torque. There are multiple motor integration options available on the market, including 'Direct Drive' drivelines, 'E-Axles' and 'Hub motors'.

Figure 4: Diagram of 'Direct Drive' driveline for battery electric buses



Direct drive drivelines are similar in layout to conventional diesel driveline architectures, where an electric motor is connected to a prop shaft through a gearbox which drives the rear-axle via a differential.

With this layout, parasitic losses tend to be higher to alternatives owing to the size and number of mechanical components required to convert electrical energy into drive.

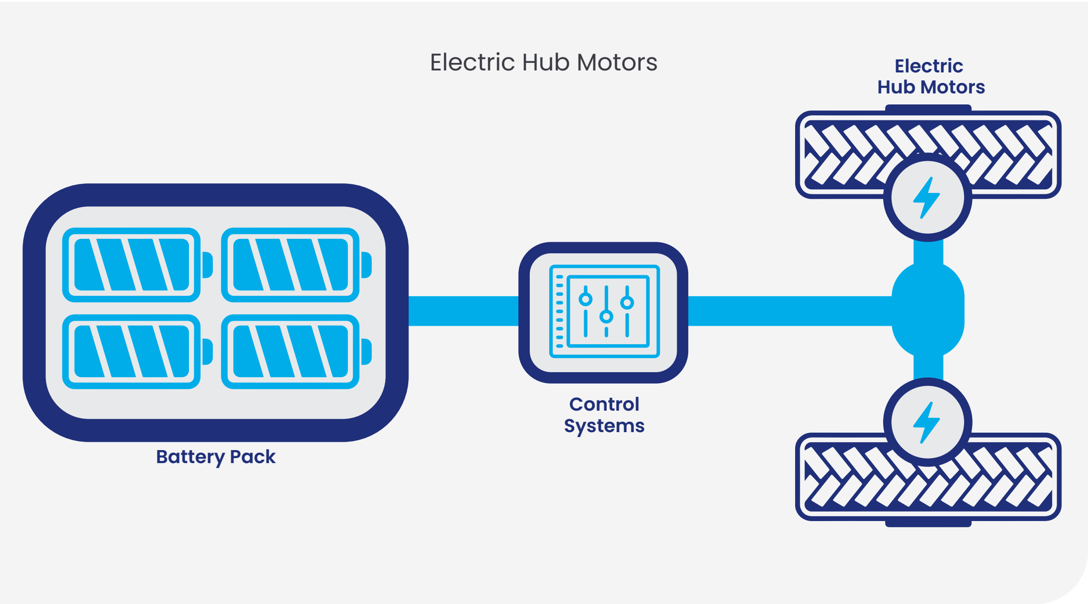
'E-Axles' incorporate the same components as a direct drive driveline into a smaller space within the rear of the chassis. Within an e-axle, an electric motor converts electrical energy of the battery into torque via a gearbox and driveshaft.

The key benefits associated with e-axles are centred around efficiency and space saving. By reducing mechanical gearing losses with the driveline, e-axles can offer higher efficiency, helping to reduce energy usage. In addition to improving overall vehicle efficiency, a smaller driveline provides more space for batteries to be stored onboard helping to increase the potential range of the vehicle.

Hub motors provide an entirely different alternative to the largely conventional idea of a motor providing torque via a driveshaft. Hub motors are incorporated directly into the hubs of the drive wheels and hence require no conversion of energy through mechanical components like gearing, helping to increase overall operating efficiency and torque response.

Incorporating the motors into the hubs themselves also helps to further free up space in the chassis for the storage of batteries. Hub motors come with some drawbacks, such as additional weight added to each wheel assembly in which they are incorporated, potentially leading to bigger disturbances from road surfaces.

Figure 5: Schematic of 'Hub Motor' driveline for battery electric buses



2.1.3. Battery Chemistry & Energy Density

The fact that BEV technology is now a commercially viable solution for many bus routes in the UK is largely down to the development of battery technology over the last decade or so. The development of batteries for mobile phones and laptops has been scaled up and transferred to the transport sector.

Crucial developments in the amount of energy stored in batteries in relation to overall weight, known as energy density (kWh/kg), have allowed BEVs to carry more passengers and travel further for the same amount of battery weight.

Energy density has been improved through combinations of different lithium-ion chemistries, as well as improvements in battery management e.g. most battery packs are now liquid cooled and pre-heated prior to charging to reduce degradation.

Improvements have seen expected battery lifetime increase from 4-5 years up to 10 years, and even longer for some chemistries. This is now reflected in 5-8 year battery warranties being offered to suppliers.

Table 5: Strengths and weaknesses of the most common lithium-ion battery chemistries used in BEV buses today.

Battery Chemistry	Strengths	Weaknesses
Lithium Iron Phosphate (LFP)	• Good thermal stability. • High current rating, long cycle life.	• Lower energy density due to low operating voltage and capacity. • Lower cost
Lithium Nickel Cobalt Aluminium Oxide (NCA)	• High specific energy, good specific power. • Long life cycle.	• Higher cost compared to alternatives.
Lithium Nickel Manganese Cobalt Oxide (NMC)	• Nickel has high specific energy; while Magnesium adds low internal resistance. • Can be tailored to offer high specific energy or power.	• Medium cost compared to alternatives • Manganese offers low specific energy.
Lithium Titanate Oxide (LTO)	• Well suited for deep cycling and high power fast charging and use in conjunction with fuel cell systems.	• Higher cost compared to alternatives.

2.2. Total Cost of Ownership

New business models are required to understand the cost saving benefits of BEVs. Operators must now look at the total cost of BEVs over their lifetime to realise cost saving benefits. Diesels buses are less costly to buy, but more costly to run. BEVs are more costly up front and require investment in charging infrastructure, but have lower operating and maintenance costs.

Batteries will need to be replaced once during the typical 15 year lifetime of the bus, representing a significant mid-life investment. The residual value of BEVs is also uncertain as the second hand market is not yet fully established making traditional leasing more challenging.

However, second-life markets for batteries are developing as batteries retain 80% of their original storage capacity after their first life in a BEV. Stationary storage applications such as domestic solar PV installations provide a potential future subsidy for battery replacement.

Importantly, BEVs use less energy compared to diesels, reducing the in-service running costs, along with reduced maintenance as there are few moving parts. BEVs are also expected to last longer than diesel buses due to reduced vibration caused by a diesel engine.

Infrastructure does require significant investment in charger equipment, civil engineering, transformers, high voltage cabling and potentially substation upgrades. Smart charging and on-site battery storage systems can enable lower cost infrastructure installations. 'Future proofing' depots by installing final power requirements of a full BEV fleet can reduce overall investment costs by reducing need for incremental works.

Unfortunately recent global events have impacted supply chains and the cost of energy, which will likely slow the short-term deployment of ZEBs. However, the global push towards zero emission technologies has increased the supply chain for critical parts, alongside innovative financing models and will drive costs down over the medium to long term.

2.3. Wider Environmental Considerations

BEVs produce no tailpipe emissions improving local air quality and are more efficient than combustion technologies, reducing the impact on global warming. BEVs use electricity from the grid which has increasing amounts of renewable energy like wind and solar, further reducing the well-to-wheel GHG emissions from bus services.

