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PROJECT REPORT MIS072

Low Emission Bus Scheme monitoring programme

Final Report

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Executive summary

The Low Emission Bus Scheme (LEBS) was a competition run by the Office for Low Emission Vehicles (OLEV) in 2016-2017. £30 million was awarded to 13 projects to purchase 326 buses using four Low Emission Bus (LEB) technologies: battery electric; diesel hybrid; Compressed Natural Gas (CNG), procuring renewable biomethane to offset their emissions; and Hydrogen Fuel Cell (HFC). By December 2021, 275 buses were in service. LEBS projects were required to provide monitoring data for a 12-month period. Of the two hydrogen fleets, one has been in service for six months and the second has experienced delays so has not yet entered full passenger service. Table 1 below summarises the LEB buses delivered by the programme and the monitoring undertaken.

Table 1: Summary of the buses delivered by LEBS and monitoring undertaken

Bus technology	Buses in service	Fleets monitored	Total distance driven during trial (million km)	Trial data available (months)
Battery Electric	64	7	3.1	84
Diesel Hybrid	104	5	6.8	56
CNG (Procuring biomethane)	88	4	6.0	48
HFC	20	1 (on two routes)	0.4	6

The buses are now saving over 10,000 tonnes of GHG per year, measured as 'Well to Wheel' (WTW) CO_2 equivalent emissions (CO_2e) compared to Euro VI diesel equivalents. Analysis of the fuel and energy consumption leads to the following conclusions about the environmental performance of the different technologies:

- The **battery electric buses were the most energy efficient**, using up to 70% less energy than diesel, reducing GHG by up to 70% with 2019 UK 'grid-average' electricity. Fully renewable electricity would reduce emissions by up to 100%.
- Battery electric bus **efficiency can be optimised by using telematics** to encourage efficient driving techniques and by heating the interior before starting operations and using with energy efficient air-source heat-pumps, with additional controllability.
- The **CNG buses used more energy than diesel**, increasing GHG by up to 7% with natural gas; however, when biomethane is procured GHG emissions were reduced by 80%.
- The **diesel hybrid buses were 15% to 37% more efficient than non-hybrid diesels**, depending on type, reducing GHG emissions in the same proportion.
- The **HFC buses used up to 58% less energy (as hydrogen) than diesel**, a significant efficiency improvement over earlier HFC models, reducing GHG emissions by up to 30% with hydrogen made using UK 'grid-average' electricity. Use of a renewable hydrogen

supply, as planned by the project, could provide savings of up to 98%. NB: this project was a central London route, so the HFC may have less advantage over diesel in less congested areas.

Operators provided feedback on their experiences with the trials. The key findings were:

- There were some reliability problems when the vehicles were first introduced, generally unrelated to the traction system. By the end of the trial **reliability was comparable to diesel.**
- Operators liked the **simpler maintenance requirements for battery electric vehicles**.
- **All the vehicles were well received by passengers and drivers**; battery electric buses were noted for ride quality and ease of driving.

GHG savings can be achieved both through improving energy efficiency and decarbonising the fuel or energy source they use. The greatest benefits occur when both decarbonised energy and improved efficiency are applied together, reducing the overall requirement for renewable energy resources that will have to be provided to decarbonise the transport system.

1 Summary and comparison of technologies

1.1 Introduction

The Low Emission Bus Scheme (LEBS) was a £30m competition run by the Office for Low Emission Vehicles (OLEV) to support the purchase of Low Emission Buses and supporting infrastructure by local authorities and transport operators across England and Wales. The 13 winning projects were announced in 2017, with £30 million allocated to purchasing 326 buses (DfT and OLEV, 2016).

LEBS funded four different low emission technologies: battery electric; diesel hybrid; Compressed Natural Gas (CNG), procuring renewable biomethane to offset their emissions; and Hydrogen Fuel Cell (HFC).

Monitoring was undertaken for a 12-month trial period, with operators providing details of refuelling and recharging events, and distance travelled, so that their energy consumption and greenhouse gas emissions (GHG) could be calculated. Operators also provided data for equivalent diesel buses operating on the same or similar routes so that a standard Euro VI diesel baseline could be calculated for comparison.

Operators were also asked to provide data on operational performance so that vehicle availability and failure rates could be compared. Because of differences in how operators collect and report such data it was not possible to undertake a detailed quantitative analysis of these indicators; however operators were asked to provide qualitative feedback on the reliability of the vehicles as part of a wider discussion of their experiences of the LEBS trials.

1.2 Energy consumption and emissions comparison

Using fuel and electricity consumption data provided, the average energy consumption per kilometre was calculated for each fleet. For electric buses this was simply the electricity supplied by the charging infrastructure in kWh, corrected where necessary to allow for charging losses. For CNG, HFC and diesel-powered buses the quantity of fuel consumed was multiplied by its calorific value (see Appendix A) to obtain an energy consumption in energy units, so that all the vehicles could be compared in the same energy consumption units.

Many early generation battery electric bus fleets used diesel heaters, so energy and emissions include heating diesel consumed (treated as untaxed ‘red diesel’ or gas-oil in this project).

Fleet average energy consumption was calculated on a monthly, quarterly and annual basis for reporting purposes.

A summary of the range and distribution of fleet average energy consumption by technology is presented in Figure 1, grouped by Double Deck (DD) and Single Deck (SD). Each vertical bar represents the overall average of an individual LEBS or diesel baseline fleet. NB: the HFC buses have not been in operation for a full year, so the average is over 6 months.

The range of fleet averages shown, especially in the diesel baseline, reflects the differences in operating conditions such as traffic, terrain and passenger loadings. As many of the LEBS projects are in large cities, the corresponding energy consumption values reflect an urban drive cycle.

GHG emissions per kilometre were calculated as Well-To-Wheel (WTW) carbon dioxide equivalent (CO_2e/km) emissions using UK Government conversion factors for greenhouse gas reporting (Department for Business, Energy & Industrial Strategy, 2019). Carbon dioxide equivalent takes account of other GHGs such as methane that can be emitted during the production or use of a fuel, as well as the carbon dioxide. As the GHG emissions from hydrogen vary significantly according to the production pathway used, and there is not currently a 'standard' emission factor, the emissions shown are based on an illustrative emission factor calculated by Zemo Partnership for hydrogen produced by electrolysis using UK grid average electricity. A comparison between GHG emissions using a wider range of emission factors is shown in Section 5 of this report. See Appendix A for a list of emission factors used. A summary of the range and distribution of fleet average greenhouse gas emissions by technology is shown Figure 2.

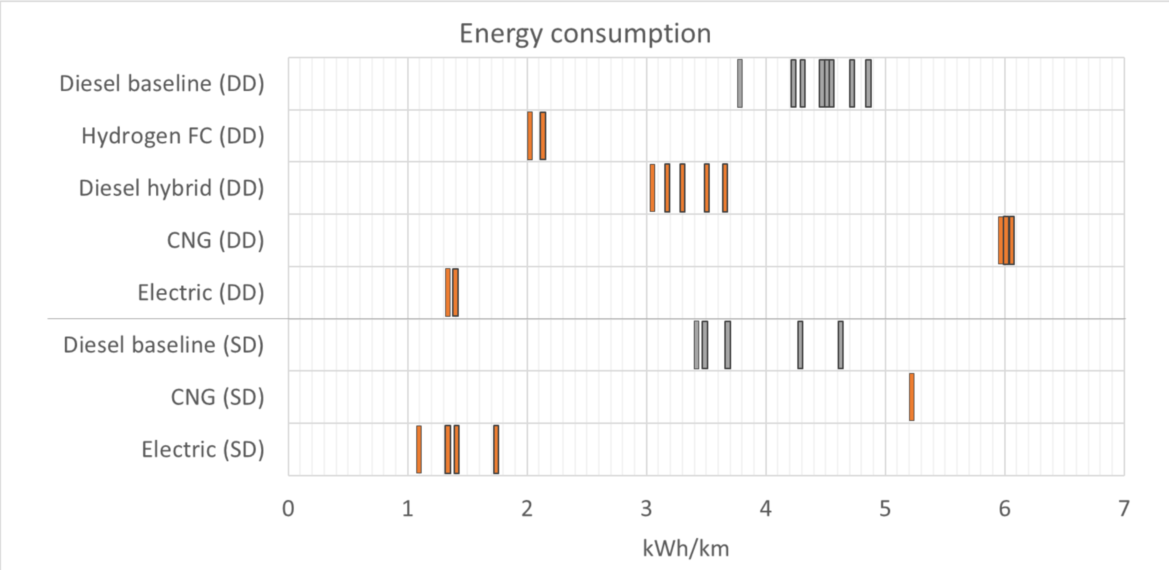

Figure 1: Overall average energy consumption of each LEBS and diesel baseline fleet by technology (Single Deck, SD; Double Deck, DD)

