Appendix H

New Generation Transport

Sub Mode Options Investigation

January 2014

Metro

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Contents

Executive Summary

The choice of vehicle mode for the Leeds New Generation Transport (NGT) system is crucial to delivering a successful project and meeting the objectives of the scheme. A previous study in 2009 considered a number of different transport modes and their suitability for use in the Leeds context, identifying a short list of three transit modes: a tram, a trolleybus or a high-specification bus. Subsequent work confirmed that a tram was not affordable within the funding envelope and thus not deliverable.

Since 2009 there have been significant developments in bus propulsion technology. These include a widespread uptake of hybrid buses, the deployment of small numbers of battery electric buses and projects to demonstrate more novel technologies such as fuel cell buses. There has also been a trend of technology convergence leading to developments such as fast charging 'plug-in' hybrid buses which can operate for some distance on battery power and electric buses which can recharge inductively or from short sections of overhead line equipment (OLE).

The purpose of this investigation is to update the previous work and fully assess these emerging technologies to ensure that the sub mode selected for the NGT project is suitable and meets the scheme objectives. The assessment considers capital costs, life cycle costs, environmental, sustainability and health impacts.

The key output of the study is a new shortlist of sub modes from a technical perspective, with supporting evidence. The conclusions of this report feed into the assessment of Alternative options for the NGT scheme, which has been undertaken by Steer Davies Gleave.

The sub modes investigated in this study are:

- Trolleybus (with OLE);
- Catenary Free Electric Bus;
- Standard diesel hybrid;
- Plug-in diesel hybrid;
- Fuel cell hybrid;
- Battery electric; and
- Compressed Natural Gas (CNG) bus powered by biomethane from waste.

Conclusions

The study concludes that fuel cell hybrid, battery electric and CNG buses should be rejected as sub mode options for NGT on the following grounds:

- Fuel cell hybrid - cost and technology risk;
- Battery electric - insufficient range and capacity of the current generation of vehicles and technology and performance risks of battery powered 18m articulated buses employing fast charging technology;
- CNG bus - overall energy inefficiency and inability to operate without any pollutant emissions in environmentally sensitive areas.

Having considered the merits of trolleybuses with OLE and catenary free electric bus technology as potential sub modes for NGT, the study concludes that catenary free electric buses, with no OLE other than for charging at bus stops, should be rejected for NGT on the grounds of the unacceptable technology and performance risks involved in reliance on rapid charging using super-capacitor technology as the primary source of traction power for NGT vehicles. However, there is merit in specifying trolleybuses with traction batteries and super-capacitors for NGT to maximise the energy efficiency of the NGT fleet.

Trolleybuses with OLE represent a well proven technology which is continuing to advance as other associated technologies become available, such as super capacitors. They produce zero on-street emissions and offer benefits in terms of route legibility and a sense of permanence to weigh against the cost and prominence of the OLE.

Having considered the merits of a plug-in hybrid bus over a standard hybrid bus, the state of development of plug-in hybrid vehicles and the associated technology risk, the study concludes that the capability, within limitations, of a plug-in hybrid to operate without any pollutant emissions in environmentally sensitive areas provides a compelling reason to prefer a plug-in hybrid over a standard diesel or gas powered hybrid as a sub mode for NGT.

Plug-in hybrid buses are expected to be in full production by late 2015. Although not yet a fully proven technology in commercial operation, the technology risk presented by the use of a plug-in hybrid bus is considered to be significantly lower than for a fuel cell bus or a catenary free electric bus and lower than for a pure battery electric bus as the driveline remains similar to the current generation of parallel hybrids but with the addition of a larger battery pack and roof mounted charging equipment based on proven heavy rail technology.

Standard hybrid buses have no capability to operate without any pollutant emissions in environmentally sensitive areas, but offer reduced CO_2 emissions, local air quality benefits and a reduction in perceived noise levels. Hybrid buses offer a mature technology with current market traction, providing a lower cost alternative to other modes but at the same time offering benefits upon standard diesel buses.

Recommendations

The trolleybus with OLE sub mode should be taken forward for further consideration as a potential option for NGT.

The plug-in hybrid sub mode should be taken forward for further consideration as a potential option for NGT.

The standard hybrid sub mode should be considered as a sub mode for a lower cost alternative option to the NGT scheme.

Glossary

CBG	Compressed biomethane gas
CHIC	Clean Hydrogen in European Cities
CNG	Compressed natural gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CUTE	Clean Urban Transport for Europe
EMC	Electromagnetic compatibility
GHG	Greenhouse gases
HVAC	Heating, ventilation and air conditioning
LCEB	Low Carbon Emission Bus
LNG	Liquefied natural gas
NGT	New Generation Transport
NMHC	Non-Methane hydrocarbons
NOx	Oxides of Nitrogen
OLE	Overhead line catenary equipment for trolleybus pole current collection
PM	Particulate matter
PVR	Peak vehicle requirement
SI	Spark ignition
TTW	Tank to wheel
WTW	Well to wheel

1 Introduction

1.1 Background and Context

One of the key transformational projects for Leeds and the City Region, the New Generation Transport (NGT) trolleybus system will create a modern, reliable and integrated transport system to support the city's future development, transform public transport and offer a real and attractive alternative to travel by car.

NGT will be modern, accessible, energy efficient and clean, providing a high quality transport system that offers passengers improved journey times and a frequent, reliable service. It will connect people to key employment sites, education, health and leisure facilities, acting as a catalyst and driver for economic growth and regeneration.

The choice of vehicle mode for the system is crucial in terms of delivering a successful project and meeting the objectives of the scheme. Studies were completed in 2009 prior to all major transport schemes being put on hold following the election of the Coalition Government. A short list of three transit modes: a tram, a trolleybus or a high-specification bus was initially identified. Subsequent work confirmed that whilst a tram would maximise benefits it was not affordable within the funding envelope and thus not deliverable.

A further study followed on from this initial work: The "Transit Mode Options – Quantified Environmental Benefits" report (236834/RPT15B, October 2009) considered the environmental issues for a Trolleybus, Hybrid Bus and a Diesel Bus on both a generic basis and in the Leeds-specific context.

1.2 Purpose of Report

Since the previous reports were prepared there have been significant developments in bus propulsion technology and the deployment of several systems in the UK and globally which are based on propulsion by means other than a diesel engine. These include a widespread uptake of hybrid buses, the deployment of small numbers of all-electric (battery) buses and demonstration projects of more novel technologies such as fuel cell buses. There has also been a trend of technology convergence leading to developments such as 'plug-in' hybrid buses which can recharge and operate for longer distances on battery power and electric buses which can recharge inductively or from short sections of overhead line equipment (OLE).

Therefore it was appropriate to update the previous work to fully assess these emerging bus sub modes to ensure that the sub mode selected for the NGT project was suitable and met the scheme objectives.

It was also decided that the bus vehicle modes should be assessed on a like for like basis so that the determination between the sub modes is the vehicle and propulsion technology, and its associated fuelling and maintenance infrastructure, rather than the overall system that is most appropriate for that sub mode.