However, BEVs start with a higher embedded carbon compared to diesels, where more emissions are produced in the construction of BEVs, particularly from batteries. Importantly the lower carbon intensity of the UK electricity grid and high mileage of buses in-service means that overall lifetime emissions of BEVs are much lower compared to diesels.

Zemo Partnership is investigating life cycle analysis of technologies and energy to continue to improve industry understanding and have the long-term goal of integration into government policy.

There are also wider environmental considerations around the materials used in BEVs. Batteries and motors contain materials which require extraction through mining which are at risk of unsustainable and unethical practices. To combat this suppliers and governments are placing increasing checks on where materials are sourced and the state of working conditions e.g. using blockchains to track origin of metals such as lithium and cobalt.

2.4. Infrastructure & Charging

Charging infrastructure required to support BEV deployment is bringing together the energy and transport sector, which have interacted very little historically. Different working practices and regulatory environments means that infrastructure deployment can be the most challenging part of BEV deployment. Extensive consultation with suppliers and OEMs together with long-term planning is needed to ensure a successful transition to zero emissions.

2.4.1. Overview

The charging strategy needs to be considered in conjunction with battery capacity and vehicle efficiency. 'Depot-Based / Overnight Charging' and 'Opportunity / On-Route Top-Up Charging' strategies bring different advantages and operational requirements. Charging strategies seek to compromise between cost and operational effectiveness, balancing battery size and replacement, charging power and frequency and vehicle range.

While chargers can be around 95% efficient, operators should expect around 20% of total energy loss between the electricity meter and the wheels of the bus.

2.4.2. Depot-Based Overnight Charging

Depot-based charging overnight mimics typical diesel bus operation and is currently the most common strategy in the UK. Vehicles charge continuously overnight before leaving the depot, typically not returning till the end of the scheduled service.

Depot-based charging typically uses conductive plug-in charging systems, which are simple and efficient. The manual process requires a staff member to plug in the vehicle when it returns to the depot.

Chargers can be either AC or DC, depending on the charging time available, service intensity and vehicle design. Some OEMs offer vehicles with both AC and DC charging capabilities to improve operational flexibility (see 2.4.3).

Most BEVs are limited as to how much power they can receive at any one time through plug-in chargers, typically around 100kW, although this is expected to rise to 200kW in future. Charge balancing of battery cells is needed every few days to ensure stability and longevity.
Considerations are needed to ensure parking layouts match scheduling requirements to ensure the first vehicle to leave the depot has sufficient energy to meet 19. Smart charging requires communication between vehicles, chargers and a charging management software.

2.4.3. AC & DC charging

Alternating Current (AC) is used to distribute electricity to homes and businesses to power lights and appliances, while batteries require Direct Current (DC) to be charged. To charge vehicles, AC needs to be converted to DC either on-board the bus or in the charging unit.

Buses using AC chargers require an 'on-board charger', or 'converter' to charge. Using AC power to charge buses is considered 'slow' (22-43kW AC), with charging time of up to 8 hours depending battery size.

AC chargers use Type 2 standard design. AC charge rates can be increased by using dual 43kW chargers to charge a bus concurrently (43kW x 2 = 86kW). Lower power ratings means AC charging is lower cost but not all bus OEMs offer AC charging, some only offer DC charging options.

Figure 6: Dual AC Type 2 charging system plug and vehicle interface providing 86kW of charge through two 43kW dual chargers.

(Credit Zenobe Energy)

For DC charging, the AC to DC conversion is performed by the charging unit, and not on the bus, meaning it can feed power directly to the vehicle's batteries. DC charging enables 'Fast' plug-in charging units (75-200 kW DC), offering charge times of 2-4 hours depending on battery capacity.

DC chargers use the latest Combined Charging Standard (CCS2) (Figure 7). Operators are deploying 150kW dual-chargers, enabling two buses to be charged at 75kW, reducing space needed for chargers. Higher power capabilities result in DC chargers being more costly compared with AC.

Figure 7: Combined Charging System 2 (CCS2) plug and vehicle interface.

(Credit Mercedes-Benz)

Choosing a charging method is subject to charging windows. If overnight, lower power charging is possible, and cost savings can be achieved. However, where depots have large numbers of vehicles, with large batteries and long daily range requirements, DC charging is likely required.

Historically the market has preferred AC charging as BEV deployment was limited to shorter length routes. As vehicle performance has improved, operators are starting to shift to DC charging. Transport for London (TfL) has recently mandated that all new BEVs must be DC CCS2 compatible to ensure one standard across the London bus fleet.

Data can also be transferred through chargers, conveying key information like vehicle ID, battery state of charge (SoC) or state of health (SoH – reflects battery degradation). Data management is crucial for charging along with vehicle scheduling and managing warranties placed on batteries to ensure longevity. Consider data transfer between the vehicles and chargers extensively and engage project partners to prevent data challenges in-service. ISO 15118 is the international standard for defining the vehicle-to-grid communication interface.

2.4.4. Opportunity & Top-Up Charging

'Opportunity' charging deploys high-power chargers to provide rapid charging at regular intervals such as at the start/end of routes, or at bus stops/stations. Schedules may also allow 'top-up' charging using depot infrastructure for a short period mid-service.

Opportunity charging commonly uses conductive pantograph systems (Figure 8), adopting the "OppCharge" standard. Pantographs provide DC power, between 300kW-450kW (up to 600kW), and typically takes 5-10 minutes. Charging occurs automatically, triggered by the driver and the position of the bus.

UK OppCharge projects have adopted 'Pantograph-Down' solutions, where the charger arm lowers down onto rails on the bus roof, while 'Pantograph-Up' is more common in Europe. The advantage of panto-down is buses don't have the weight and maintenance of individual pantographs on each bus.

Opportunity charged buses are typically deployed with smaller battery sizes (200-350kWh) compared to those using overnight only charging. Battery sizes could be smaller but operators have sought minimum ranges in the event of charger faults.

Depot-based chargers are typically used in conjunction with opportunity charging to provide contingency and allow for battery balancing to maintain battery health. Opportunity charging adds cost and additional planning requirements, however it allows effectively unlimited daily range and can be more cost effective over a whole bus network.

Figure 8: Opportunity on-route using conductive 'Pantograph-Down' charging system installed at bus stop.

(Credit Harrogate Bus Company)

2.4.5. Wireless Inductive Charging

Wireless inductive charging provides an alternative for opportunity charging to pantographs. The same technology used for wireless phone charging, inductive charging transfers energy between the grid and bus via coils installed in the road and underside of the bus.

Wireless charging has the advantage of minimal street furniture and no physical connection, reducing hazards and clutter. Power capabilities of up to 200kW are possible.

Wireless charging has been trialled in the UK and elsewhere, becoming increasingly popular in the US. While efficiency is close to that of conductive charging, challenges remain with maintaining charger coils installed in the ground which require cranes to access.

2.5. Grid connections

A grid connection is potentially the most challenging aspect of BEV deployment, requiring coordination across multiple suppliers and the local Distribution Network Operator (DNO).