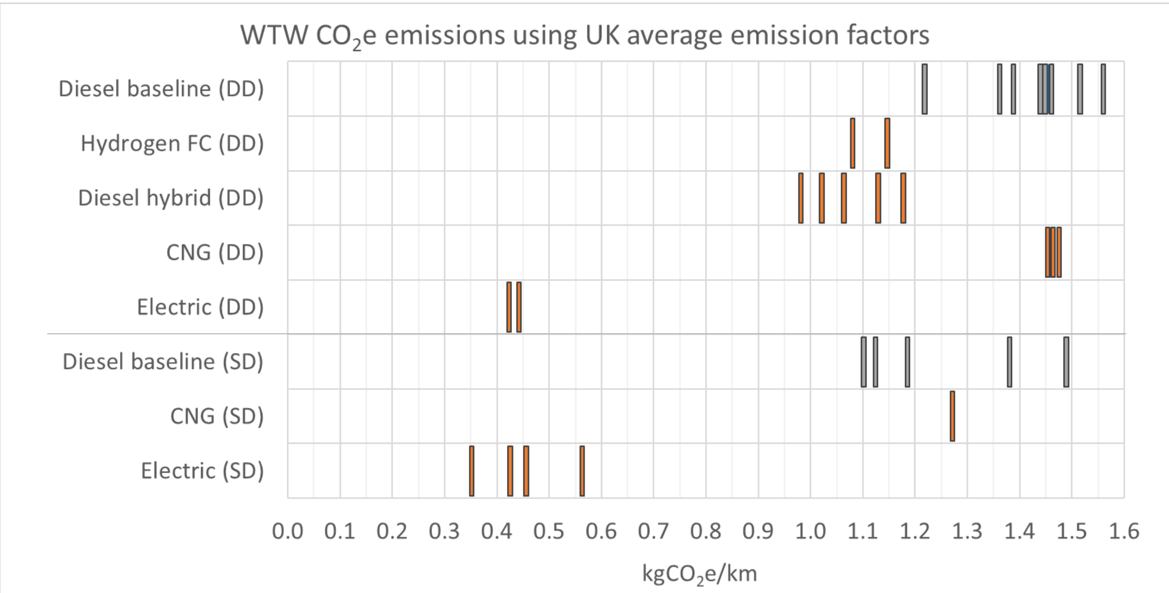

Figure 2: Overall average greenhouse gas emissions of each LEBS and diesel baseline fleet (WTW CO_2e, UK 'grid-average' emission factors) by technology

A comparative summary of the performance of the LEB vehicles in comparison to their diesel baselines for energy consumption, WTW GHG and estimated energy cost per kilometre is given in Table 2. The standard unit costs assumed for fuel and energy are given in Appendix A. Costs are for fuel/ energy only, not including the capital cost of vehicles or infrastructure.

For the CNG and HFC buses two values are shown for the greenhouse gas savings, which are for UK 'grid-average' and renewable energy conversion factors, recognising those projects' use of renewable energy procurement. An illustrative emission factor is used for renewable hydrogen, calculated by Zemo Partnership for hydrogen produced using renewable electricity.

It is important to note that renewable energy sources are available for all of the technologies, so comparisons between savings reported using renewables for one technology with savings under 'grid-average' emission factors for another should be undertaken with caution.

Table 2: Comparison between the LEBS diesel baselines for energy consumption, WTW CO_2e and energy cost per km

Technology	No. fleets	No. buses	Energy consumption relative to baseline	WTW CO_2e relative to baseline	Fuel Cost relative to baseline
CNG/ biomethane SD	1	19	+50%	CNG: +13% Biomethane: -80%	-45% to -48%
CNG/ biomethane DD	3	69	+33% to +42%	CNG: +1% to +7% Biomethane: -78%	-45% to -48%
Battery electric SD	5	47	-59% to -70%	-59% to -70%	-59% to -78%
Battery electric DD	2	29	-69% to -70%	-69% to -71%	-64% to -66%
Diesel hybrid DD LV	2	48	-15% to -22%	-15% to -22%	-35% to -41%
Diesel hybrid DD HV	3	56	-13% to -37%	-13% to -37%	-35% to -55%
HFC DD* (incomplete data set)	1	20	-55% to -57%	'Grid-average': -25% to -29% Renewable: -98%	+10% to +17%

Notes on table:

- Buses were Single Deck (SD) or Double Deck (DD).
- Diesel hybrids were Low Voltage (LV) or High Voltage (HV).
- *The HFC comparison is based on the first six months data from one of the projects, August to November 2021.

As noted above, the energy consumption and emissions of many LEBS projects reflects urban traffic conditions. In particular, the HFC buses represent a central London drive cycle. Battery electric and HFC buses would be expected to have greatest advantage over diesel in congested traffic, where regenerative braking provides the largest energy savings; so the savings may not be as great when the vehicles are operated on less congested routes.

1.3 Implementation and operational performance

When the vehicles were first introduced some operators encountered initial reliability problems with some models of all technologies. However, the reasons why a vehicle was out of service were not generally a result of faults with the electric, CNG, hybrid or HFC technology. The time taken to repair a vehicle was often longer initially because spare parts for new models needed to be ordered from the manufacturer, whereas those for established models might be kept in-house or are widely available from a range of suppliers. However, by the end of the trial period operators reported reliability comparable to diesel. Operators commented positively on the simpler maintenance requirements for electric vehicles, which have fewer moving parts than internal combustion engine vehicles and no exhaust emission systems or additives. It was noted that diesel hybrid buses are the most mechanically complex, combining the maintenance requirements for both diesel and electric systems. There is currently very limited experience of HFC bus maintenance to date, with no conclusive information available from existing LEBS programmes.

Operators reported that the new vehicles of all technologies were well received by passengers and drivers. The battery electric buses in particular were liked for their smooth acceleration, lack of vibration and quiet ride.

Low voltage hybrids did not perform as well as traditional high voltage hybrids, providing on 15% energy consumption savings compared with an expected 30% savings. Low voltage hybrids are now no longer offered by OEMs, with some of the technology applied to efficient diesels.

With the battery electric buses that used diesel heaters, 10% to 40% of the total energy consumption was used for heating. There was a wide range between operators in the proportion of energy that was used for heating, and evidence that heating use was not always well correlated with outside temperature. This highlights the importance of managing heating efficiently. However, one fleet used air-source heat-pumps and had less variation between summer and winter energy consumption than the fleets with diesel heaters, suggesting that this is an efficient method of providing heating.

One battery electric bus fleet used its advanced telematics system to monitor the energy consumption achieved by individual drivers, to encourage efficient driving techniques. These vehicles demonstrated good overall energy efficiency in comparison with the expectations for this model, indicating that driver performance is an important factor in optimising range. Full visibility of vehicle performance through data analytics will be key to achieving lower cost zero emission bus operation in future.

1.4 Overall findings

Using the results of analysis of the energy consumption data from the trial, the following key conclusions can be drawn about how the technologies compare in terms of energy consumption and WTW greenhouse gas emissions:

- All the technologies, with the exception of CNG, demonstrated lower energy consumption than an equivalent standard Euro VI diesel bus.
- All the technologies, apart from CNG buses running on fossil gas, deliver greenhouse gas savings relative to an equivalent standard Euro VI diesel bus using current UK 'grid-average' energy sources.
- The battery electric buses were the most energy efficient, using up to 70% less energy than an equivalent standard Euro VI diesel bus, reducing GHG by up to 70% with 2019 UK 'grid-average' electricity. These savings will increase over the coming years in line with the ongoing decarbonisation of the electricity supply. Fully renewable electricity would reduce emissions close to 100%.
- Battery electric bus efficiency can be optimised by using telematics to encourage efficient driving techniques, scheduled maintenance and by heating the interior with air-source heat-pumps.
- The CNG buses used more energy than an equivalent standard Euro VI diesel bus, increasing GHG by up to 7% with natural fossil gas; however when biomethane is procured, as used by the LEBS projects, GHG are reduced by 80%.
- The diesel hybrid buses were 15% to 37% more efficient than non-hybrid diesels, depending on type, the HV types delivering the greater savings, reducing GHG in the same proportion.
- The HFC buses used between 55% and 57% less energy than an equivalent standard Euro VI diesel bus, reducing GHG from 25% to 29% with hydrogen made using UK 'grid-average' electricity. When the project's supply chain moves to a fully renewable hydrogen supply, greenhouse gas savings of up to 98% would be expected.

The results from the trials show how greenhouse gas savings can be achieved at two levels: through improving energy efficiency, as is demonstrated by the diesel hybrid vehicles, and through decarbonising the fuel supply, as demonstrated by the projects' use of biomethane and renewable hydrogen. The greatest savings are achieved when greater energy efficiency can be combined with lower carbon energy, as demonstrated by the battery electric buses. This has the benefit of reducing the overall requirement for renewable energy resources that will have to be provided to decarbonise the transport system.

The following recommendations for future trials are based on lessons learned from the LEBS programme:

- Ensure that data collection is undertaken using telematics, using standardised indicators, capturing heating/cooling demand, charging losses, and regeneration;
- Improve the quality of baseline data by ensuring that drive cycle data (speed, passenger loads, local traffic, route gradients, etc.) are collected so that in-service performance can be more accurately compared with the baseline vehicle and with test certificate results; and
- Allow phasing in the trials so that vehicles and charging/fuelling infrastructure are fully operational before monitoring commences.

2 Overview of the LEBS projects and technologies

A list of the LEBS projects and the technologies used is given in Table 3. To qualify for LEBS funding, vehicles were required to produce at least 15% lower Well-to-Wheel (WTW) greenhouse gas emissions (GHG)[1] compared with an equivalent Euro V diesel bus, as measured over the LowCVP UK Bus cycle on a rolling roads under lab conditions. The qualifying buses are issued with Low Emission Bus Certificates by Zemo Partnership[2] and are eligible for the Low Carbon Emission Bus (LCEB) incentive payment of 6p/km. All LEBS funded buses either meet Euro VI or equivalent emission standards or produce zero tailpipe emissions. The four technologies funded by LEBS are summarised below. Further information on bus technologies is available from Zemo Partnership's Low Emission Bus Guide (Zemo Partnership, 2016).

CNG buses (operated using 100% biomethane procurement) - 3 projects

Compressed Natural Gas (CNG) buses are fuelled at on-site facilities connected to the mains gas distribution network. They use spark-ignition which has a lower energy efficiency than the compression ignition diesel engine, however the resulting increase in GHG emissions is partly offset by the lower carbon intensity of CNG compared with diesel. In order to qualify for the LCEB incentive the CNG projects purchase renewable biomethane credits from producers (typically anaerobic digestion of food waste or crop residues) to offset the gas they use. With 100% renewable biomethane the LEB certificates for the CNG buses report reductions in WTW GHG of 82% compared with Euro V diesel equivalent buses.