1.3 Objectives and Outputs

The objectives of this high level study are to look at the alternative (vehicle) sub mode options available to meet the scheme objectives, capacity requirements and performance targets for the Leeds NGT project. This will include looking at the advantages and disadvantages associated with trolleybuses versus alternative fuel vehicles, including technologies such as battery electric, fuel cell, diesel-electric hybrid and gas powered vehicles.

The key outputs of this study will be:

- Evidence to support the case for whichever sub mode option is seen to be the most advantageous, taking into account capital costs, life cycle costs, environmental, sustainability and health impacts.
- A new shortlist of sub modes from a technical perspective, to feed into the assessment of Alternative options for the NGT scheme, which has been undertaken by Steer Davies Gleave. This study considers the optimum option from a business case perspective, considering preferred next best and low cost options.

1.4 Key Assumptions

- The vehicle configuration will be single-articulated buses circa 18 m in overall length.
- It is assumed that all of the sub modes will be assessed on the same basis in terms of infrastructure, this will include the following;
  - Same length as the NGT alignment, therefore 14km;
  - Same gradient profile as the NGT alignment, therefore some inclines of 10%;
  - Similar level of passenger demand as the NGT system;
  - Similar core service frequency as the NGT system, therefore 10 vehicles per hour;
  - The same level of segregation for all sub modes;
  - The same level of high signal priority as the NGT system for all sub modes.
- A requirement for a new depot for all sub modes.

1.5 Sub Modes for Consideration

The sub modes considered previously in the “Transit Mode Options – Quantified Environmental Benefits” report (236834/RPT15B, October 2009) report were:

- Diesel bus;
- Diesel hybrid bus; and
- Trolleybus

Based on the conclusions of previous work, a conventional diesel bus has been excluded from further consideration for NGT on environmental grounds. A new set of alternative vehicle sub modes has therefore been identified for consideration in this study. This will enable trolleybuses and diesel hybrid buses to be compared with vehicles powered by alternative fuels, including technologies such as battery electric, fuel cell and gas propulsion.

There have been significant developments in battery and fuel cell vehicle technology since the previous work in 2009 which warrant a fresh look at these options.

Gas powered vehicles are a proven technology globally but until recently there has been little interest in this technology from UK operators. This lack of interest has not encouraged vehicle manufacturers to develop and offer gas buses in right hand drive configuration for the UK market. The situation has changed since 2009, with the Green Bus Fund and the availability of biomethane as a transport fuel stimulating significant interest in gas buses.

The recent emergence of the plug-in hybrid concept has also been taken into consideration and the conclusion reached that this is significantly distinct from a 'standard' diesel hybrid bus to warrant inclusion as a sub mode in its own right.

The sub modes for this study are thus:

- Trolleybus (with OLE);
- Catenary Free Electric Bus
- Diesel hybrid;
- Plug-in hybrid;
- Fuel cell hybrid;
- Battery electric; and
- Compressed Natural Gas (CNG) bus powered by biomethane from waste.

1.6 Report Structure

The report is structured as follows:

Chapter 2 reviews the alternative sub mode technologies, considering their maturity, state of development and current commercial application. Further detail is provided within the case studies in **Appendix A**.

Chapter 3 presents a comparison between the sub modes, considering vehicle characteristics, operations, power usage, energy efficiency and infrastructure requirements including depot facilities.

Chapter 4 considers the expected whole life costs of the alternative sub modes, focusing on the key differentiators between the sub modes from a cost perspective.

Chapter 5 presents an environmental comparison of the sub modes, highlighting the key environmental and health issues relevant to sub mode choice.

Chapter 6 presents conclusions for each sub mode, discusses the key issue of technology risk and recommends a shortlist of three sub modes.

2 Alternative Sub Mode Technologies

2.1 Introduction

The environmental issues associated with the use of diesel oil as a fuel for urban public transport systems, the demand for cleaner and greener alternatives and concerns about future dependency on fossil fuels have encouraged the development of a wide range of alternative technologies to enable public transport vehicles to be powered by electricity, gaseous fuels and biofuels.

The use of alternative power sources and fuels can contribute to both improved local air quality by reducing pollutant emissions from vehicles and to reduced emissions of carbon dioxide and other greenhouse gases. Both the emissions generated in producing the fuel ('well to tank') and consuming it ('tank to wheel') should be considered.

A recent trend has been the development of hybrid propulsion technology for public transport systems, combining an internal combustion engine or fuel cell with electric drive systems and a battery allowing on-board energy storage and regenerative braking.

The maturity, state of development and commercial application of these technologies varies widely, with electric trolleybuses – a mature and proven technology in use world-wide - at one of the scale and the still developing technology of hydrogen fuel cell buses at the other. While publicly funded demonstration projects have proved that hydrogen buses can be operated reliably in well-controlled trials, the cost of this technology must fall significantly before it can gain any real commercial traction.

Each of the alternative fuel technologies relevant to the sub modes considered in this report is discussed briefly below, with further detail provided within the case studies in **Appendix A**.

2.2 Electric Vehicle Technology

One of the main benefits of electric vehicle technology is that under normal operation there are no exhaust emissions of any kind on the streets where electric vehicles operate.

2.2.1 Trolleybus Technology

Electrically powered buses have traditionally taken the form of the trolleybus, a bus powered by electricity from overhead wires.

Following experiments in the late 1800s, the world's first passenger-carrying trolleybus using what is now recognised as the standard trolleybus current collection system of two parallel overhead wires and rigid trolley poles spring-loaded to hold them up to the wires commenced operation in Germany in 1901.

Traditionally trolleybuses were introduced because of their operational performance, energy efficiency and reliability, although they were replaced by diesel buses in some locations as fuel costs dropped in the 1950s and diesel engines became more reliable.

The first trolleybus operations in the UK commenced in Leeds and Bradford in 1911 and Bradford was also the last UK city to operate trolleybuses, with its system closing in 1972.

Trolleybuses remain common in many European countries as well as Russia and China. Worldwide, around 300 cities or metropolitan areas are currently served by trolleybuses. Many of these cities are continuing to renew and extend their trolleybus systems.

Environmental considerations have been one of the main drivers for renewed interest in trolleybus systems. This has stimulated further developments in trolleybus technology leading to improvements in vehicle performance and energy efficiency. The appearance of today's trolleybuses confounds perceptions that this is an outdated technology.

With modern OLE systems, it is possible to achieve aesthetically pleasing and non-intrusive solutions in sensitive urban areas. However, in some cases, the OLE at road junctions can be more prominent where trolley pole crossing frogs are located to switch the direction of the trolleybus's poles. Where these frogs are used it may be necessary to use items of equipment that require extensive OLE supports to maintain their position

A case study of Zürich, Switzerland, a city with a modern and expanding trolleybus network using articulated vehicles is in **Appendix A**.

Figure 2.1: Solaris Trollino 18 Metrostyle Articulated Trolleybus

Source: Solaris

In operational terms trolleybuses are essentially similar to conventional diesel powered buses, but with an electric motor and motor controller instead of a diesel engine for propulsion.

Modern standard trolleybuses can move around obstacles such as parked cars, or run off-wire for short distances using auxiliary power units in the form of batteries, a flywheel or diesel alternator unit. The trolley booms can be automatically lowered enabling vehicles to continue off-wire without stopping. Automatic rewiring can be achieved using ‘pans’ fitted to the overhead at appropriate locations.