Extensive consultation and exploring connection options, including private wire connections and using Independent DNO's (IDNO) or Independent Connection Providers (ICPs) can unlock cost and time savings.

Cost and time for connection is highly variable as it depends on the location of the depot to the nearest substation and the amount of power available at the substation.

Historically a rough guide to grid upgrade costs is £1m for every 1MW of power to site. However, an ongoing Significant Code Review of how new connections are funded has been conducted by Ofgem, with a view to share the cost of upgrades across all users. Engagement with suppliers will enable you to understand the impact of these future changes on overall project cost.

Figure 9: Stages of installing charging infrastructure on site.

Site survey by infrastructure company engineer includes looking at power supply on site and determining the availability of three-phase capacity.

If power capacity is insfficient either a power supply upgrade or a new power supply from DNO will be suggested. New connection can take 6-24 months. Enegry supplier is responsible for meter installation - takes a few weeks.

Civil work such as trenching, ducting, trunking are usually performed by the same team which does charge point installation.

Charge point installation. The IET COP and BS7671 guidelines are followed, with the installer generating a test certificate provided to infrastructure provider and operator.

Infrastucuture provider sends commissioning engineer run a test charge with the electric bus.

2.5.1. Power requirements

Most depots will have an existing grid connection, but will likely need an upgrade to accommodate the large amounts of power needed to charge BEVs. Operators will need to engage with OEMs, charge point providers and scheduling analysts to understand power requirements and charge windows.

A site survey will be needed as part of the grid upgrade assessment to understand any limitations related to the site, as well as alternative charging strategies and how installation works may impact existing service operation.

Table 6: Simple example of power requirements based on fleet size, battery capacity and charging window.

Number of BEVs	Battery Capacity	Total Energy Requirement	Charge Window	Peak Power Requirement
10	300 kWh	3 MWh	20:00 – 06:00 (8 hours)	0.375 MW
50	500 kWh	25 MWh	22:00 – 05:00 (7 hours)	3.6 MW
100	450 kWh	45 MWh	23:30 – 04:30 (5 hours)	9 MW

Table 6 gives a simplified look at how operators estimate grid upgrade requirements. In reality, not all buses will need charging from 0-100% every day, reducing the peak power requirement.

Measures can be deployed to reduce peak power requirement such as efficient scheduling, on-site energy storage and smart charging. There are different connection types such as unconstrained (available 24 hours a day) or constrained (limited to certain hours only); the latter can enable you to pay much lower rates of electricity, usually at night, when the local demand on the grid is very low.

2.5.2. Distribution Network Operators & Upgrade

Distribution Network Operators (DNOs) are regulated monopolies that run electricity networks (wires and distribution equipment) in regional areas, connecting the National Grid's high-voltage transmission grid to electricity users including homes, businesses and industry.

Most projects will need to engage with DNOs to access a grid upgrade. Connecting to the transmission grid is a possibility but would involve moving depots to where infrastructure already exists.

Table 7: Summary of Distribution Network Operators (DNOs) in the UK

Area	Distribution Network Operator (DNO)
East England	UK Power Networks
East Midlands	National Grid Electricity Distribution
London	UK Power Networks
North Wales, Merseyside and Cheshire	SP Energy Networks
West Midlands	National Grid Electricity Distribution
North East England	Northern Powergrid (Northeast)
North West England	Electricity North West
North Scotland	SSE (Scottish Hydro Electric)
South and Central Scotland	SP Energy Networks
South East England	UK Power Networks
Southern England	SSE (Southern Electric)
South Wales	National Grid Electricity Distribution
South West England	National Grid Electricity Distribution
Yorkshire	Northern Powergrid (Yorkshire)

Existing DNO connection processes have been setup for housing or renewable energy projects rather than more time and space constrained bus depot conversions. These processes can mean managing project design and implementation is challenging.

For a grid upgrade, an application must be submitted to the DNO for a request for power and may include a cost (circa £1.5k) to cover design works and time. The DNO will then take up to 10 working weeks to calculate costs and respond with a quote. The quote will detail which local substation(s) to be connected to or if a new substation is needed and may include costs for 'contestable' and 'non-contestable' works.

Non-contestable work must be done by the DNO legally, while contestable works can be carried out by other contractors such as IDNOs or ICPs which may reduce project costs.

A key aspect of the quote for connection works is that it is time limited, usually 6 working weeks. If an offer expires a DNO may require another new application to be made, placing significant pressure on aligning grid upgrades with vehicle and equipment procurement and grants and funding decisions.

In parallel to grid upgrades, design work to map out charger locations and bus movements to limit lost parking space will be required. This will include new cabling locations, civil works and depot alterations such as barriers to protect staff, chargers and ensure safe vehicle movements.

Factors to consider when upgrading the electricity network:

- On-site distance to and capacity of the nearest sub-station from depot
- Whether onsite energy storage, constrained connections and smart charging will reduce grid upgrade requirements
- Timeframe for upgrading work and new connection, preparing legal contracts and negotiations with the DNO – timeframes may be lengthy

Once designs, connection work and project funding is agreed, civil works on site can commence. Grid connections tend to be the time limiting element to any project, although recently supply chains have impacted delivery times for transformers and electrical components.

2.5.3. Independent Distribution Network Operators (IDNO)

An Independent Distribution Network Operator (IDNO) is a company licensed by Ofgem, to own and operate electricity networks. The IDNO will create a small private network (which may include on-site generation, energy storage, chargers), managed separately to the local power network. The IDNO will be responsible for managing and operating the new private network and may provide potential revenue.

2.5.4. Independent Connection Providers (ICP)

An Independent Connection Provider (ICP) is an accredited company that carries out works on the electricity network. An ICP generally carries out 'contestable works' for the DNO or IDNO which can reduce project costs.

2.6. Training and knowledge development

BEVs will require training and knowledge development for staff, including drivers, shunters, engineers and operations staff.

2.6.1. Drivers

Drivers' training will focus on the importance of regenerative braking and ensuring the vehicle's state of charge (SoC) is sufficient to complete the service. Understanding the improved torque of BEVs compared to diesels will also be needed to ensure passenger comfort.

Regenerative breaking can capture up to 30% of daily energy use, providing a critical role in BEV daily range and cost. Telematics systems can provide operation managers with useful information to help manage drivers and vehicles.

2.6.2. Maintenance

BEV maintenance is typically reduced compared to diesels due to fewer components and less moving parts. Upskilling staff can be done by OEMs to enable quick on-site solutions and EV training packages are becoming more widespread. Engineers will require new knowledge on maintaining high-voltage (HV) cables, batteries and motors. Telematics can flag technical faults to engineers, optimising maintenance and improving vehicle availability.

Technicians must also be aware of BEV-specific maintenance, such as inert electrostatic coolant for batteries' management. If depots have both diesel and BEV vehicles in operation, extreme caution must be taken to separate and label powertrain-specific equipment to avoid negative consequences for vehicles and staff.