Diesel hybrid buses - 5 projects

Hybrid buses combine a diesel internal combustion engine with an electric traction system and an internal battery. They use regenerative braking, capturing energy that would normally be lost during deceleration, storing it in the battery for later use. Vehicles with two different voltage systems were used: Low Voltage (LV: 24V - two fleets) and High Voltage (HV: 600V - three fleets). LEB certificates for the hybrid buses report average WTW GHG savings of 37% for HV hybrids and 18%-35% for LV hybrids, compared with a Euro V diesel equivalent.

Battery electric buses - 6 projects

The battery electric bus fleets were powered entirely by electric batteries that are recharged, mostly overnight, at a depot-based charging facility. One of the fleets was also equipped to charge while in service, by connecting to an overhead power supply through a pantograph while stationary at the bus station (known as opportunity charging). All the buses use regenerative braking to improve energy efficiency. To provide interior heating the majority of the LEBS buses used a diesel heater. However, the most recent models used an electrically powered heat-pump. Zero emission heating solutions are now standard for battery electric buses in the UK. The LEB certificates report WTW GHG emissions savings between 62% and 68% for the single deck (SD) buses, and about 45% for the double deck (DD) buses, compared with Euro V diesel equivalent buses.

[1] The sum of all of the greenhouse gases emitted in the production and use of energy; expressed as an equivalent amount of carbon dioxide (CO_2e). It combines 'tailpipe' emissions (Tank-To-Wheel, TTW) from the vehicle with those from the production of the fuel (Well-To-Tank, WTT).

[2] Details and certificates are available on the Zemo Partnership website https://www.lowcvp.org.uk/Hubs/leb/scheme.htm

HFC buses - 1 project, with fleets in two cities

The HFC buses have electric traction motors powered by a fuel cell supplied by hydrogen compressed at up to 350 Bar. Fuel cells operate more efficiently when their power output is kept constant within an optimal range so an on-board battery, charged from the fuel cell, is used to provide additional power for acceleration. The battery also stores energy from regenerative braking, improving the overall energy efficiency.

Like battery electric vehicles, hydrogen fuel cells produce zero tailpipe emissions apart from water vapour, so their WTW emissions are determined by the pathway used to provide the hydrogen to the vehicle. Further information on hydrogen pathways is available from Zemo Partnership "Hydrogen Vehicle Well-to-Wheel GHG and Energy Study" (Zemo Partnership, August 2021).

Table 3: LEBS funded projects

Project lead and operator	Technology	No. buses	Single or Double Deck (SD/DD)
West Yorkshire Combined Authority (WYCA), First Group	Low voltage diesel hybrid	2	SD
Transport for London (TfL), Go Ahead	Plug-in battery electric	13	SD
Nottingham City Transport (NCT)	CNG/biomethane	53	DD
Sheffield City Region Combined Authority (Sheffield), First Group and Stagecoach	Low voltage diesel hybrid	26	DD
Nottinghamshire County Council (NCoC)	Plug-in battery electric	2	SD
Kingston University (Kingston), RATP	High voltage diesel hybrid	7	DD
Reading Buses (Reading)	CNG/biomethane	16	DD
Harrogate/ Transdev Blazefield (Harrogate)	Battery Electric with pantograph charging (at bus station)	8	SD
Arriva/Merseytravel	High voltage diesel hybrid	51	DD
	Plug-in battery electric	12	SD
	CNG/biomethane	19	SD
West Midlands Travel Limited (WMTL- part of National Express group)	Plug-in battery electric	29	DD
	Low voltage diesel hybrid	22	DD
Birmingham City Council (BCC) led HFC projects: Birmingham/ WMTL	HFC	20	DD
BCC led HFC projects: Transport for London (TfL)	HFC	20	DD
Nottingham City Council (NCiC)	Plug-in battery electric (awarded funding for charging infrastructure only)		

3 The LEBS Monitoring Programme

The LEBS programme funded a monitoring programme to gather evidence on the real-world performance of each technology: their energy consumption and WTW GHG emissions, and to understand their reliability and operational performance. TRL was appointed as the independent monitoring contractor and worked with the project operators to collate and analyse a range of performance data for a 12-month monitoring period. The data requested covered:

- Refuelling / recharging events
- Vehicle distance travelled
- Vehicle availability and reliability

Although operators were asked to provide quantitative data on operational performance so that vehicle availability and failure rates could be compared, it was found that, because of differences in how operators collect and report such data, it was not possible to undertake a detailed quantitative analysis. However, in addition to quantitative data collection, TRL held meetings with each project team to gather qualitative feedback on their experiences of the LEBS trials, including the reliability of the vehicles and how well the vehicles had been received by passengers and drivers.

LEBS buses were compared with a Euro VI diesel equivalent baseline, using fuel consumption data provided by the operator from diesel buses on a comparable route. Where Euro VI buses were not available to provide baseline data, data from buses of other Euro stages was adjusted to a Euro VI equivalent using the COPERT drive cycle (emisia, 2019).

The raw fuel or electricity consumption data were cleaned where necessary and used to calculate energy consumption (kWh per km), using standard calorific values for fuels (see Appendix A), to enable the different technologies to be compared on the same basis. The resulting WTW GHG emissions, measured as gCO_2e/km, were calculated using government emission factors provided by BEIS for environmental reporting (Department for Business, Energy & Industrial Strategy, 2019) (see Appendix A for the values used)

UK 'grid-average' emission factors were used to compare the GHG emissions performance of technologies. CNG and HFC vehicles were also assessed using renewable emission factors to reflect the use of renewable fuel procurement by the LEBS schemes. Note that renewable energy sources are available for all the fuel and energy sources used by LEBS buses, including diesel; however, the use of biomethane is specifically noted in this report as it is the basis of the Low Emission Bus certification awarded to the vehicles.

Some projects deployed multiple LEB technologies and/or operated LEBs on multiple routes. The results are therefore presented as separate fleets, designated by a series of anonymised letter codes. Table 4 summarises the fleets and their ID codes by technology and the dates for which monitoring data was provided.

Table 4 Summary of the LEBS fleets monitored

Technology	No. fleets analysed	Total no. buses	Single/ Double Deck (SD/DD)	Monitoring periods	Fleet ID
CNG/ biomethane	1 3	19 69	SD DD	Jan 2019 to Mar 2019 Mar 2018 to Feb 2019 Mar 2018 to Feb 2019 Jul 2018 to Jun 2019	G D, E, and F
Low voltage diesel hybrid	2	48	DD	May 2018 to Mar 2019 Oct 2019 to Aug 2020	H and L
High voltage diesel hybrid	3	56	DD	May to Jul 2018 and Sep 2018 to Feb 2019 Jan 2019 to Dec 2019 Jan 2019 to Dec 2019	I, M, and N
Plug-in battery electric	4 2	39 29	SD DD	Jul 2018 to Jun 2019 Jul 2018 to Jun 2019 Jul 2018 to Jun 2019 Jan 2019 to Dec 2019 Sep 2020 to Aug 2021 Sep 2020 to Aug 2021	P, Q, R, and S T and U
Battery Electric with pantograph	1	8	SD	Feb 2019 to Feb 2020	V
HFC	1	19	DD	Aug 2021 to Dec 2021	Z

In the analysis that follows for each technology the monthly average fuel and energy consumption is presented as a time series, so that that seasonal effects can be investigated. The annual average energy and CO_2e emissions for each project are then compared with their diesel baselines, and a summary of operator feedbacks on vehicle reliability and operational performance provided.

4 Battery electric buses

4.1 Energy consumption

The annual average energy consumption for each fleet is shown in Figure 3, compared with its baseline and the average energy consumption reported on the corresponding LEB Certificate for the vehicles concerned. Five of the fleets used diesel heating (P, Q, R, S and V), for which consumption data was available for four. The litres of heating diesel consumed were converted into kWh and added to the electrical energy total. Fleets T and U used an electrically powered heat pump for heating and cooling; while fleet V used a combination of electrical heating plus diesel for the coldest weather. As electricity used for heating was not recorded separately it is included with 'traction' energy in Figure 3.

The average total energy consumption, i.e. traction and heating combined, varied from 1.1 kWh/km to 1.7 kWh/km for the SD buses, and from 1.3 kWh/km to 1.4 kWh/km for the DD buses.

Using the data for diesel heated buses, where consumption was separately recorded, the energy spent for heating on the SD buses accounted for 27% to 40% of the total energy consumption.

Compared with the corresponding baseline buses:

- SD buses saved between 59% and 70% of energy
- DD buses saved approximately 69%-70% of energy

Traction energy performance was close to the LEB certificate results for the majority of fleets. The double-deckers, T and U, performed better than their LEB test certificate. Fleet V had electrical heating, which was not included in the test certificate.

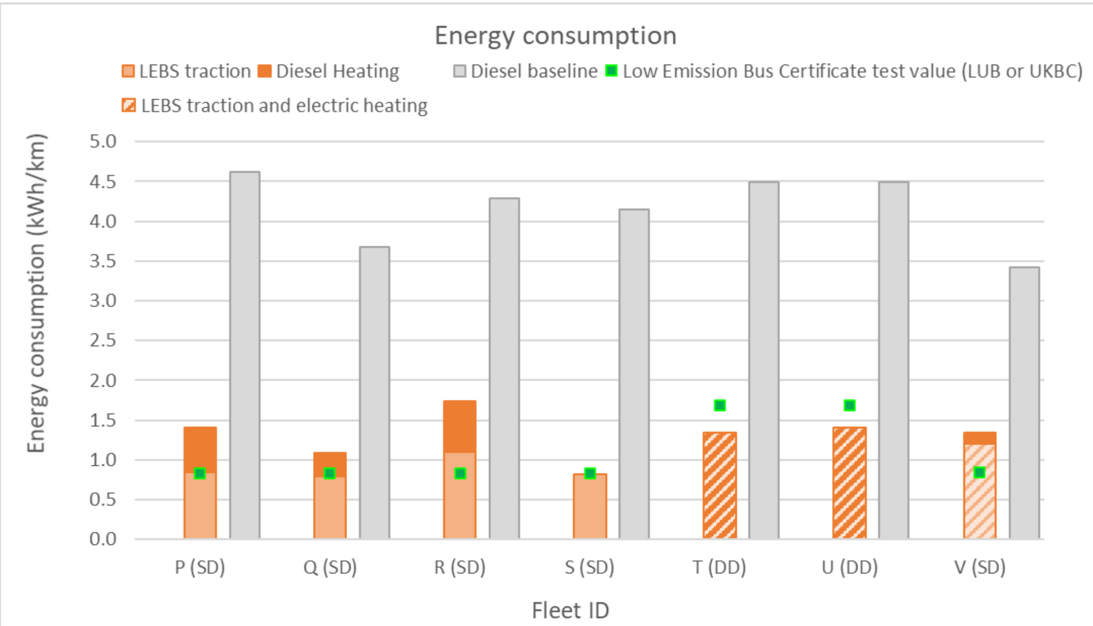

Figure 3: Comparison of the energy consumption between the plug-in battery electric LEBS fleets, the diesel baseline buses and LEB certificate

Figure 4 shows the monthly average total energy consumption (heating plus traction) for each fleet as a time series, to show any seasonal variations. Please note that the trials did not necessarily take place over the same exact time period, so the monthly values have been reorganised to a standard calendar, so that the overall seasonal variation can be observed.