Figure 2.2: Van Hool AG300T Articulated Trolleybus with Super-capacitors and Traction Battery, Genoa, Italy

Source: Mott MacDonald

Modern dual mode trolleybuses can be as flexible in operation as conventional buses, running without wires in historic city centres and other sensitive areas or if diversions from wired routes are required. Thus only parts of routes need to be electrified and vehicles can operate in battery (or biofuel) mode on the central section of routes, as is the practice in Rome and Beijing. However, the additional equipment fitted to dual mode vehicles does carry a weight penalty relative to a standard trolleybus.

The ability to use regenerative electrical energy, recuperated during trolleybus braking, to feed regenerated electrical power back to the overhead line has been a standard feature on trolleybuses for many years. Suppliers are claiming potential for savings in propulsion energy consumption of 25-30%. However, such reductions can only be achieved if the urban 750 V dc power supply uses suitably designed overhead line configurations to accept the regenerated power back into the OLE system, and the trolleybus service headway is sufficiently low, typically 5 minutes or less, which would not bus suitable to the NGT system which is proposed to have a headway of 6 minutes.

However, more recently super-capacitors and traction batteries in combination have been developed as an on-board energy saving technology for trolleybus systems. This equipment enables the capture of the electrical energy recovered during dynamic braking and the subsequent storage of the energy on-board the vehicle. This recovered and stored electrical energy can then be used to:

- Supplement the traction power energy demand from the OLE to improve the overall energy efficiency of the trolleybus system by reducing the peak demand for traction power supplies, especially during trolleybus acceleration on departure from a bus stop; this is a technique also known as “peak load shaving”;
- Stabilise energy traction power networks by reducing the overall traction energy demand;
- Facilitate increased trolleybus operation during peak periods, without the need for traction power supply strengthening.

2.2.1.1 Partially Catenary Free Technology

The development of on-board super-capacitor and traction battery technology also offers the potential for ‘catenary free’ trolleybus operation without OLE over varying distances depending upon operating conditions, gradients and on-board storage capacity.

This option is particularly relevant where trolleybuses are passing through areas of historical or aesthetic importance or across complicated road junctions, where the OLE would be either undesirable or difficult and complicated to install and maintain.

The trolleybus can also be powered past sensitive receptors, such as adjacent hospital and university buildings using only battery power, greatly reducing the possible effects of electromagnetic compatibility (EMC) on any delicate equipment installed in these buildings.

Finally, battery power can be used for trolleybus movement and operation in depot and workshop areas, with a consequent reduction in the extent of the OLE installation required at the depot.

Figure 2.3: Solaris Articulated Trolleybus with Traction Battery and Super-capacitors

Source: Barnimer Busgesellschaft mbH

The Eberswalde vehicles referred to in our case study are trolleybuses, but with a capability to operate in service without OLE over a substantial part of the route. This type of operation is referred to as “partially catenary free”. There are currently no examples of completely catenary free trolleybus systems operating worldwide. A case study of the partially catenary free operation of articulated trolleybuses equipped with super-capacitors in Eberswalde, Germany is included in **Appendix A**.

2.2.2 Catenary-Free Electric Bus

There are several alternate bus vehicle modes which have trailed different technology to bridge the gap between a trolleybus and an electric bus. These have generally involved removal of the trolley poles and therefore necessity for OLE, replacing this with recharging points. These modes additionally attempt to reduce the weight of any on board energy storage, presumably in an effort to reduce weight and improve efficiencies in energy usage.

2.2.2.1 Super Capacitor Electric Bus - Capabus

In its ultimate form, super-capacitor technology offers even further flexibility, with the potential to reduce overhead wires to short sections, optimally located at bus stops, to act as charging points.

Unlike batteries, super-capacitors store energy through a physical rather than chemical process. As they allow a very high current, it is possible to charge them in a very short time period; typically around 20-30 seconds for a full charge. This allows them to be fully charged during the typical dwell time at bus stops.

Additionally regenerative braking can also be included which allows the energy potentially lost to braking to be recouped and to recycle back into the super capacitors.

The first fully electric super-capacitor buses (Capabus) were introduced in the city of Shanghai, China in 2010. A fleet of 17 Sunwin vehicles operates Route 11 through the downtown area. The bus design is similar to a trolleybus but the super-capacitors are charged at bus stops via short sections of OLE, avoiding the need for overhead wires over the whole length of the route. It should be noted that these buses do not have traction batteries, only super capacitors.

Figure 2.4: Sunwin Super-capacitor Electric Bus, Shanghai

Source: Wikimedia Commons – Public Domain

When the Capabus dwells at the bus stop a T-shaped connector is raised to touch two connector rods fixed under a gantry reaching out over the bus as shown in Figure 2.4. The length of the connector rods is sufficient to avoid the need for the positioning of the bus to be very precise. The charging process takes around 30 seconds. Charging typically takes place at every third bus stop, with the buses running for approximately 1.5 km between each recharge.

It has been reported that there have been issues with the super capacitors during the trial of the Capabus vehicles. The super capacitors tended to overheat during hot weather and led to some of the vehicles breaking down. In addition during warm conditions the buses used more electricity and therefore had to stop more often to recharge. The lack of sufficient charging points led to drivers having to turn off auxiliary systems, such as air conditioning, and having to electrical power. These issues led to the installation of additional charging points.

Although this mode is based upon trolleybus technology in the design of the chassis of the bus and the charging infrastructure, which is similar to OLE, it does not have the capability to draw power from an overhead catenary system while in motion. In addition this mode is distinct from a battery electric bus in that it stores energy in a physical process, via the super capacitors, rather than a chemical process, as is the case for traction batteries.

The inductive transfer of power from a ground based supply installed under the road surface at charging points offers the potential for the completely catenary-free operation of buses fitted with super-capacitors and batteries. This method of charging would not offer the speeds of flash charging but could top up batteries in a relatively fast period of time. The Milton Keynes battery electric buses which recently entered service are charged inductively at 120kW per transfer. A 10 minute charge is therefore sufficient to replenish two thirds of the total battery capacity.

2.2.2.2 Trolleybus Optimisation Systeme Alimentation (TOSA)

The TOSA system is an electric bus which is currently being trailed in Geneva. The vehicle is a 19m long articulated bus, similar to a trolleybus. Instead of OLE to provide power to the vehicle, charging points are provided at regular intervals along the route. The vehicle has a small traction battery pack which is provided in conjunction with super capacitors which allow ‘flash’ charging at the charging points. The vehicle is also capable of regenerative braking in order to re-cycle energy back into the super capacitors. The vehicle currently operates on a 1.8km section of an existing bus route, between Geneva Airport and the Palexpo Exhibition Centre.

It is reported that the TOSA vehicle can ‘flash’ charge at an intermediate ‘boost’ charging point in 15 seconds. The vehicle stops under the charging point and then an overhead connector (laser guided moving arm) on top of the vehicle connects to the charging station in as little as 1 second. The vehicle then recharges at a rate of 400kw, which gives the vehicle enough charge to cover 3-4 stops. The connector on the charging station is only energised when there is a vehicle connected to it and the charging stations are integrated into the bus stops with typical dwell times allowing sufficient time for recharging. At the end of the route the vehicle receives a full charge, which takes approximately 4 minutes, from an ultrafast charging station.