2.6.3. Depot Management

Oversight of vehicle charging is crucial. Depot staff will need to be trained to ensure vehicles are plug-in and charged at the right time in a safe and efficient manner. BEVs are very quiet and therefore the need for high visibility and safe walkways is important.

2.6.4. Operations

BEVs will need new management practices to operate effectively. Important factors to consider include timetabling and service allocation. Routes with electric vehicles may need to be altered to allow for opportunity charging, or even shortened and re-routed to achieve the required daily mileage on a single charge. Once again the use of vehicle telematics systems which can play a vital role, relaying live information such as efficiency and state of charge (SoC).

2.7. Accredited BEVs

The following section details BEVs that have been tested and certified by Zemo Partnership to date. Certificates are updated annually in line with changes to GHG emission factors and any potential model changes such as battery capacity improvements.

As set out in section 1.3 above, Zemo Partnership has developed an accreditation process for certifying ZEBs to ensure value for money and a consistent and transparent process of evaluating energy and emissions performance.

Bus OEMs test vehicles to achieve certification that is then used in incentive schemes offered by DfT and Transport Scotland. Visit the Zemo Partnership website to download ZEB certificates to access more information.

Visit the Zemo Partnership website to download ZEB certificates to access more information.

zemo.org.uk

2.7.1. Single Deck

The following single deck BEVs have been certified under the ZEB Accreditation Scheme.

Alexander-Dennis BYD Enviro200EV

(Credit ADL / BYD)

Vehicle Information	
Manufacturer	Alexander-Dennis BYD
Model	Enviro200 EV
Vehicle Length	9.6m – 11.6m
Total Passenger Capacity	65
Zero Emission Capability	
Battery Capacity	348 kWh
Vehicle Energy Consumption	1.10 kWh/km
Estimated Range	up to 301 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	404.2 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	63%
WTW GHG per passenger km	6.2 g CO_2e/ pass km

Switch Mobility Metrocity

(Credit Switch Mobility)

Vehicle Information	
Manufacturer	Switch Mobility
Model	MetroCity
Vehicle Length	8.7m – 11.5m
Total Passenger Capacity	60
Zero Emission Capability	
Battery Capacity	226 kWh
Vehicle Energy Consumption	0.95 kWh/km
Estimated Range	up to 219 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	336.9 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	68%
WTW GHG per passenger km	6.2 g CO_2e/ pass km

Caetano e.City Gold

(Credit Caetano)

Vehicle Information	
Manufacturer	Caetano
Model	e.City Gold
Vehicle Length	10.7m
Total Passenger Capacity	65
Zero Emission Capability	
Battery Capacity	385 kWh
Vehicle Energy Consumption	0.93 kWh/km
Estimated Range	up to 331 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	356.2 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	67%
WTW GHG per passenger km	5.5 g CO_2e / pass km

Volvo BZL Single Deck

(Credit Volvo)

Vehicle Information	
Manufacturer	Volvo
Model	BZL Single Deck
Vehicle Length	9.5m – 13.0m
Total Passenger Capacity	86
Zero Emission Capability	
Battery Capacity	376 kWh
Vehicle Energy Consumption	1.08 kWh/km
Estimated Range	up to 278 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	367.3 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	72%
WTW GHG per passenger km	4.3 g CO_2e/ pass km

Please note vehicle energy consumption presented is an average over the UK Bus Cycle. Zemo Partnership use the average carbon intensity of the UK Grid to report GHG performance of ZEBs (using 'Government conversion factors for company reporting of greenhouse gas emissions' 2021, to be updated annually).

EVM Novus

(Credit EVM)

Vehicle Information	
Manufacturer	EVM
Model	Novus
Vehicle Length	7.4m
Total Passenger Capacity	15
Zero Emission Capability	
Battery Capacity	115 kWh
Vehicle Energy Consumption	0.37 kWh/km
Estimated Range	up to 249 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	147.7 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	76%
WTW GHG per passenger km	9.8 g CO_2e/ pass km

Mellor Sigma 7

(Credit Mellor)

Vehicle Information	
Manufacturer	Mellor
Model	Sigma 7
Vehicle Length	7.0m
Total Passenger Capacity	30
Zero Emission Capability	
Battery Capacity	142 kWh
Vehicle Energy Consumption	0.57 kWh/km
Estimated Range	up to 197 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	182.2 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	76%
WTW GHG per passenger km	6.1 g CO_2e/ pass km

Mellor Sigma 10 / Sigma 9 / Sigma 8

(Credit Mellor)

Vehicle Information	
Manufacturer	Mellor
Model	Sigma 10 (applies to Sigma 8 and 9)
Vehicle Length	10.3m
Total Passenger Capacity	54
Zero Emission Capability	
Battery Capacity	up to 260 kWh
Vehicle Energy Consumption	0.75 kWh/km
Estimated Range	up to 281 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	254.8 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	74%
WTW GHG per passenger km	4.7 g CO_2e/ pass km

Yutong E12 / E10 / E9

(Credit Yutong)

Vehicle Information	
Manufacturer	Yutong
Model	E12 (applies to E10 and E9)
Vehicle Length	12.2m (10.9m)
Total Passenger Capacity	70
Zero Emission Capability	
Battery Capacity	422 kWh
Vehicle Energy Consumption	0.84 kWh/km
Estimated Range	up to 443 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	265.3 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	77%
WTW GHG per passenger km	3.8 g CO_2e/ pass km

2.7.2. Double Deck

The following double deck BEVs have been certified under the ZEB Accreditation Scheme.

Alexander-Dennis BYD Enviro400EV

(Credit ADL / BYD)

Vehicle Information	
Manufacturer	Alexander-Dennis BYD
Model	Enviro400 EV
Vehicle Length	10.3m – 10.8m
Total Passenger Capacity	85
Zero Emission Capability	
Battery Capacity	382 kWh
Vehicle Energy Consumption	0.92 kWh/km
Estimated Range	up to 333 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	267.3 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	80%
WTW GHG per passenger km	3.1 g CO_2e/ pass km

Switch Mobility MetroDecker EV

(Credit Switch Mobility)

Vehicle Information	
Manufacturer	Switch Mobility
Model	Metrodecker EV
Vehicle Length	10.5m – 11.1m
Total Passenger Capacity	98
Zero Emission Capability	
Battery Capacity	300 kWh
Vehicle Energy Consumption	1.14 kWh/km
Estimated Range	up to 219 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	423.6 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	70%
WTW GHG per passenger km	4.3 g CO_2e/ pass km

Volvo BZL Double Deck

(Credit Volvo)

Vehicle Information	
Manufacturer	Volvo
Model	BZL Double Deck
Vehicle Length	10.9m
Total Passenger Capacity	81
Zero Emission Capability	
Battery Capacity	470 kWh
Vehicle Energy Consumption	1.09 kWh/km
Estimated Range	up to 331 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	429.1 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	65%
WTW GHG per passenger km	5.3 g CO_2e/ pass km

Wrightbus StreetDeck Electroliner

(Credit Wrightbus)

Vehicle Information	
Manufacturer	Wrightbus
Model	StreetDeck Electroliner
Vehicle Length	10.6m
Total Passenger Capacity	87 - 98
Zero Emission Capability	
Battery Capacity	340 / 454 kWh
Vehicle Energy Consumption	0.68 / 0.75 kWh/km
Estimated Range	400 / 484 km
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	230.3 g CO_2e/km
GHG saving compared to Euro VI diesel equivalent:	84%
WTW GHG per passenger km	2.4 g CO_2e/ pass km

2.7.3. Coaches

To date, only Transport Scotland have supported the purchase of zero emission coaches under the ScotZEB and SULEBS capital grant schemes.