Energy consumption tended to be higher in the coldest months (from October to March) and lower in the warmest months (from April to September). This reflects greater use of heating in winter, whether diesel or electricity, but will also include lighting. To ensure that the use of heating is optimised, automatic thermostat control is necessary rather than manual, removing preferences of individual drivers. Electrically powered heating has the advantage of greater controllability; however, it is necessary to ensure that the electricity used for heating and air-conditioning is recorded and monitored separately from traction energy if it is to be managed optimally.

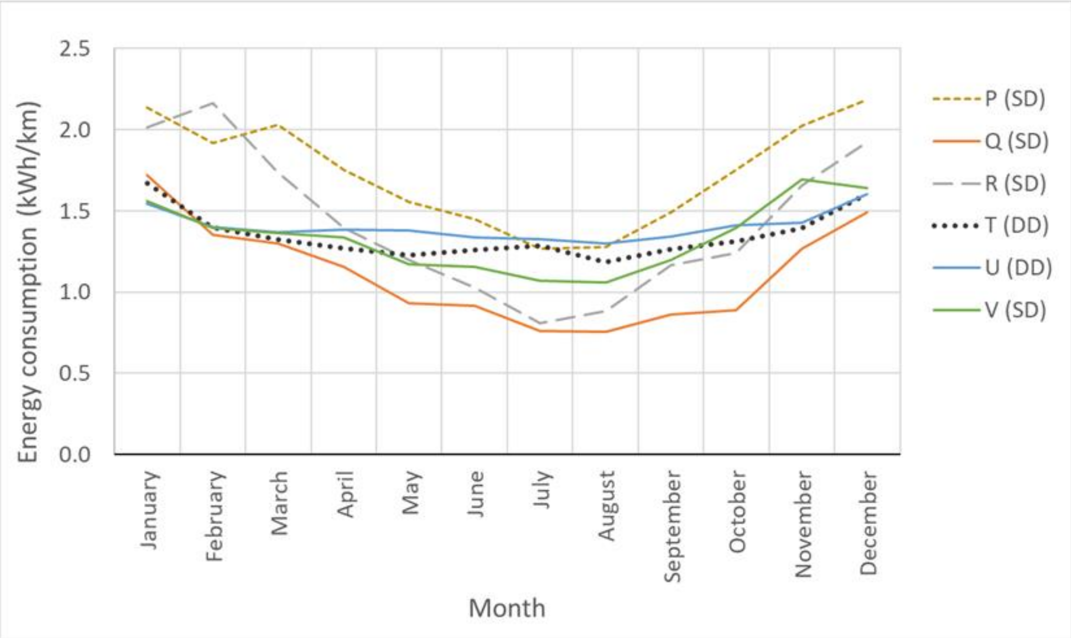

Figure 4: Monthly average energy consumption (traction plus heating) for the LEBS plug-in battery electric fleets

It is noteworthy that the double deck fleets, which used air-source heat-pumps for interior heating and cooling, had an annual average energy consumption below that expected from the LEB certificate, and also showed substantially less seasonal variation in total energy consumption than the buses with diesel heaters. The operator reports that they fitted air filtration systems to their vehicles to allow for the safe recirculation of air, in order to reduce heating and cooling demand, and observed an improvement in range when this was installed. This operator also uses its vehicle telematics to monitor the energy consumption and use of regenerative braking by drivers, to encourage efficient driving techniques.

4.2 Well-to-wheel greenhouse gas emissions

Electrical energy and heating diesel consumption was converted to WTW GHG emissions using UK 'grid-average' conversion factors. The annual average WTW GHG per kilometre is shown in Figure 5, showing both traction and heating emissions where available, and compared with the diesel baseline. Overall, including heating, WTW emissions from the battery electric buses relative to baseline were 59% to 70% lower for the single deck buses and 69% to 71% lower for the double deck.

Heating diesel significantly affects energy and WTW emissions (contributing to 11% to 41% of overall WTW GHG).

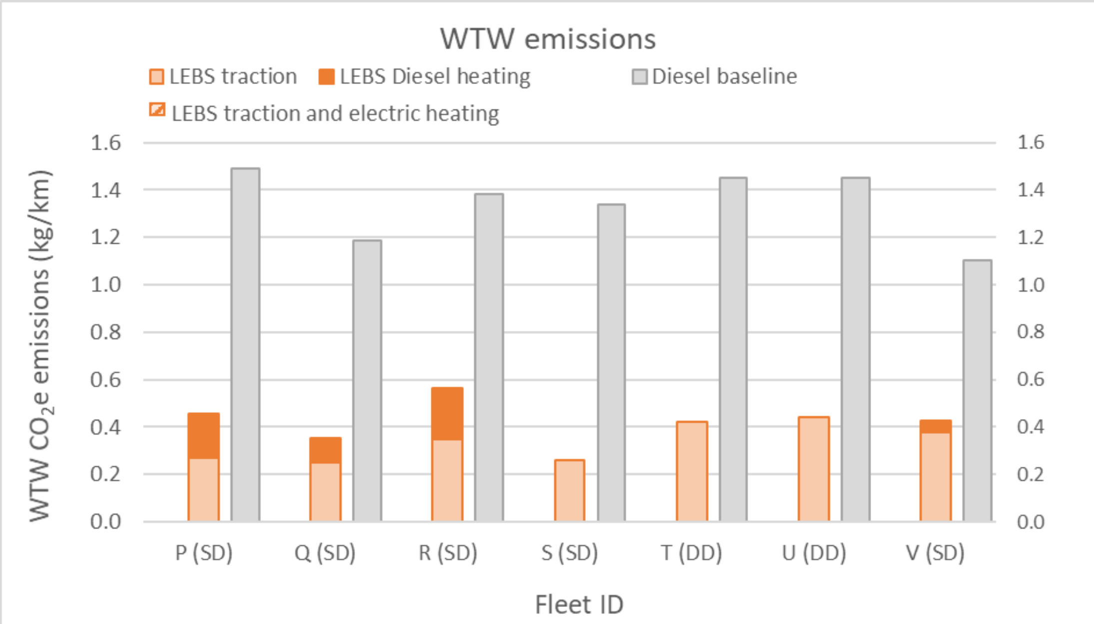

Figure 5: Comparison of the WTW emissions between the plug-in battery electric LEBS fleets and the baseline buses

4.3 Energy cost

The energy running costs were calculated for the LEBS buses, using a standard cost of 12.9p/kWh for electricity, 105 p/litre for diesel and 59 p/l for heating diesel ('red diesel' or gas-oil, as untaxed fuel can be used for heating). This means that there are two components to the fuel cost, as shown in (Figure 6). Compared to the diesel baseline, the battery electric SD buses were 59% to 78% cheaper to run while the DD were 64% to 66% cheaper. The Low Carbon Emission Bus (LCEB) incentive (6p/km) accounts for 24% to 42% of the savings.

4.4 Range

An estimate of vehicle range on one charge was made by dividing the nominal battery capacity for each model by the average electricity consumption. This estimate does not necessarily fully reflect the actual range, as it does not take account of variations in battery capacity arising from battery degradation or other factor such as temperature.

It also does not reflect differences in how different charging systems operate, for example there may be maximum or minimum State of Charge (SoC) limits (to minimise degradation) that reduce the capacity that is available in practice. Figure 7 summarises the estimated range for each fleet, based on minimum and maximum monthly average energy consumption observed.