Figure 2.5: TOSA Electric Bus at Charging Station

Source: ABB News.cision.com

The main driver behind the development of this technology is to introduce a system of mass transit with electric ‘flash’ charging at stops. The removal of the OLE of the existing Trolleybus fleet appears to be one of the main considerations in the development of the system, but still maintaining the capacity of articulated vehicles but without the weight of a full bank of traction batteries to therefore maintain energy efficiency. At present this technology remains as a demonstrator project with no commercial availability or systems operating under normal operating conditions. This system was only unveiled in 2013 and the technology is therefore not considered advanced enough to consider as a viable contender for the Trolleybus system.

2.2.3 Battery Electric Vehicle Technology

Electrically powered buses may also take the form of a battery electric vehicle using chemical energy stored in rechargeable battery packs. Such vehicles use electric motors and motor controllers instead of internal combustion engines for propulsion.

Battery powered electric vehicle technology has been under continuous development since the 1970s, but until recently the limited range and performance of such vehicles has been a fundamental barrier to their use for mainstream urban public transport operations.

A further issue with batteries as a propulsion technology is the susceptibility of batteries to rapid charge cycles and deep discharges, both of which can result in some loss of life expectancy and of overall performance. Batteries also require routine maintenance and inspection, and regular charge and discharge cycles to maintain peak performance and optimise battery life.

New Lithium Ion battery technology has enabled the development of battery packs that have higher power and energy density, providing better acceleration and greater range from fewer batteries. The deployment of this and other advances in battery technology led by Chinese companies has seen the size of commercially available battery electric buses grow from the previous generation of small buses to full size single deck buses of 11 to 12m in length.

Increases in the range of battery electric buses combined with the development of fast charging technology are beginning to make battery electric buses a practical option for the operation of services with low intensity or low mileage duty cycles providing opportunities for top-up fast charging within individual vehicle operating cycles. Many of the early examples of the operation of battery electric buses are on short city centre shuttle routes with duty cycles that can accommodate the current limitations of this technology.

The Optare Versa EV, powered by Lithium Ion batteries, is the first commercially available fast charging full-size electric bus in the UK, with a claimed range of 120-150 km. A case study of the operation of a small fleet of these vehicles on a Park and Ride service in Coventry is in **Appendix A**.

Figure 2.6: Optare Versa EV battery Electric Bus, Coventry

Source: Route One

The Chinese BYD ebus is an all-electric 12m single deck bus powered by a Lithium Iron Phosphate battery. This vehicle is claimed to have a range of 250 km (155 miles) under urban road conditions, on a normal 6hr charge.

Following tests involving a single vehicle in numerous European cities, a fleet of six BYD ebuses has been operating on the Dutch island of Schiermonnikoog since May 2013. The manufacturer won the order via an open tender and is supporting the operation of the vehicles via a 15-year maintenance contract.

Transport for London and bus operator Go-Ahead London have announced a trial of two 12m BYD ebuses on London bus routes 507 and 521 connecting Waterloo Station with Victoria Station and London Bridge Station via the City to commence in December 2013. These are short commuter services with duty cycles within the range limitations of the BYD ebus, so that vehicles will be able to operate for a full day without the need to recharge, with charging taking place overnight. The performance and reliability of the buses will be assessed to establish whether the technology can stand up to the rigours of an intensive urban operation.

Figure 2.7: BYD ebus, London

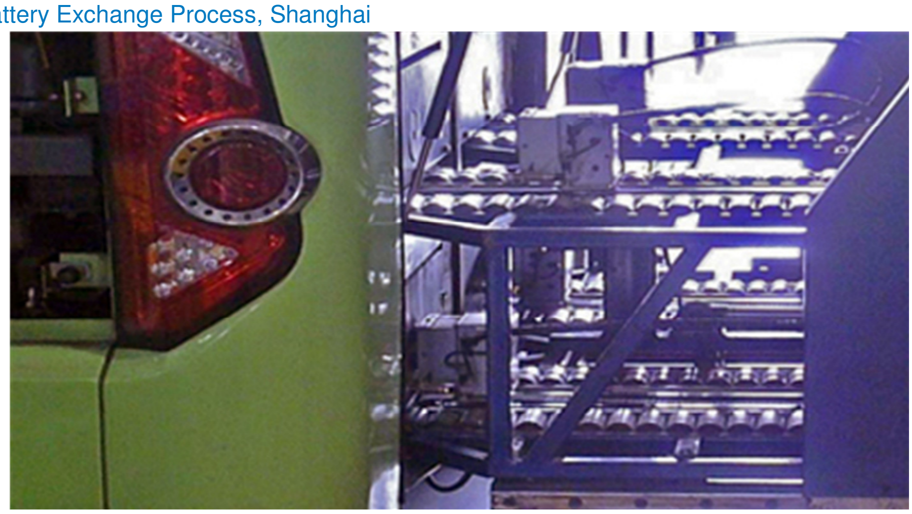
Source: Bus and Coach Buyer

A fleet of around 160 Sunwin battery electric buses operates in Shanghai, China Figure 2.8). The majority of these vehicles use a battery exchange system, where the buses are equipped with battery packs lasting for 2-6 hours' operation, depending on the duty cycle and utilisation of the air conditioning. The battery exchange station in Shanghai (Figure 2.9) can swap batteries on eight buses simultaneously. Battery exchange is one possible option for buses with long working hours and harsh duty cycles, but has the significant disadvantages of requiring an increase in fleet size to allow vehicles to be taken out of service and returned to the battery exchange station plus the additional cost of the exchange batteries and infrastructure.

Figure 2.8: Battery Electric Buses using Battery Exchange System, Shanghai

Source: Volvo Bus

Figure 2.9: Battery Exchange Process, Shanghai



Source: Volvo Bus

A trial of wireless charging technology will see a fleet of eight 9.5m battery electric buses manufactured by Wrightbus entering service in Milton Keynes with bus operator Arriva, with operations expected to commence in early 2014. The Wrightbus Streetlite EV (Figure 2.10) has 150kWh of roof-mounted Lithium batteries, giving a range of 76 miles before the state of charge reaches 30%.

The buses will be charged inductively by power transmitted from a primary coil buried in the road and picked up by a secondary coil fitted to the bus, with a transfer efficiency of 95%. It is claimed that 10 minutes parked over a coil will replenish two thirds of the energy consumed on each journey. Charging points will be placed at three points on the bus route and the buses will charge in the time scheduled for driver breaks at the end of the route. A two to three hour top up charge and battery balancing will take place overnight.

Figure 2.10: Wrightbus Streetlite EV for Milton Keynes

Source: Bus and Coach Buyer

Concerns about battery life are frequently cited as a disadvantage of battery electric vehicles, but Lithium Ion batteries only degrade gradually and even if fully drained prior to recharging should retain around 80% of their capacity after eight years of use. With more sympathetic top up recharging cycles such that batteries never go below 40% of the maximum charge, vehicle suppliers are claiming that there is the potential for batteries to last for the life of the bus. BYD claim that the batteries on the ebus vehicles currently being trialled in London have a life of over 4,000 cycles from fully charged to discharged and back to fully charged, which at one charge per day equates to a life of almost 11 years. There is emerging evidence of heavy vehicle battery packs having achieved a service life of at least 5-7 years. The upper end of this range is comparable to the life of a diesel engine.