Zemo Partnership is working with the government, Confederation of Passenger Transport (CPT) and industry to develop a Zero Emission Coach Certification Scheme which could be adopted by government incentive schemes to encourage the development and deployment of more zero emission coaches in the UK.

Yutong TCe12

(Credit Yutong)

Vehicle Information	
Manufacturer	**Yutong**
Model	**TCe12**
Vehicle Length	**12.4m**
Total Passenger Capacity	**50**
Zero Emission Capability	
Battery Capacity	**281 kWh**
Vehicle Energy Consumption	**0.90 kWh/km**
Estimated Range	**up to 275 km**
Environmental Credentials	
Well-to-Wheel Greenhouse Gas emissions:	**366.6 g CO_2e/km**
GHG saving compared to Euro VI diesel equivalent:	**61%**
WTW GHG per passenger km	**7.3 g CO_2e/ pass km**

2.7.4. Future Accreditation

Zemo Partnership anticipates the following battery electric vehicles gaining ZEB accreditation in the future, subject to a valid test result:

Table 8: Battery electric buses which Zemo Partnership anticipates will achieve ZEB accreditation.

Manufacturer	Model
Alexander Dennis	Single Deck: Enviro100EV Double Deck: Enviro400EV
EVM	Single Deck: Isuzu NovoCiti Volt
Equipmake	Double Deck: Jewel E
Irizar e-Mobility	Single Deck: ie Tram, ie Bus
Mercedes-Benz	Single Deck: eCitaro
Scania	Single Deck: Fencer EV
Switch Mobility	Single Deck: Solo EV
Wrightbus	Single Deck: Wrightbus GB Kite Electroliner BEV
Yutong	Double Deck: DD

2.8. Case studies

Case Study: Depot Based / Overnight Charging
Operator: Abellio, London
Fleet: 34 x Caetano e.City Gold
Infrastructure Provider: Zenobe Energy

Thirty-four Caetano e.City Gold electric buses were introduced during 2020 on the P5 (Nine Elms-Elephant and Castle) and C10 (Canada Water-Victoria) from Abellio London's Walworth depot. At the end of 2021, the first EV double deck buses were introduced to the depot with a fleet of BYD/ADL Enviro400EV buses entering service on route 63, bringing the share of EV buses to over 35% of the depot's allocated fleet.

Abellio London worked with EV fleet and battery storage specialist Zenobē to deliver the initial depot-based plug-in charging infrastructure at Walworth, later working with Siemens on the project for the double decker buses. The initial depot installation included a 1.2MW stationary battery-storage solution to help with the charging management.

The Zenobē battery supports the power requirements of the fleet, allowing Abellio to use a smaller grid connection. The stationary battery charges during the day while the electric buses are in service, and the stored energy charges them overnight. The battery's energy can also be used during peak hours when energy from the grid is more expensive, reducing Abellio's energy costs for charging the fleet.

Credit: Caetano

Case Study: Opportunity Charging
Operator: Harrogate Bus Company (Transdev)
Fleet: 8 x Volvo 7900E
Infrastructure Provider: ABB

In 2018, Harrogate Bus Company, part of Transdev Blazefield, introduced eight Volvo 7900E battery electric buses to the town's bus network with the support of £2.25m of UK Government Low Emission Bus funding.

The buses adopt an 'opportunity charging' strategy to ensure each 'Harrogate Electrics' bus can efficiently and reliably perform throughout a full day of service without interruption. Using pantograph charging systems installed at Harrogate Bus Station, top-up charging takes place during layover periods in service while the vehicle stands. This top-up charge supplements overnight charging at the company's Starbeck depot, which is required to balance the battery packs.

The charging equipment and substation installed at the bus station are supplied by ABB, and utilise the 'pantograph-down' methodology which features a pantograph extending down from an overhead mast to connect with charging rails mounted on the roof of the bus.

The system charges vehicles at up to 300kW, allowing each bus to be charged in less than 10 minutes, eliminating the need to wait for long charging periods during service. The units are compatible with the OppCharge interface, enabling compatibility with potential future expansion using other vehicle models.

Credit: Harrogate Bus Company

3. Hydrogen Fuel Cell Electric Buses

Hydrogen Fuel Cell Electric Buses (FCEVs) provide an alternative zero emission solution to battery electric buses and charging infrastructure. FCEVs offer potentially greater range compared to EVs with similar refuelling times to diesel, producing only water vapour at the tailpipe.

There are over 60 hydrogen FCEVs in service, with key fleets in Aberdeen, London and Birmingham. There were 55 hydrogen FCEVs buses registered in 2021, all of which were double decks. The first single deck FCEVs funded by the DfT's Ultra-Low Emission Bus (ULEB) Scheme are expected to go into service around Gatwick/Crawley in 2023.

Hydrogen FCEVs have been identified as a solution for long distance, zero emission heavy duty vehicles as compressed hydrogen can store significant amounts of energy. Storage space for hydrogen tanks rather than battery weight becomes the limiting factor for FCEVs daily range.

The vehicle technology is improving with recent in-service data for double deck FCEVs reporting 6-7.5kg/100kms, a 30-40% improvement on previous generations introduced 5 years ago. Challenges remain around the limited sources of hydrogen in the UK and internationally, especially low carbon hydrogen supply.

The UK government published the 'UK Hydrogen Strategy' in 2021 which sets a target of 5GW of low carbon hydrogen production capability by 2030. The UK government also published the 'UK Low Carbon Hydrogen Standard', defining low carbon as hydrogen with a carbon intensity of 20g CO_2e/ MJ.

The following manufacturers supply FCEVs to the UK market:
- Alexander-Dennis
- Caetano
- Wrightbus
- Van Hool

Table 9: Key factors for consideration for FCEV deployment.