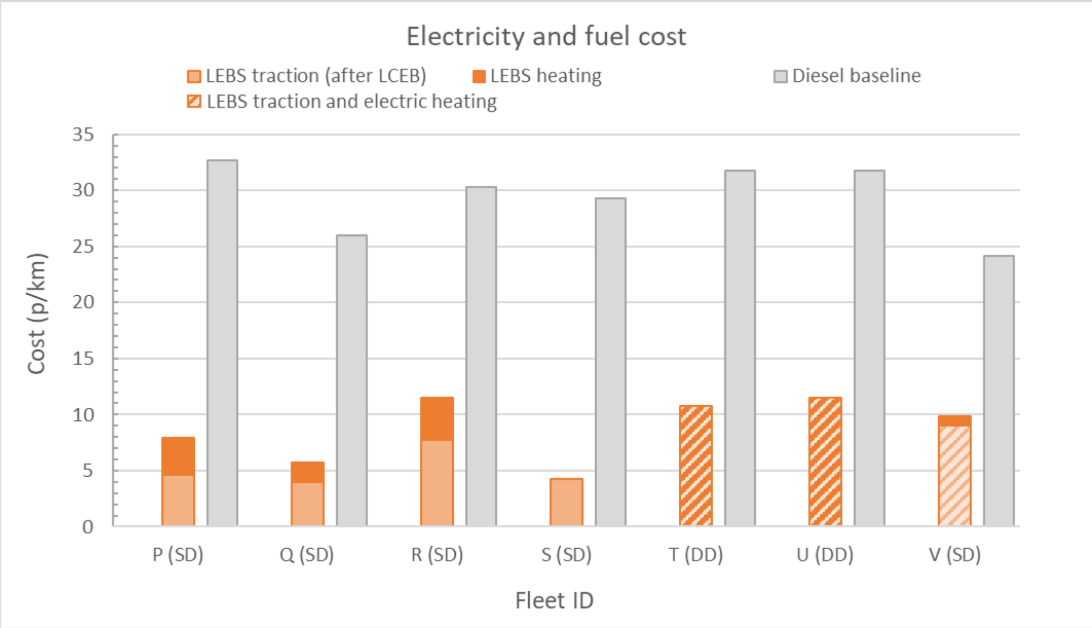

Figure 6: Comparison of the energy running costs between the LEBS battery electric buses and baseline

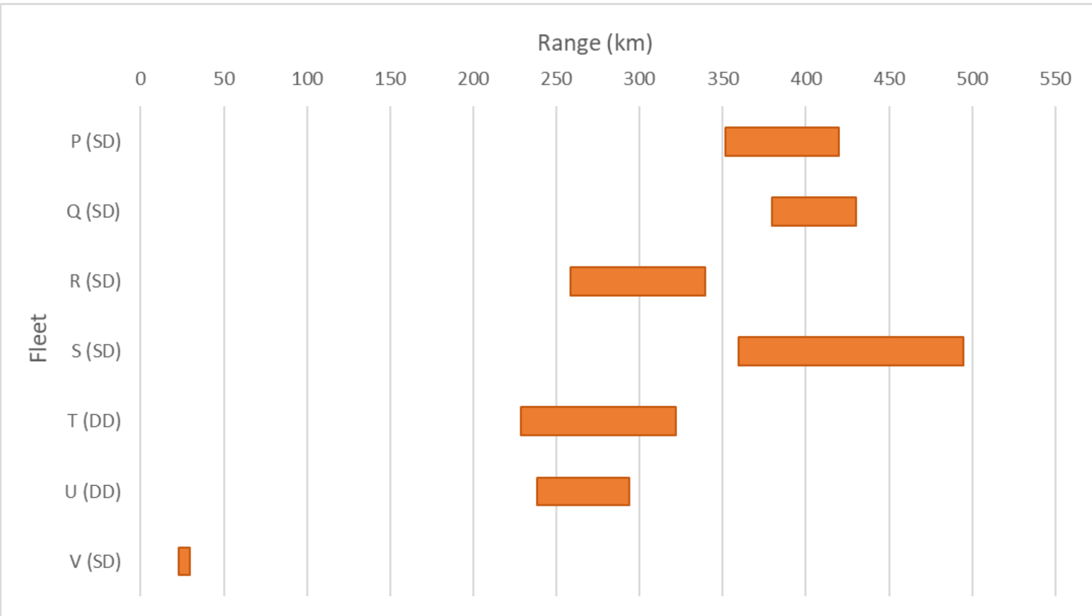

Figure 7: Estimated range per LEBS battery electric fleet (note that Fleet V uses opportunity charging to frequently charge the battery during operation via a pantograph)

4.5 Operator feedback

Operators were asked to provide feedback on their experiences with the vehicles, their performance, reliability, customer satisfaction and any lessons learned.

Buses' reliability

Although there were some reliability problems with some models when first introduced, these were not generally related to the electric drive system and were resolved by the end of the monitoring programme. Because the vehicles are currently a relatively small fleet of a new type, it can take longer to obtain spare parts, including those not part of the drive train. These problems are decreasing as the UK market and supply chain expands. Operators are now very satisfied with their reliability, considered to be at least as good as diesel vehicles, and routine maintenance is simpler because there are no exhaust systems or fuel additives and fewer moving parts. It was noted that hybrid buses have more complex maintenance requirements as they retain the diesel engine with associated emission control systems and additives, as well as an electric traction system.

Opportunity for efficiency improvement

Operators were aware of the importance of heating and cooling. While the vehicles introduced earlier in the programme used diesel heaters, the newest use air-source heat pump and operators expected this technology to become standard. Although electrically powered heating directly affects battery range, experience from the double deck buses shows that it can be controlled efficiently, and heating energy consumption minimised, through the use of air filtration to enable safe recirculation of air.

To get the maximum benefit out of regenerative braking it is necessary for drivers to use the right techniques. All the operators undertake some driver familiarisation and the operator of the double deck buses using their telematics system to assess driver efficiency and provide feedback. The energy consumption of this particular fleet was lower than might be expected from the LEB Certificate, which could be as a result of optimal driving.

Satisfaction with buses

Although no operator reported having undertaken formal market research, they said that customers like the vehicles. They are also popular with drivers, being simpler, quieter and smoother to drive.

All operators expressed interest in expanding their EV fleets but noted that the additional capital costs were still a barrier and ongoing government support would be needed.

5 Hydrogen Fuel Cell (HFC) buses

5.1 Fuel consumption

One of the two fleets of HFC buses went into passenger operation in summer 2020, with monitoring beginning in August 2021. From September 2021 the vehicles started to be used on a second route. As a full year's data was not available for this report the full analysis has not been undertaken. The routes are in London so represent an urban drive cycle. The diesel baseline used was based on a laboratory emissions test of a standard representative diesel bus conducted on behalf of the operator. This had an average fuel consumption over the MLTB test cycle of 47.2 l/100km. Table 5 summarises the average consumption by month and a comparison with the diesel baseline over the six months for which data were available at the time of writing.

Table 5: HFC bus monthly average fuel consumption

Bus route	Average hydrogen consumption (kg_{H2}/100km)						Energy consumption compared with diesel					
	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22	Aug-21	Sep-21	Oct-21	Nov-21	Dec-21	Jan-22
A	7.0	6.5	6.2	6.1	6.3	6.4	-51%	-54%	-56%	-57%	-55%	-55%
B		6.2	5.9	6.0	6.1	6.3		-56%	-58%	-58%	-57%	-55%

The first month of the trial recorded the highest fuel consumption with 7.0 kg_{H2}/100km used on average on route A. Subsequently the average hydrogen consumption on route A gradually decreased in each month down to 6.1 kg_{H2}/100km in November 2021, to then increase again in the winter months of December 2021 and January 2022 (6.3 and 6.4 kg_{H2}/100km, respectively). A similar trend was observed on route B where the fuel consumption slightly decreased from September 2021 to October 2021 (6.0 and 5.9 kg_{H2}/100km, respectively), to then gradually increase again in the following months up to 6.3 kg_{H2}/100km in January 2022. It is worth noting that route B is less central than route A, therefore it is reasonable to expect less congestion and hence a lower fuel consumption.

The corresponding (hydrogen) energy consumption is just above 2 kWh/km on all routes (Figure 8), and between 51% and 58% lower than the baseline consumption (4.7 kWh/km). HFC buses use electric traction so can benefit from regenerative braking. As driver behaviour can make a significant difference to the use of regenerative braking, it is possible that greater driver familiarity and experience is one factor in the improved energy consumption observed. Although energy consumption increased during the winter months, this was still below the highest values recorded in the summer months. Fuel cell vehicles are able to use waste heat from the fuel cell for heating, reducing the need for additional heating energy to be consumed.

5.2 Greenhouse gas emissions

When comparing the GHG emissions of HFC vehicles with other technologies it is important to note that the figures represent 'tank-to-wheel (TTW)' energy consumption. As hydrogen always has to be produced from other energy sources, with associated conversion losses, the equivalent 'well-to-wheel' energy consumption will be significantly greater. WTW energy consumption was not calculated for the LEBS technologies; however it is reflected in the corresponding WTW GHG emissions. To calculate the WTT emissions, conversion factors provided by Zemo Partnership for different hydrogen pathways from production to the vehicles' tank were used, based on a study of well-to-wheel hydrogen pathways (Zemo Partnership, August 2021; Zemo Partnership, October 2021):

- UK average (Hydrogen Electrolysis on-site - UK grid 2021)
- Renewable hydrogen (Hydrogen Electrolysis on-site - electricity produced on site from a waste wood incinerator)
- Off-site electrolyser, powered by renewable electricity, road tanker delivery of compressed H_2 (350kg for shipment round distance of 340 km)
- Off-site electrolyser, powered by renewable electricity, road tanker delivery of compressed H_2 (1000kg for shipment round distance of 340 km)
- Chloro-alkali process with H_2 as a by-product using grid electricity, road tanker delivery of compressed H2 (350kg for shipment round distance of 640 km)
- Chloro-alkali process with H_2 as a by-product using grid electricity, road tanker delivery of compressed H2 (1000kg for shipment round distance of 640 km)
- Steam Methane Reformation (SMR) with retrofitted with Carbon Capture and Storage (CCS), road tanker delivery compressed H_2 (350kg for shipment round distance of 200 km)

Using these conversion factors, the calculated WTW GHG and savings compared to a diesel baseline ranged from 1.1 kg/100km and 25% to 29% savings for 'UK average' hydrogen, on route A and route B respectively, to 0.03 kg/100km with 98% savings using renewable hydrogen. The wide range of WTW GHG emissions for different hydrogen pathways is illustrated in Figure 9 (where the overall route is the sum of route A and route B). Nonetheless, there are GHG savings relative to the diesel baseline for the pathways considered.

It is important to note that the reported GHG savings arise because of the energy efficiency of the HFC bus compared with its baseline. The hydrogen consumption measured is significantly lower than has been reported in previous trials with older models, demonstrating considerable recent improvements in the technology. It is also important to note that the only LEBS hydrogen data available so far is from the London routes, whose congested nature is likely to give HFCs, with electric traction and regenerative braking, the greatest advantage over diesel. The savings relative to diesel may not be as great when data becomes available from HFC buses operating in outer urban or rural areas.