While battery electric vehicle technology has developed significantly over the last five years, the tipping point at which pure battery electric buses will become an uncompromised option for intensive urban public transport operations involving all day operation with limited opportunities for recharging have not yet been reached. They will not be reached until battery technology develops to the point where a full size 12m bus can comfortably travel 250 to 300 miles on a single charge or the concept of rapid top-up charging during bus stop dwell times is fully proven. At present it is unclear when either milestone is likely to be reached, but if development continues at the current pace the energy density of heavy vehicle battery packs is likely to increase by between 3-5% per year, which could lead to less batteries and a lighter bus. It should be noted that it is considered that the big increases in battery energy densities have already been accomplished and that future increases will be slow and steady.

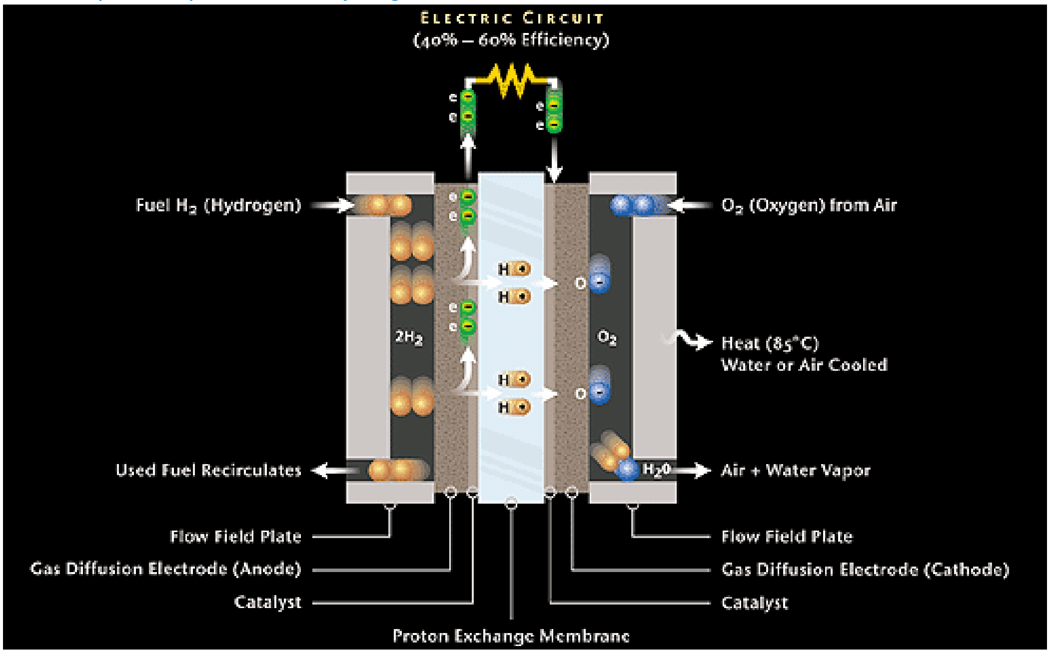
An articulated battery electric vehicle is not yet commercially available, therefore there is not currently the option to service routes which have the highest passenger demands and require vehicles with greater capacities. Further advances in battery technology and performance will also be required to make pure battery electric, high capacity, articulated buses a reality.

2.3 Fuel Cell Vehicle Technology

A fuel cell is an electrochemical conversion device which generates electricity by a proton-exchange mechanism, using fuel on one side and an oxidant on the other, which react with each other in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. The diagram in Figure 2.11 provides a visual representation of this process.

Fuel cells can operate virtually continuously as long as the necessary flows are maintained. Fuel cells are different from batteries in that they consume reactant, which must be replenished, whereas batteries store electrical energy chemically in a closed system. Additionally, whilst the electrodes within a battery react and change as a battery is charged or discharged, a fuel cell's electrodes are catalytic and relatively stable. Many combinations of fuel and oxidant are possible: a hydrogen cell uses hydrogen as fuel and oxygen gas (from the air) as the oxidant. Other fuels include hydrocarbons and alcohols, whilst other oxidants include air, chlorine and chlorine dioxide. However, the hydrogen-oxygen combination is generally favoured for vehicles.

Figure 2.11: Principles of operation of a hydrogen fuel cell



Source: Transport for London

Fuel cells for transport use may provide either primary propulsion or range-extending capability for vehicles. Fuel cell vehicle technology provides an alternative to all-electric drivetrains for urban bus operations without pollutant exhaust emissions. The only emissions produced by a hydrogen fuel cell bus are water vapour, but the energy used in the production of the hydrogen fuel should also be considered.

The first experimental fuel cell buses appeared in North America in 1993-4 and in Europe from 1997. From 2003 onwards there has been a succession of European Union funded demonstration projects. In late 2010 it was estimated that approximately 110 fuel cell buses would be in day to day service worldwide by the end of 2011.

The Clean Urban Transport for Europe (CUTE) project tested the first generation of fuel cell buses. 27 Mercedes Benz Citaro hydrogen fuel cell buses were operated in public service in nine European cities, including London, between 2003 and 2005. During this period the buses operated in service for more than one million kilometres and carried over four million passengers.

The CUTE buses were equipped with tanks holding 44 kg of gaseous, compressed hydrogen. These fed into two fuel cell modules providing more than 250 kW of electrical power and delivering performance levels comparable to standard diesel engines. The fuel cell system and additional equipment are located on the roof of the bus, with an electric traction system located at the left rear of the bus.

Standard bus components such as automatic transmission, gearbox and some auxiliary components were used as much as possible. This design philosophy was successful in meeting the reliability objectives of the project, with the CUTE fleet achieving average availability of 81.6%, but led to many of the potential energy efficiency benefits of a fuel cell drive train not being captured.

The CUTE project concluded that in order to realise the potential of fuel cell vehicles and to meet operational requirements for mainstream urban public transport services:

- Vehicle energy efficiency needed to be improved to be equal to or better than equivalent diesel buses;
- Vehicle weight needed to be reduced to be comparable with a diesel bus;
- Vehicle noise needed to be reduced.

It was suggested that these objectives could be achieved by:

- Utilising a hybrid drive train;
- Eliminating a design requirement for the fuel cells to always produce a minimum current; and
- Changing the auxiliary systems.

Seven cities took part in a one year extension known as HYFLEET:CUTE, with the objective of enabling the existing fuel cell buses to be worked harder and longer to test the limits of the fuel cell stack durability and further test the refuelling chain technology.

This was followed by the Clean Hydrogen in European Cities (CHIC) project, which seeks to make the next step leading to the full commercialisation of hydrogen powered fuel cell buses.

The project involves 26 buses in daily use on urban bus routes in five locations across Europe – Aargau (Switzerland), Bolzano/Bozen (Italy), London (UK), Milan (Italy), and Oslo (Norway). The objective of CHIC is to move these demonstration vehicles towards full commercialisation starting in 2015.