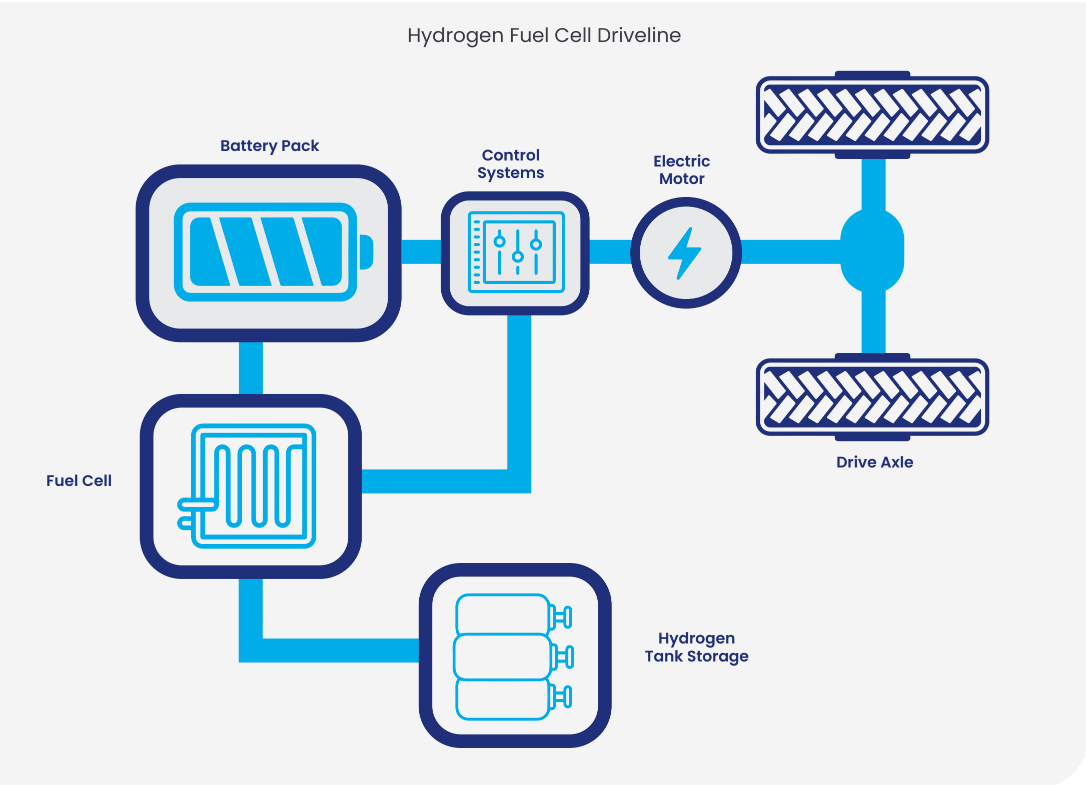
Operations	Infrastructure	Maintenance
• Route length and topography • Hydrogen storage capacity, fuel consumption and range • Vehicle refuelling schedule • Hydrogen delivery schedule • Using telematics data effectively • Driver training to optimise energy efficiency and range	• On-site or off-site refuelling • Source and carbon intensity of hydrogen • Compressed or liquid hydrogen storage • Potential grid upgrade • Upgrades to maintenance facility e.g. hydrogen detectors, extractor fans • Engagement with local planning and emergency services	• Staff training on hydrogen safety and new equipment e.g. hydrogen body sensors • Parts upkeep (battery, fuel cell, pumps, storage tanks) • Vehicle warranty • Telematics data to optimise maintenance

3.1. Technology Overview

Hydrogen FCEVs are essentially electric buses (hence Fuel Cell Electric Vehicle), with energy stored in compressed hydrogen tanks rather than in batteries, extending daily range up to 500km.

A fuel cell bus powertrain typically comprises of a fuel cell stack and storage tanks, in combination with batteries or super-capacitors. FCEVs also have regenerative braking to recoup energy in the same way as BEVs.

Figure 10: Schematic of hydrogen fuel cell bus driveline.



3.1.1. Fuel Cell & Batteries

Fuel cells are electrochemical cells that convert the chemical energy stored in a fuel (i.e. hydrogen) and oxygen (taken from the air) into electrical energy. To achieve sufficient electrical power to propel a vehicle, multiple cells must be compiled into a fuel cell 'stack'.

Fuel cells' currently in use on hydrogen buses are rated between 30kW – 50kW. The leading fuel cell type for automotive applications is the polymer electrolyte membrane fuel cell or "PEM". A fuel cell lifetime is measured in hours rather than years,

Fuel cells design means they produce an constant power output, so a battery or supercapacitor is needed to act as an intermediary energy store to provide variable levels of power to the motor, as the driver accelerates at different rates throughout the service.

As compressed hydrogen is the main energy store, battery packs in FCEVs can be much smaller, reducing weight and space batteries are sized between 25 - 50kWh and most commonly utilise Lithium Titanate Oxide (LTO), which is more suitable to constant charge/discharge cycling.

3.1.2. Hydrogen Tanks & Compression Rates

Hydrogen is an extremely light gas with very low volumetric density at atmospheric temperature (25ºC) and pressure (1.01 bar). To store sufficient amounts of energy for use in bus it must be compressed. FCEV buses adopt a pressure of 350 bar at atmospheric temperature.

In order to meet range requirements, 25-50kg of hydrogen is ukept on board stored in 5-6 tanks. These tanks are typically installed on the roof of single deck buses, and in the rear of double deck buses.

There are multiple 'types' of storage tanks which denote the materials used, with Type III tanks most often used for FCEV buses at 350 bar. Type III tanks are fully wrapped composite (carbon fibre) tanks with metal lining, which are lighter than Type I and II. Type IV tanks use carbon fibre wrapping with a plastic lining providing even lighter tanks and higher storage pressures, but remain very costly.

Increasing system pressure up to 700 bar, as used in FCEV cars, would effectively double the amount of hydrogen stored, increasing vehicle range or reducing need for storage tanks. Some truck OEMS are assessing the use of liquid hydrogen to further increase on board energy storage. However, higher pressures and liquid storage are more costly as materials must be more robust, with liquid hydrogen requiring energy intensive cooling.

Figure 11: Engine bay of Alexander Dennis Enviro400FCEV highlighting packaging layout of fuel cell and hydrogen tanks

(Credit Alexander Dennis)

3.2. Total Cost of Ownership

Hydrogen FCEVs buses, like BEVs, are more costly up front compared with diesels. The limited supply of low carbon hydrogen in the market means that hydrogen is also higher cost compared with diesel. Costs are expected to fall as the supply chain grows and more FCEVs are put into service, with the UK government investing in hydrogen production facilities and supporting renewable fuels through the Renewable Transport Fuels Obligation (RTFO).

A fuel cell lifetime is expected to be between 5-10 years subject to operational intensity. After this period, the fuel cell can be refurbished or replaced. As with BEVs, battery packs will also need replacing after 7-10 years subject to chemistry and usage. Storage tanks are expected to last 15 years but require regular inspection and pumps may also need replacing during the lifetime of the bus.

For infrastructure, significant cost savings are achieved at scale, where costs become comparable to high power DC charging once a fleet size reaches 50-60 vehicles. Higher volumes will result in a lower unit cost of hydrogen.

Refuelling infrastructure may need an electricity grid connection upgrade for compressors and will require a maintenance regime to ensure effective operation.

Once a fleet reaches over 100 vehicles, storing hydrogen on site in liquid form may reduce the need for storage tanks and provide space and cost savings. Sharing refuelling infrastructure can provide opportunities for alternative sources of funding and potential revenue.

3.3. Wider Environmental Considerations

Hydrogen FCEV buses produce zero tailpipe emissions aside from water vapour, offering clear benefits to air quality in towns and cities. However, the production methods and energy used in hydrogen production are highly influential on the overall well-to-wheel greenhouse gas emissions.

Different colours are often used to refer to different energy sources, with grey hydrogen produced using fossil natural gas, blue referring to fossil gas with carbon capture and storage and green referring to renewable energy.