Installation of refuelling infrastructure is still ongoing, having been delayed because of the Covid restrictions, amongst other things.

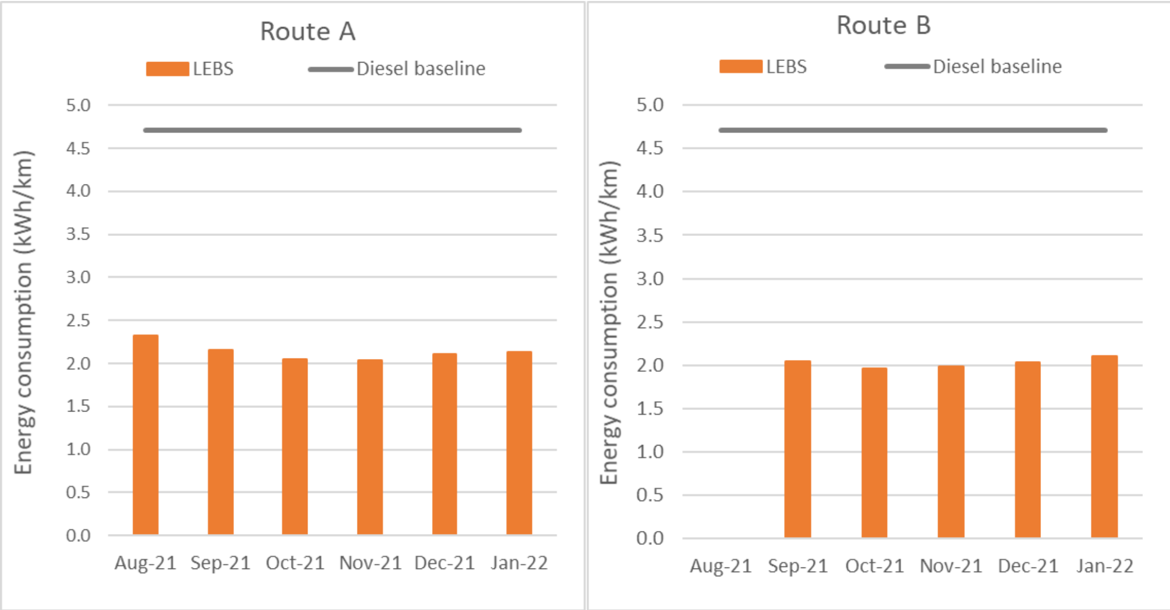

Figure 8: Average monthly energy consumption of the HFC buses compared with the baseline

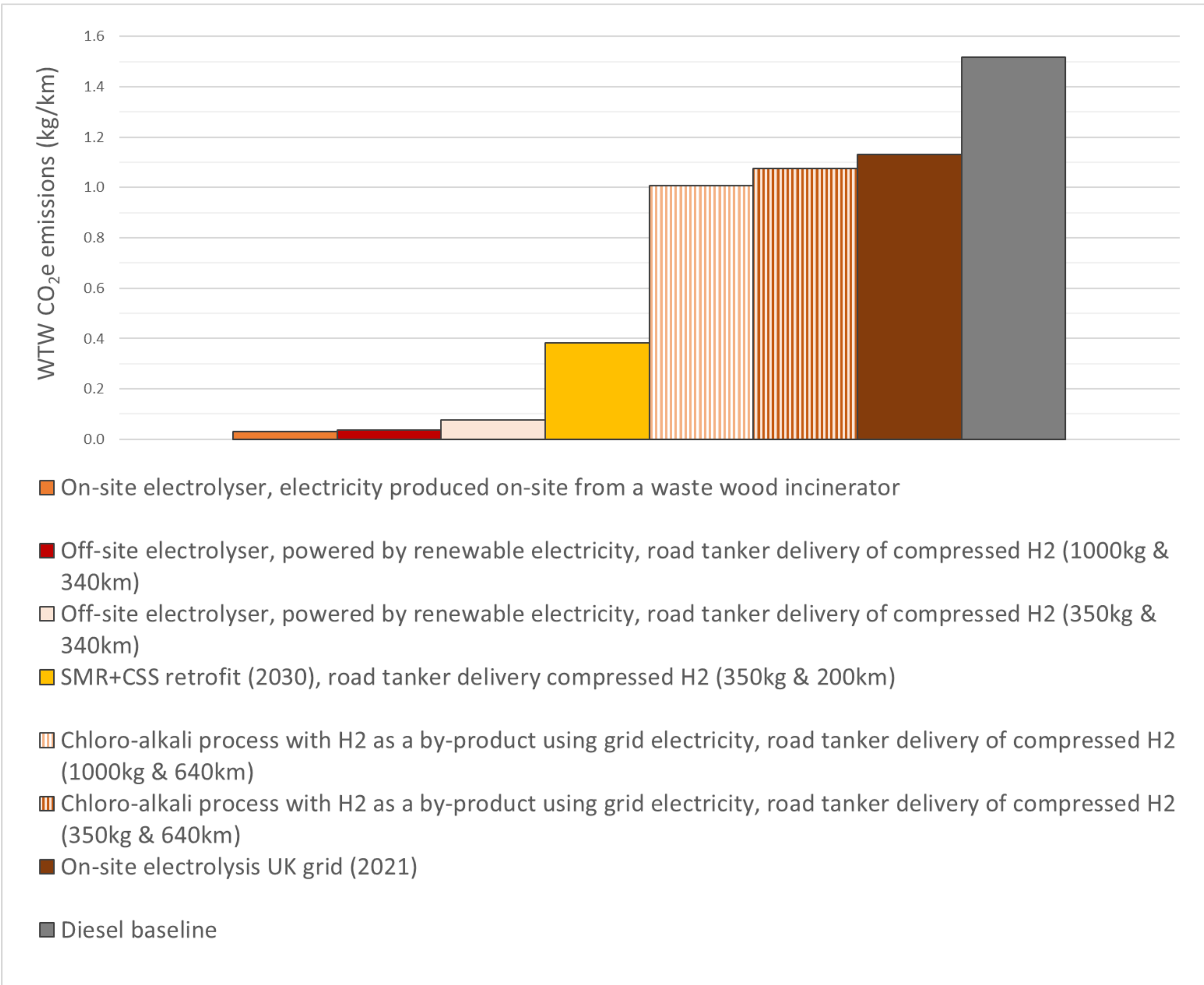

Figure 9: WTW emissions of the HFC buses for seven hydrogen pathways compared with the diesel baseline

6 Compressed Natural Gas (CNG) buses

6.1 Fuel and Energy consumption

Fuel consumption (kg_{CNG}/100km) was calculated from fuelling records for each vehicle, in some cases combined with trip distance data from vehicle telematics. The annual average fuel consumption for each fleet is shown in Figure 10, together with the equivalent energy consumption calculated from the calorific value of the fuel; compared with diesel baseline and LEB certificate.

Compared with diesel, energy consumption increased from 33% to 50%, which is expected because spark ignition engines used for CNG are not as energy efficient as diesel engines. Three of the four projects showed energy consumption slightly greater than the LEB certificate, potentially reflecting the use of the buses in more congestion than is represented by the average test cycle.

While some variation in monthly average fuel consumption was observed, for most fleets the variation was less than 5%, and peaks outside this range occurred in both summer and winter months with no clear seasonal variation observed. Figure 11 shows the monthly average fuel consumption for each fleet as a time series, to show any seasonal variations. Please note that the trials did not necessarily take place in the same years, nor with the same starting month, so the monthly values have been reorganised to a standard calendar, so that the overall seasonal variation can be observed.

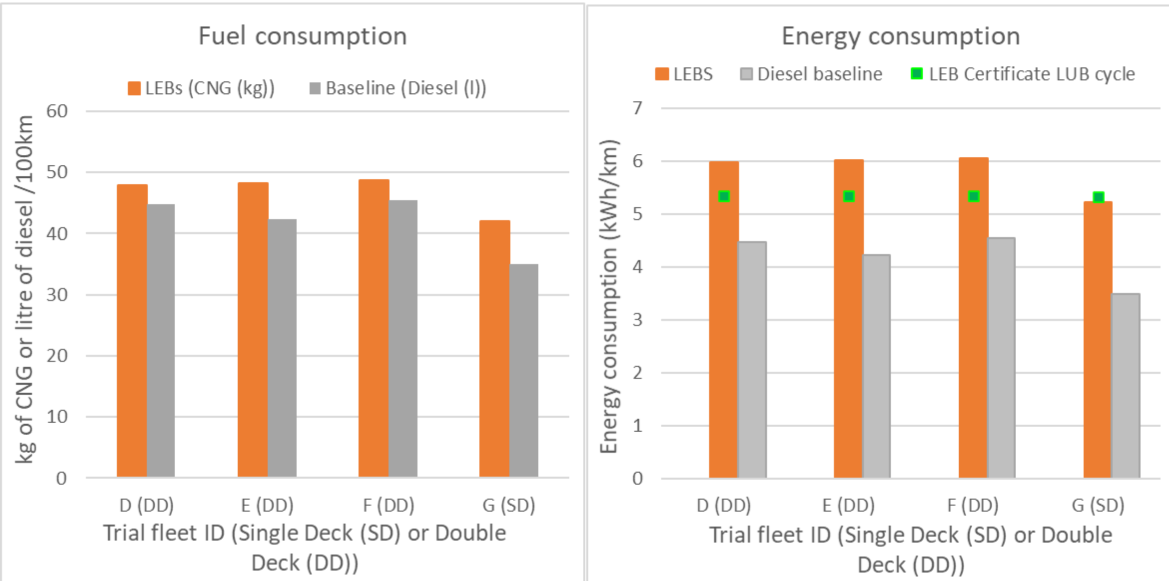

Figure 10: CNG consumption compared with the diesel baseline (LHS); Energy consumption compared with the diesel baseline and LEB certificate (RHS)