The buses deployed in the CHIC project are latest generation of fuel cell hybrid buses, designed to address the findings from CUTE. Electricity produced by the fuel cell is stored by roof mounted super-capacitors, allowing energy to be recaptured when decelerating through regenerative braking. The buses will be supplied by three different manufacturers and the hydrogen refuelling infrastructure will involve the main industrial players active in hydrogen infrastructure development around the world.

The world's largest single fleet of 20 fuel cell buses was introduced by BC Transit in Whistler, Canada in 2009. This was a demonstration programme to showcase fuel cell technology during the 2010 Winter Olympic Games. The vehicles cost $2.1 million each and both fuel and maintenance costs have proved to be higher than the conventional diesel buses they replaced. BC Transit has recently said that it cannot afford to continue to operate and maintain the fleet after the demonstration programme ends in spring 2014.

In summary, early hydrogen fuel cell buses suffered from a large weight penalty relative to diesel buses, limited range and poor fuel efficiency. Hybridised fuel cell buses have demonstrated far better fuel economy than the previous generation of non-hybridised vehicles, offering a commensurate increase in range and making all day operation on urban bus routes a viable proposition.

It is thus expected that fuel cell hybrid technology will be the basis for progress towards the future commercialisation of hydrogen buses. The performance and service availability of these vehicles is improving and their cost falling, but the largest single barrier to the adoption of hydrogen fuel cell technology for urban bus operations remains outright cost.

Figure 2.12: APTS Phileas Fuel Cell Hybrid Articulated Bus, Cologne

Source: ELTIS

A 2010 report produced by the European Commission funded NextHyLights project looked at the historical techno-economic performance of fuel cell buses, the cost structure of a hybrid fuel cell bus and made cost projections for the total cost of ownership of hybrid fuel cell buses in comparison with diesel, diesel hybrid and trolleybuses over the period 2010-2030.

Based on the set of assumptions made, this study indicates that fuel cell technology has the potential to provide a more flexible and cost effective solution on a total cost of ownership basis than trolleybuses in the period between 2015 and 2020, whilst converging towards diesel-fuelled bus total ownership cost levels by approximately 2025 to 2030. However, this prospect is caveated by the need to overcome the considerable challenge of creating sufficient demand for fuel cell hybrid buses in the short term while the buses remain significantly more expensive than alternatives, in order to justify the technology developments required to achieve further cost reduction. There is thus a high level of uncertainty regarding the realism of the scenario assumed in this study.

2.3.1 Fuel Supply Network

Fuel cell buses also pose the challenges of producing hydrogen economically and with minimal environmental impact, developing a hydrogen supply chain and refuelling infrastructure and handling hydrogen safely within the depot environment.

Demonstration projects have involved the use of industrially produced hydrogen delivered to site by tanker and hydrogen produced on-site through natural gas reforming or water electrolysis.

Hydrogen can be stored in compressed or liquid form but needs to be compressed for vehicle fuelling to keep the size of on-board tanks to a reasonable level, and to ensure sufficient range for bus operation.

The main components of a filling station for compressed gaseous hydrogen storage and dispensing are;
- Compressor;
- Storage vessels; and
- Dispenser with filling nozzle.

The main components for a filling station for compressed gaseous hydrogen dispensing with liquid storage are;
- Cryogenic vessel;
- Cryogenic pump for pressurising the liquid; and
- Vaporiser and dispenser.

Turn-key solutions, including for on-site hydrogen generation, have been developed based on compact, modular units and components that can be integrated into existing depot facilities.

A case study of the operation of fuel cell-hybrid articulated buses in the Rhineland, Germany is included in **Appendix A**.

2.4 Natural Gas Vehicle Technology

Compressed Natural Gas (CNG) consists of natural gas formed from buried organic material, and has methane as the dominant component. Natural gas for use as a transport fuel is normally compressed at high pressure (200 to 250 Bar) with on-vehicle storage in tanks either under the floor or on the roof of buses.

Natural gas can also be produced by anaerobic digestion of organic material including agricultural, animal and food waste, sewage sludge or energy crops. This is biogas or, in upgraded form with carbon dioxide and other contaminants removed to make it suitable for use as a transport fuel, biomethane. In compressed form it is known as Compressed Biomethane Gas (CBG).

Biomethane is thus a renewable transport fuel which, dependent on the production pathway, is claimed by its advocates to be close to carbon neutral. When used in vehicles it has very low exhaust emissions, thus contributing to improved local air quality. Gas powered vehicles are also considerably quieter than conventional diesel vehicles.

CNG was amongst the alternative fuel technologies considered in the 2009 Transit Mode Option Study for NGT, but there have subsequently been two key developments relevant to the deployment of this technology within the UK.

- The commercial production within the UK of biomethane of sufficient quality for use as a transport fuel has commenced. This can either be used directly to power vehicles or injected into the gas grid to offset the use of fossil natural gas from a mains supply.
- The Department for Transport's Green Bus Fund, offering capital grants towards the additional cost of Low Carbon Buses relative to comparable diesel powered buses, has stimulated renewed interest in gas powered buses from both UK vehicle suppliers and bus operators.

The first of six of 13 MAN EcoCity CNG buses part-funded by the third round of the Green Bus Fund entered service with Go-Ahead Group operator Anglian Bus in Norfolk and Suffolk in December 2012. These have been followed by the introduction of 21 similar buses by Arriva in Runcorn (10) and Darlington (11) from March 2013.

Figure 2.13: MAN EcoCity CNG Bus, Norwich

Source:

Both the Anglian Bus and Arriva buses are actually fuelled by fossil gas from a mains supply, but the operators are buying biogas which is injected into the grid to offset the gas taken from the grid to power the buses. This avoids the use of energy to transport biogas to operators' depot sites by road.

The successful bids for the fourth round of Green Bus Fund announced in May 2013 are expected to lead to orders for a further 31 CNG buses from UK operators.

The availability of new build gas buses means that costs for conversion of engines to run on CNG are no longer a consideration and also that the complete vehicle is covered by the manufacturer's warranty.

2.4.1 Engine Technology

Dedicated methane gas engines are spark ignition (SI) engines optimised to run on 100% methane. Such engines display significantly lower combustion noise than their diesel equivalents but are also less energy efficient than diesel engines employing compression ignition technology.

SI engines may be configured either as lean burn or with a stoichiometric control system. The stoichiometric system, in theory, should be less fuel efficient due to the throttling of the air intake under part load conditions leading to greater pumping losses. This may particularly affect vehicles operating urban bus services. The throttling of the engine would make it more prone to high oil consumption, which could lead to a higher level of lubricant derived particulate emissions compared with an un-throttled engine.

Lean burn engines run un-throttled, may be less fuel composition tolerant and will require a methane capable oxidation catalyst to achieve compliant low total hydrocarbon emissions. Methane catalysts require quite high exhaust temperatures for optimum performance and thus may not be best suited to urban bus operations.

Dual fuel engine technology is also available, with vehicles retaining a standard diesel engine and fuel tank, with the addition of a methane tank and a secondary methane injection system to the inlet manifold. The use of diesel enables pilot ignition of the gas fuel in the compression ignition engine. The ability to run on 100% diesel fuel is retained in the event of gas being unavailable. This technology is best suited to heavy goods vehicles making long haul movements, during which they will spend much of the time at high speed and load. When used on such operations vehicles will maximise their consumption of gas and thus gain the greatest cost and emissions benefits.