Zemo Partnership has prepared a ‘Hydrogen Vehicle Well-to-Wheel GHG and Energy Study’ that details the different production methods of hydrogen and provides indicative well-to-wheel greenhouse gas emissions estimates for impact of different hydrogen production pathways and their subsequent use in FCEVs.

The study demonstrated that hydrogen produced from renewables can offer significant greenhouse reductions compared to fossil diesel, while using hydrogen produced using fossil gas should be avoided for use in transport.

To support the industry with greater transparency and understanding of low carbon fuels, Zemo has created a ‘Renewable Fuels Assurance Scheme’ (RFAS). The scheme audits the supply chain of individual renewable and low carbon fuel suppliers to UK operators. This enables operators to have greater confidence in the source and carbon impact of the fuels they are using.

As hydrogen FCEVs have much less battery storage compared to BEVs, greenhouse gas emissions associated with vehicle production (“embedded carbon”) will be lower. However, some materials, such as platinum used in the fuel cell and carbon fibre used in storage tanks do involve energy intensive refining and production processes.

3.4. Infrastructure & Refuelling

As with BEVs, Hydrogen fuel cell buses require new additional infrastructure capable of refuelling vehicles. Considerations will need to be made for infrastructure location (in the depot or off-site), the hydrogen supply (tanker or on-site electrolysis), amount of hydrogen needed, potential grid connection upgrade, planning and local authority engagement.

3.4.1. Overview

Refuelling a hydrogen FCEV is a more familiar process for operators transitioning from diesel. The process itself can take between 5 and 15 minutes per bus and requires a nozzle being plugged into the vehicle manually (see Figure 12).

Once the nozzle is secure, refuelling is automated until the pressure on the vehicle reaches the desired pressure (typically 350 bar). Refuelling nozzles are designed so that a 350 bar nozzle can refuel a 700 bar vehicle, however a 700 bar nozzle cannot refill a 350 bar vehicle to avoid over pressurising systems.

Refuelling infrastructure stores hydrogen in tanks and then uses compressors to reach the required pressure. The number of tanks and compressors will depend on number of buses and operational intensity. Compressors require an electricity connection which may need to be upgraded subject to scale.

3.4.2. Refuelling strategies

To date, operators have approached refuelling in two ways, either on-site in the depot or off-site at a public site that is typically multi-modal.

For depot based refuelling, operators will have identify a suitable refuelling location and schedule in refuelling time, typically before or after a day's service. As timescale and refuelling methods are similar to diesel, this method is seen as least disruptive to scheduling and parking.

Depot refuelling typically involves hydrogen being supplied by tanker, so operators will need to account for additional vehicle movements of larger truck trailers at the depot.

Refuelling off-site, typically at a location refuelling other vehicle types, means some operation changes will need to be made to refuel vehicles, including potentially additional staff or retraining drivers.

Off-site refuelling means less infrastructure work is required at the depot but may involve additional project partners, adding complexity. Off-site refuelling is often paired with an electrolyser where hydrogen is produced on demand using grid connected electricity.

3.4.3. Production

Hydrogen can be generated via the electrolysis of water, which produces hydrogen and oxygen from splitting water molecule using electricity. This method facilitates the production of 'green' hydrogen via the use of renewable electricity, reducing the well-to-wheel greenhouse gas impact of FCEV operations.

Electrolysers may be situated at the depot or at a strategic off-site location. Modern electrolysers use the same efficient PEM technology used in fuel cells. Hydrogen can also be produced through the reformation of methane (SMR) or as a bi-product from industrial processes. These production pathways, however, tend to generate high GHG emissions. See Zemo Partnership's 'Hydrogen Vehicle Well-to-Wheel GHG and Energy Study' for more information on hydrogen production pathways.

Early indications from the developing supply chain are that economies of scale will see hydrogen production in large quantities at industrial sites and ports linked to renewable energy projects and transported by trailer to refuelling locations.

Figure 12: Off-site multi-modal hydrogen refuelling station in Aberdeen
(Credit First Bus / Wrightbus)

Figure 13: 350 bar hydrogen nozzle connected to vehicle during refuelling. During this process, the bus is earthed by an earthing cable to reduce static electricity.
(Credit First Bus / Wrightbus)

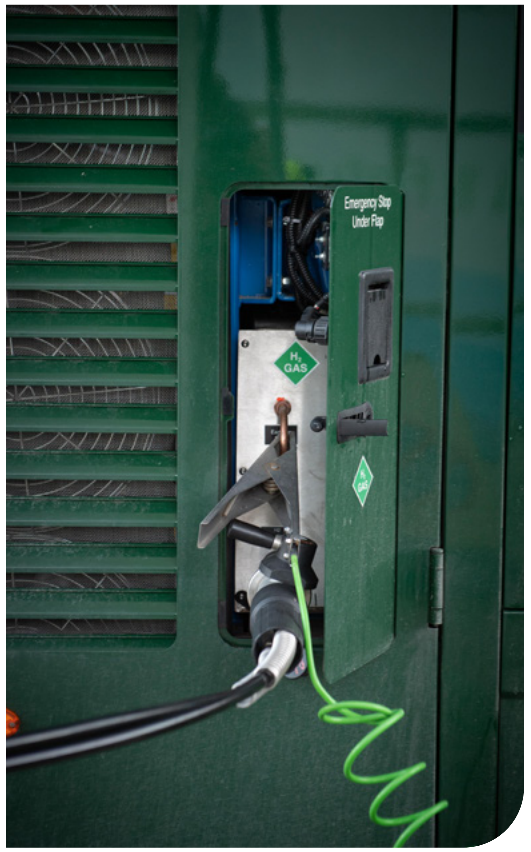


Figure 14: Depot-based hydrogen refuelling dispenser at Metroline's Perivale depot in London.

3.4.4. Transportation and Storage

Hydrogen can be transported as compressed hydrogen in tube trailers at 350 or 700 bar and stored in dedicated tanks or the trailer can be left on site for direct refuelling. Hydrogen trailers typically carry 350-500kg per trailer, with industry seeking to develop 1000 kg trailers.

Hydrogen refuelling infrastructure and storage has a relatively small physical footprint, taking the equivalent of 2-5 bus parking spaces subject to design. Typical installation and commissioning of refuelling infrastructure period is 12 - 18 months.

For fleets looking at 100+ hydrogen FCEV buses, storage capacity of 4-5 tonnes of hydrogen will usually be needed. Once a project has over 2 tonnes of hydrogen, 'Planning Hazardous Substance Consent' is needed and additional Control of Major Accident Hazards (COMAH) regulations apply once a project is over 5 tonnes.

In addition, the industry is working with government to develop existing regulations to restrict the use of hydrogen as a road fuel in certain circumstances. For example, transportation of hydrogen by tube trailer must still be done using a diesel truck, rather than a FCEV truck.

Figure 15: Compressed hydrogen tube trailer.

3.5 Training and knowledge development

FCEVs will require training and knowledge development for staff, including drivers, shunters, engineers and operations staff.