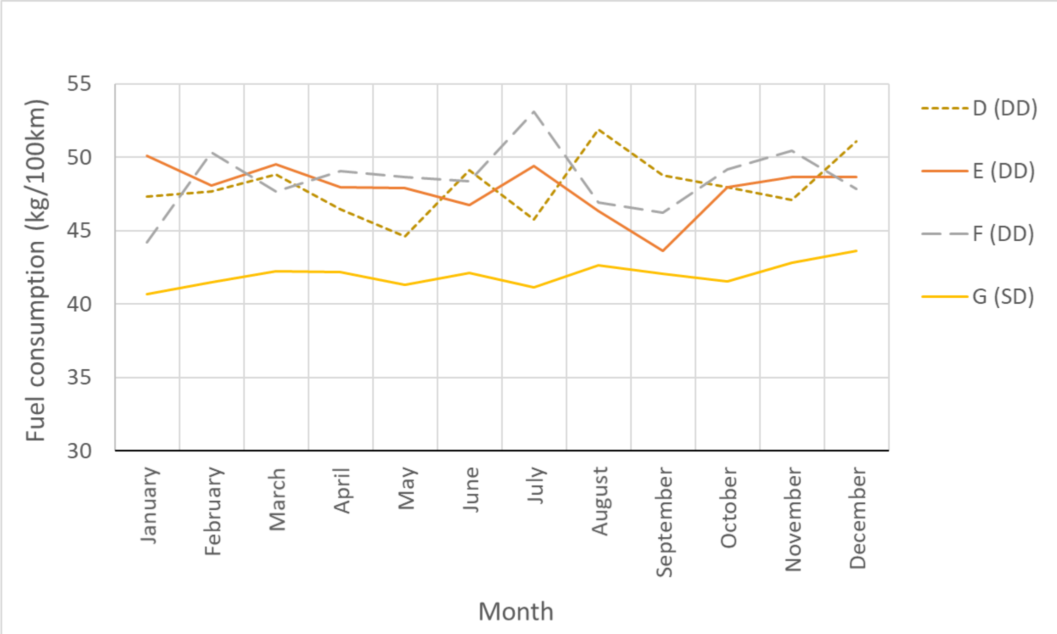

Figure 11: Average fuel consumption for the LEBS CNG fleets by month

6.2 Well-to-Wheel Greenhouse Gas emissions

WTW CO_2e emissions were calculated from the fuel consumption using BEIS conversion factors for both UK 'grid-average' CNG and for biomethane, reflecting the use of mass-balanced biomethane procurement by the LEBS operators to offset their emissions. The annual average WTW emissions per kilometre are shown in Figure 12, compared with the diesel baseline. When using 'grid-average' CNG there was a 1% to 13% increase compared with diesel (reflecting the greater energy consumption of the CNG vehicles); while with biomethane the much lower carbon intensity of the fuel results in 80% savings compared with diesel.

6.3 Fuel cost

With the standard assumed fuel costs of 65p/kg for CNG/biomethane and 105p/l for diesel; and the Low Carbon Bus incentive of 6p/km for biomethane, there is a 45% to 48% saving relative to diesel. The LCEB accounts for 33% to 54% of the savings.

6.4 Operator feedback

Some operators reported initial reliability problems, and some problems with the availability of spare parts, but these were resolved during the monitoring period. Some additional training was required for maintenance staff, as was the case for all technologies. Operators considered the vehicles to be at least as reliable as standard diesel by the end of the trial, with the benefit that they do not require particulate filters to be cleaned, nor additives for emission control.

The operators reported that passengers like the vehicles and it was noted that they provided a comfortable interior temperature during cold weather.

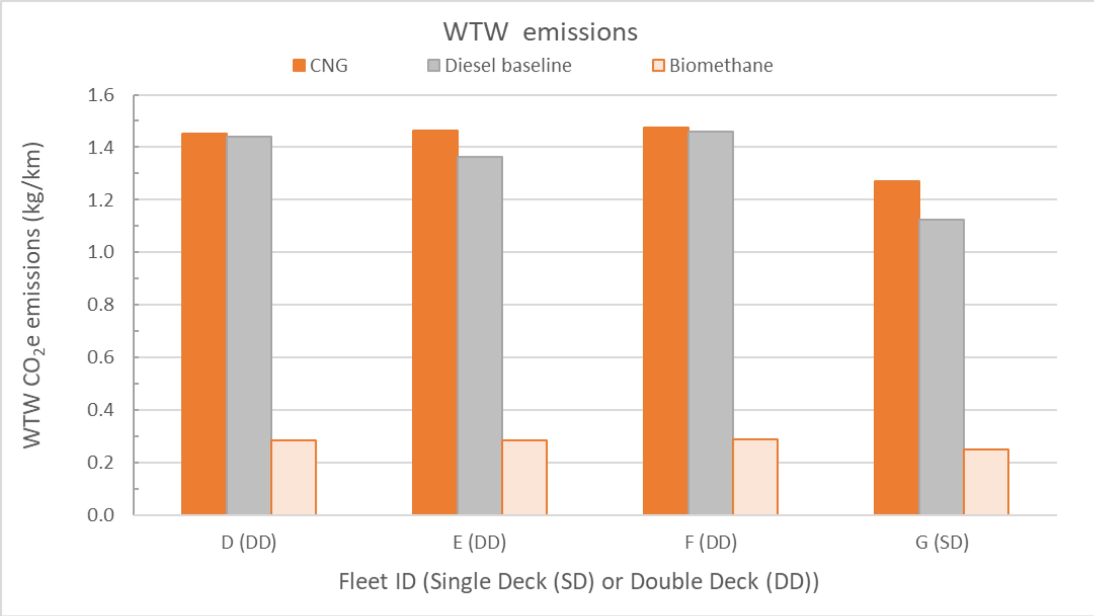

Figure 12: WTW emissions using CNG or 100% renewable biomethane, compared with the diesel baseline

7 Diesel hybrid buses

7.1 Fuel and energy consumption and emissions

Fuelling records and vehicle trip data were provided to TRL by the operators and used to calculate the average fuel consumption in l/100km. As both the LEBS hybrid and diesel baseline buses use the same fuel type then comparison is straightforward, because fuel, energy consumption and WTW CO_2e emissions will all change in the same proportion.

Figure 13 compares the annual average fuel consumption of each fleet with its baseline and also with the fuel consumption reported on the LEB Certificate for the Zemo Partnership Bus (LUB) Cycle for the vehicles used.,.

As there were both high voltage (HV) hybrids and low voltage (LV) 'mild' hybrids, which would be expected to achieve quite different levels of saving compared with standard diesel, these types should not be directly compared.

Because fuel consumption savings relative to the baseline are in direct proportion to energy and WTW CO_2e emissions, it can be seen that the LV hybrids achieved 15% to 22% fuel and emissions savings while the HV hybrids achieved 13% to 37% savings. The LV savings are within the range that would be expected from their LEB certificates; however two of the HV fleets appeared to demonstrate significantly lower savings than would be expected. In both cases, while fuel consumption was closer to the Inner London cycle, the corresponding baseline was not as high as might be expected for such a congested drive cycle; suggesting that the routes used by the baseline buses were not fully representative of the LEBS routes.

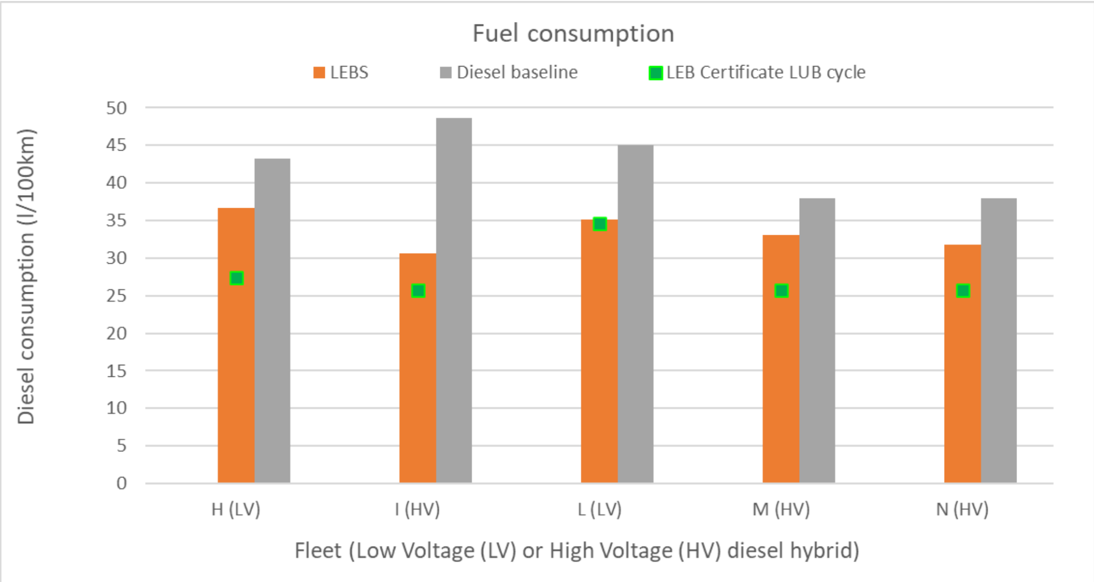

Figure 13: Fuel consumption of diesel hybrid fleets compared with the diesel baseline and LEB certificate

Figure 14 shows the monthly average fuel consumption for each fleet as a time series, to show any seasonal variations. Please note that the trials did not necessarily take place in the same years, nor with the same starting month, so the monthly values have been reorganised to a standard calendar, so that the overall seasonal variation can be observed. Fleet H is missing one month of data (April), while fleet I is missing three months of data (March, April and August). Fleet L's trial period coincided with the Covid 19 restrictions and a significant fall in fuel consumption can be seen in March 2020, which is likely to be associated with significant falls in passenger loads and road traffic during the first lockdown period.