2.4.2 Fuelling Requirements

There are no specific fuel quality standards for natural gas or biomethane analogous to those that exist for gasoline and diesel fuel. However gas standards do exist for vehicle emissions testing to Euro standards and there is a Swedish standard for biogas produced by anaerobic digestion for use as a transport fuel. Biogas produced to this standard is able to be used in engines designed for natural gas without modification.

Methane may be stored on vehicles in either compressed form (CNG) or liquefied form (LNG). In compressed form the gas is stored in pressurised tanks at either 200 or 250 bar. In liquefied form the gas is cooled to minus 162^{o}C, compressed to a liquid and stored in insulated tanks on the vehicle akin to a large 'Thermos' flask. In common with other pressure vessels, compressed methane tanks must be inspected every three years.

Liquefying the fuel allows storage of a greater energy density of fuel for a given volume. This offers range benefits for long distance haulage, but fossil LNG is more expensive than CNG and the energy overhead for liquefaction is greater than that required to compress the gas. As the range of current CNG buses is more than sufficient for all day operation on urban bus routes there is no advantage in using LNG for urban public transport to offset its cost and environmental disbenefits relative to CNG.

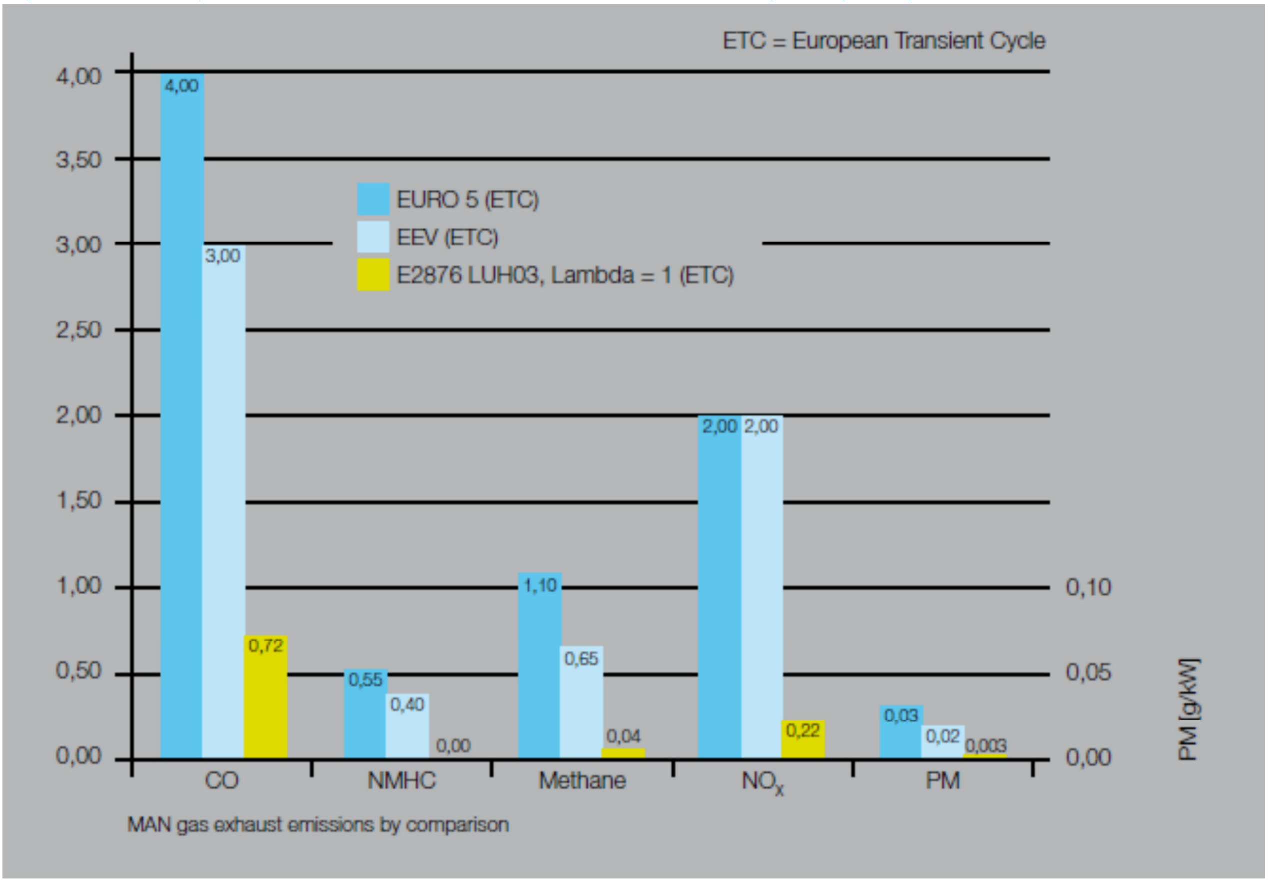
There are two basic methods of fuelling CNG vehicles: slow fill and fast fill. Slow fill systems take gas directly from the compressor into the vehicle. The refuelling time for a large vehicle can be in excess of three hours, but slow fill systems may be suitable for bus operations where vehicles can be refuelled overnight. Fast fill systems use compressors and cascade fuel storage tanks and can refuel vehicles in times similar to diesel powered vehicles.

2.4.3 Vehicle Emissions

Emissions data enabling a direct comparison to be made between biomethane buses and diesel vehicles of the same Euro standard is not readily available and the data we have found shows some large variations in air quality emissions performance for heavy vehicles relative to a Euro IV diesel vehicle. However, the general picture is that emissions of both oxides of nitrogen (NOx) and particulates (PM) are typically significantly lower for CNG buses than comparable diesel vehicles.

Figure 2.14 shows the emissions performance of the MAN E2876 LUH03 gas engine used to power both 12m rigid and 18m articulated buses relative to the Euro V and EEV emissions standards. An updated version of this chart published by MAN in January 2012 shows that this performance also comfortably exceeds the latest Euro VI standard of 4.0g/kWh Carbon Monoxide (CO), 0.16g/kWh Non Methane Hydrocarbons (NMHC), 0.5g/kWh Methane, 0.46g/kWh NOx and 0.01g/kWh Particulates (PM).

Figure 2.14: Comparison of exhaust emissions for MAN E2876 LUH03 gas engine against Euro V and EEV standards



Source: MAN Truck and Bus

In overall terms, CNG buses are comfortably the cleanest vehicles powered by an internal combustion engine available for urban bus operations and continue to better the emissions performance of the latest Euro VI diesel engines.

2.4.4 Vehicle Availability

There are large numbers of natural gas powered buses operating worldwide, notably in China, India, Russia, the USA and several Western European countries with, prior to 2012, the notable exception being the UK.

Mercedes, Volvo, Scania, Iveco, Cummins Westport and MAN have all developed CNG engines for use in trucks and buses. Both MAN and Scania are now offering new build gas buses with spark ignition engines in right hand drive configuration suitable for use in the UK. The Scania / Alexander Dennis Enviro300SG vehicle only has around 40 unique parts compared to the standard diesel version of the Enviro300.