3.5.1. Drivers

As with battery electric buses, drivers will require new knowledge on how to operate hydrogen FCEVs safely and efficiently to maximise daily range. Smooth acceleration and deceleration utilising the regenerative braking will ensure efficiency.

As is the case for battery electric vehicles, hydrogen fuel cell buses are very quiet in operation and therefore safe parking practices, particularly in depot environments, are essential.

3.5.2. Maintenance

Maintenance facilities will need to be upgraded to become hydrogen safe or new facilities be built. Common improvements include hydrogen sensors to detects leaks and raising the roof to reduce the risk of hydrogen pooling in corners. Additional extractor fans can be added to ensure quick air evacuation from the maintenance facility.

As with BEVs, staff will require training to work with high voltage systems. Staff will also need to understand the intricacies of high pressure systems and health and safety procedures relating to hydrogen.

Additional equipment will be needed, including hydrogen body sensors for maintenance technicians. Hydrogen FCEV vehicle and infrastructure suppliers offer training and engagement to support operators.

Telematics data can assist OEMs and engineering staff in identifying technical faults and optimising vehicle maintenance.

3.5.3. Depot Management

Depots staff will need to be educated about new parking arrangements. Although hydrogen refuelling systems are typically automated, the process still involves an operative correctly connecting the bus to the refuelling. Consideration of new vehicles and staff arriving on site for hydrogen refuelling and FCEV maintenance is needed.

3.5.4. Operations

As FCEV range and refuelling times are more relatable to diesels, operational changes will be limited. Thought is needed around where and when refuelling will take place, especially for off-site refeuelling. Vehicle range is unlikely to be a significant issue but use of vehicle telematics systems will support effective operation.

3.6. Future Accreditation

There are currently no ZEB accredited hydrogen fuel cell buses due to challenges with independently testing hydrogen vehicles at present as well as very limited refuelling infrastructure. Zemo are working with test houses and government to identify interim solutions for ZEB accreditation for hydrogen FCEVs. This may include temporary certification estimates based on simulations or in-service fuel consumption data.

Zemo Partnership anticipates the following hydrogen fuel-cell vehicles gaining ZEB accreditation in the future, subject to a valid test:

Credit: Alexander Dennis

Manufacturer:
Alexander Dennis

Model
Double Deck:
Enviro400FCEV


Credit: Caetano

Manufacturer:
Caetano

Model
Single Deck:
H2.City Gold


Credit: Wrightbus

Manufacturer:
Wrightbus

Model
Single Deck:
GB Kite Hydroliner FCEV

Double Deck:
StreetDeck Hydroliner

3.7. Case study

Case Study: Hydrogen Off-Site Refuelling
Operator: First Bus, Aberdeen
Fleet: 25 x Wrightbus StreetDeck Hydroliner
Infrastructure Provider: BOC

First Bus have introduced twenty-five double deck hydrogen FCEV buses into service in Aberdeen following historic trials. The project saw the rollout of 10 buses, the world's first hydrogen double deck fleet. These buses were jointly funded by the EU JIVE Project, Scottish Government and Aberdeen City Council and followed by a further 15 vehicles funded as part of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) JIVE II project.

Aberdeen City Council has invested consistently in developing the hydrogen economy for transport, investing £19m since 2015 in infrastructure and vehicles, creating the world's first combined hydrogen production and multi-modal refueling station.

The hydrogen is generated via a 1 MW on-site electrolyser operated by BOC. The site is supplied with renewable energy purchased by the council from a local wind farm, ensuring low carbon hydrogen production. This enables each FCEV bus to save a total of 84 tonnes of greenhouse gases per year compared to the previous diesel fleet.

Credit: First Bus / Wrightbus

4. Zero Emission Repowering

Zero emission "repowering" is the process of converting an existing diesel bus into a zero tailpipe emission vehicle. Repowering a vehicle involves the complete removal of the existing diesel powertrain and replacing it with an entirely zero-emission powertrain.

4.1. The case for repowering

Suppliers in the UK are offering both battery electric and hydrogen fuel cell repowers. Different suppliers have different approaches determined by the number of new components which are used in the repower and who carries out the repower installation.

Repowering buses could provide a cost-effective solution for operators compared to buying new vehicles, particularly for smaller operators who normally procure second-hand vehicles. This could also mean smaller initial investment in grid upgrades and charging infrastructure or maximising use of hydrogen refuelling infrastructure that has future proofed for future fleet replacement.

Repowering one or two existing diesel vehicles could enable operators to better understand new operational practices while upskilling staff without committing to a full zero emission fleet. Repowering also provides an opportunity to support the UK supply chain and design engineering. Converting a diesel bus to zero emission is not straightforward and conversion times for vehicles can take between 5-10 weeks once a design and specification have been agreed.

4.2. Zero Emission Repower Accreditation Scheme (ZEVRAS)

Zemo is developing the "Zero Emission Repower Accreditation Scheme" (ZEVRAS) in partnership with suppliers, government and other stakeholders to accredit fully zero tailpipe emission repower solutions.

ZEVRAS accredited suppliers and models will be able to access the DfT's BSOG Zero Emission Bus 22p/km uplift incentive in England. Repowered buses will also be able access to Clean Air Zones without penalty. Zemo is engaging with other government agencies to further promote the adoption of the ZEVRAS standard.

ZEVRAS accreditation will focus on:
- Developing minimum standards for zero emission repowers,
- Detailing the registration process, installation standards and provenance of parts,
- Ensuring safe, robust and reliable installations and in-service operation,
- Meeting the Zero Emission Bus (ZEB) definition.

4.3. Suppliers and Case Studies

A number of suppliers are offering zero-emission repowers in the UK currently, including both battery electric and hydrogen fuel cell repowering:

- Equipmake
- KleanBus
- Ricardo
- Magtec

4.4. Case study

Case Study: Battery-Electric Repower
Operator: Big Lemon, Brighton
Fleet: 2 x Magtec Repower of Optare Solo

Big Lemon is a bus and coach operator based in Brighton, with a long term aim of operating a community owned zero-emission bus fleet powered by renewable energy by 2030. This is in line with Brighton and Hove City Councils ambition for a zero-emission bus fleet by 2030.

In 2016, Big Lemon raised £250,000 through a bond offer open to the public and to retrofit and refurbish two second-hand single deck diesel buses with Magtec's Repower battery electric system. The repower system comprised of 132kWh battery capacity with a range of 100 miles, with an operational window of around 10 hours on one charge.

A further £25,000 was raised through crowd funding and M&S Energy Awards to install a 120 panel (21kW) solar PV array to generate renewable energy to offset the electricity used to charge the bus overnight. 'Om Shanti', the UK's first solar powered bus went into service in April 2017 and is now operating with 10 other single deck EVs in the Brighton and Hove region.

Credit: Big Lemon

Zemo Partnership
Accelerating Transport to Zero Emissions

Zemo Partnership
3 Birdcage Walk, London, SW1H 9JJ

T: +44 (0)20 3832 6070
E: Hello@Zemo.org.uk
Visit: Zemo.org.uk

@Zemo_org
Zemo
Zemo YouTube Channel