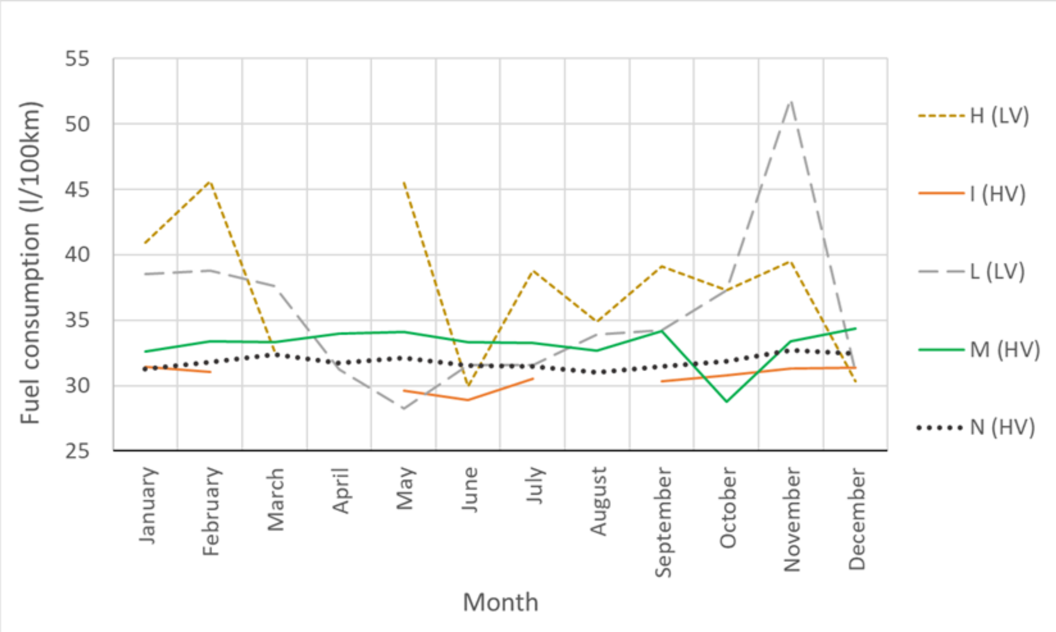

Figure 14: Average fuel consumption for the LEBS diesel hybrid fleets by month

Although the LEBS vehicles use the same fuel as the baseline, in addition to fuel cost savings arising from lower fuel consumption they also benefit from the LCEB incentive of 6p/km. This means that the overall fuel cost savings relative to the standard diesel baseline were 35% to 41% for the LV hybrids and 35% to 55% for the HV. The LCEB incentive accounts for between 32% to 64% of the savings.

7.2 Operator feedback

Although there was no quantitative data on vehicle reliability, the operators reported the HV hybrid buses as being generally as reliable as diesel; however there were some ongoing reliability concerns with one of the LV models. Some staff training was required, to avoid having to use external contractors. HV hybrids have been in widespread use in the UK for a significant time now, so the industry is familiar with their requirements. Some operators noted that a disadvantage of hybrids is that they combine both diesel and electric systems, so are more complex to maintain than a fully electric vehicle, including the requirement for continued maintenance of emission systems.

8 Lessons learned and recommendations for future bus trial programmes

The LEBS monitoring programme provided significant experience in how large-scale fleet trials are conducted. The range of technologies and operators presented a significant challenge in the consistent collection of monitoring data. The key lessons learned are discussed below.

Telematics is key to monitoring

A key message is the importance of using telematics for collecting fuel and energy consumption data directly from vehicles. This was available from the newer technologies introduced later in the programme; however, for many of the first fleets that were monitored, a combination of data sources was often used, including manual fuelling records. These are more prone to error than telematics data and do not allow analysis to be undertaken at the level of individual trips.

While the battery electric and HFC fleets used telematics data, there were differences in the range of parameters measured and time resolution of data available. Energy used for heating was not recorded separately, which limits the extent to which heating demand can be monitored and optimised. Some data were provided as trip averages, others as weekly summaries, which limited the level of analysis that could be undertaken.

The fleets with the most sophisticated telematics systems are able to use it to optimise drive technique and also to highlight congestion hotspots, which can be used to show local highway authorities where bus priority measures would be advantageous.

Charging infrastructure data

Only limited analysis could be undertaken of charger efficiency and operation. This has a bearing on fully understanding the losses that affect the ‘well to wheel’ emissions, and also on how vehicle range can be optimised. Some evidence was found that there can be errors in how State of Charge is measured, and different approaches are taken to maximum and minimum SoC accepted during the charging and in service, which affects how effective range is calculated.

Defining a robust baseline

While all projects were asked to provide baseline data for an equivalent diesel bus operating on a comparable route, in some cases there was evidence that baseline and LEBS vehicles were being used in different traffic conditions. If vehicle speeds and more detailed information about routes were available, then the drive cycles could be compared quantitatively between trial and baseline vehicles to check the validity of the baseline. Comparison would also be easier with the results of the controlled tests undertaken on most of the vehicles in order to gain their Low Emission or Zero Emission Bus certification, which report fuel consumption for defined drive cycles.

Reliability and introduction of new vehicles

Reliability problems were found with some of the new models of all technologies. Problems included availability of spare parts and the need to train engineering staff or engage external contractors. Although not necessarily specifically related to the drive technology, such problems reduced availability during the earlier part of the 12-month monitoring period for some fleets. Delays in the installation of refuelling or recharging facilities also caused issues. Allowing more time for the introduction of vehicles before formal monitoring commences would provide a more complete data set, more representative of normal in-service operation.

Recommendations for future trials:

- Ensure that data collection is undertaken using telematics, using standardised indicators across different fleets, and that interior heating/cooling demand, charger losses, and regeneration can be analysed;
- Collect complete datasets from charging/ refuelling infrastructure as well as from vehicle telematics;
- Improve the quality of the baseline by ensuring that drive cycle data (speed, passenger loads, local traffic, route gradients, etc.) are collected so that in service performance can be more accurately compared with the baseline vehicle and with test certificate results; and
- Allow phasing in the trials so that vehicles and charging/fuelling infrastructure are fully operational before monitoring commences.

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Appendix A Parameters employed in the analysis

The parameters used in the calculations, energy density, carbon emission, cost and rebates of the fuels are summarised in Table 6, Table 7, Table 8 and Table 9 respectively.

Table 6: Energy density of the fuels analysed (Department for Business, Energy & Industrial Strategy, 2013; Energy Research Partnership, 2016; EU, 2014)

(Net CV)	Diesel (average biofuel blend)	CNG	Biomethane	Gas oil ('Red diesel')	Hydrogen (Lower Heating Value)
kWh/kg		12.44	13.61	11.83	33.33
kWh/litre	9.97			10.10	
GJ/tonne			49.0	42.57	120

Table 7 CO_2e emission of the fossil fuels considered and electricity from the UK grid (Department for Business, Energy & Industrial Strategy, 2019)

	Diesel (average biofuel blend) ($kgCO_2e/l$)	CNG ($kgCO_2e/kg$)	Biomethane ($kgCO_2e/kg$ / $kgCO_2e/kWh$)	Gas oil ('Red diesel') ($kgCO_2e/l$)	Electricity ($kgCO_2e/kWh$)
TTW	2.59	2.54	0.01 / 0.0004	2.76	0
WTT	0.62	0.49	0.64 / 0.0472	0.63	315.98
WTW	3.21	3.03	0.65 / 0.0476	3.39	315.98

Table 8: Hydrogen GHG emissions for different pathways

Hydrogen pathway	WTT (gCO_2e/MJ)	Source
On-site electrolyser at bus depot, using electricity produced on site from a waste wood incinerator	3.8	(Zemo Partnership (formerly the LowCVP))
Off-site electrolyser, powered by renewable electricity, road tanker delivery of compressed H2 (350kg & 340km)	10.2	
On-site electrolyser at bus depot, using electricity from the UK grid (2021)	148.4	
Off-site electrolyser, powered by renewable electricity, road tanker delivery of compressed H2 (1000kg & 340km)	4.8	

Chloro-alkali process with H2 as a by-product using grid electricity, road tanker delivery of compressed H2 (350kg & 640km)	141.0	
Chloro-alkali process with H2 as a by-product using grid electricity, road tanker delivery of compressed H2 (1000kg & 640km)	131.9	
SMR+CSS retrofit (2030), road tanker delivery compressed H2 (350kg & 200km)	50.0	(Zemo Partnership, August 2021)

Table 9: Fuel costs and rebates

	Diesel	CNG/ biomethane	Gas oil	Electricity	Hydrogen	Sources
Cost	£1.05/l	£0.65/kg	£0.59/l	£0.12/kWh	£7/kg	(Department for Business, Energy & Industrial Strategy, 2013) (Department for Business, Energy & Industrial Strategy, 2013) (Market Information Platform, 2019) (ULEMCo, 2019)
Bus Service Operators Grant (BSOG)	p35/l	p18.8/l	n/a	n/a	n/a	(DfT, 2015)
Low Carbon Emission Bus (LCEB)	n/a	p6/km	n/a	p6/km	p6/km	

Low Emission Bus Scheme monitoring programme

The Low Emission Bus Scheme (LEBS) was a competition run by the Office for Low Emission Vehicles (OLEV) in 2016-2017. £30 million was awarded to 13 projects to purchase 326 buses using four Low Emission Bus (LEB) technologies: battery electric; diesel hybrid; Compressed Natural Gas (CNG); and Hydrogen Fuel Cell (HFC). Monitoring was undertaken for a 12-month trial period, with operators providing details of refuelling and recharging events, and distance travelled. Energy consumption and greenhouse gas emissions (GHG) per km were calculated and compared with a standard Euro VI diesel baseline bus. Operators were also asked to provide data on operational performance so that vehicle availability and failure rates could be compared.

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