At least MAN and Volvo currently offer gas powered articulated buses for European markets and it is probable that manufacturers would be willing to offer right hand drive versions if there was the prospect of a substantial order for such vehicles for operation in the UK.

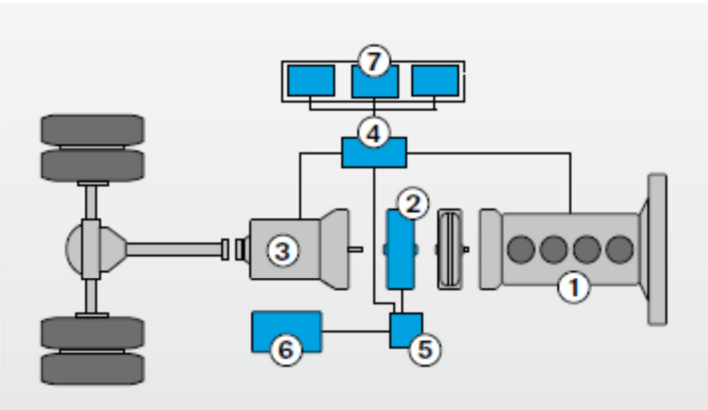
Case studies of the replacement of a complete diesel bus fleet by CNG buses, including some articulated vehicles in Frankfurt Oder, Germany and the use of CNG buses in Norfolk and Suffolk by Anglian Bus are included in **Appendix A**.

2.5 Hybrid Vehicle Technology

Hybrid vehicles provide an alternative step between internal combustion and electric power by providing two forms of propulsion that operate either independently of each other or in tandem.

The engine and batteries of hybrid buses may be designed and configured to operate in series or parallel. Series hybrids have the engine engaged at all times to charge the battery, which powers the wheels via an electric motor. Parallel hybrids can deliver propulsion from the engine or batteries or both at the same time.

Figure 2.15: Parallel Hybrid Driveline



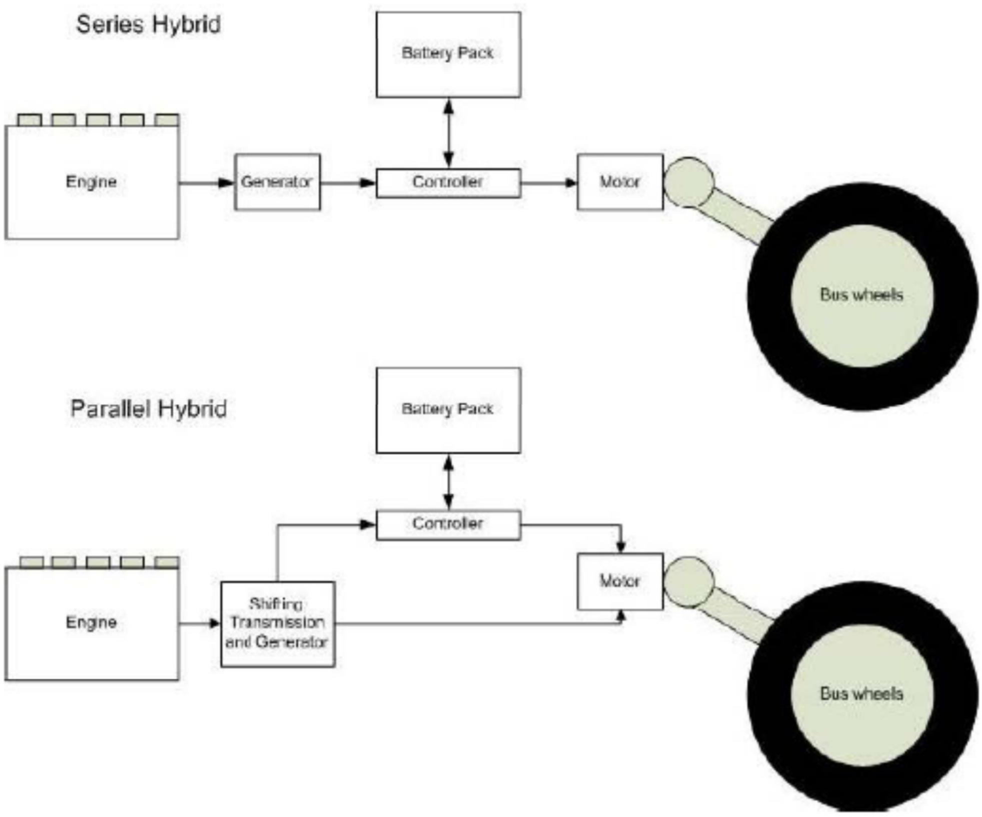
Key

1. Diesel engine
2. Electric motor/generator
3. Transmission
4. Electronic control unit
5. Energy converter 600V DC to 24V DC
6. Battery pack
7. Electrified auxiliary systems

Source: Volvo Bus

The simplified diagrams of series and parallel hybrid drivelines in Figure 2.16 highlight how these differ.

Figure 2.16: Comparison of Series and Parallel Hybrid Drivelines



Source: Transport for London

- In a series hybrid there is no mechanical link between the engine and drive axle. The engine powers a generator that charges the battery pack. The battery pack drives an electric motor that turns the bus wheels via a conventional rear axle.
- In a parallel hybrid the engine powers the drive axle and a generator that can either charge the battery pack or directly drive the axle.

The series hybrid approach typically utilises a smaller engine coupled with a larger battery relative to parallel hybrids. As the engine is not mechanically coupled directly to the drive axle it can run at a steady speed. Manufacturers promoting this approach claim that it is more suited to the low speed start-stop nature of city bus operation, but there is emerging evidence from the operation of significant numbers of buses employing both approaches that parallel hybrid designs are delivering better real world fuel economy.

The internal combustion engine of a hybrid bus is typically smaller than that required in a conventional bus as it is not the sole driving force of the vehicle. The engine capacities of hybrid buses operating in London range from 1.9 to 6.7 litres, with the majority in the range 4.5 to 5.0 litres.

Hybrid vehicles offer substantial emissions benefits, with manufacturers claiming significant improvements in fuel economy of 30 to 40% versus equivalent diesel buses.

Extensive testing of hybrid buses undertaken by Transport for London has confirmed that they produce fewer greenhouse gas emissions, harmful pollutants and lower noise levels compared with diesel buses, with the following results cited:

- 30 per cent reduction in fuel use;
- 30 per cent reduction in Carbon Dioxide;
- 3 dB(A) reduction in perceived sound levels;
- Reduced oxides of Nitrogen and Carbon Monoxide.

As the engine of a hybrid vehicle is used to recharge the batteries there is no need for a dedicated recharging infrastructure.

The first hybrid buses produced were diesel hybrids, but hybrid propulsion technology has subsequently been developed for vehicles powered by other fuels including hydrogen and natural gas.

Hybrid buses were first introduced in the UK by Transport for London in 2006. The Department for Transport's Green Bus Fund, offering capital grants towards the additional cost of Low Carbon Emission Buses relative to comparable diesel powered buses has encouraged vehicle manufacturers including Alexander Dennis, Optare, Volvo and Wrightbus to develop a range of diesel hybrid single and double deck buses for production for the UK market.

A Low Carbon Emission Bus (LCEB) is defined as a bus that is capable of achieving the LCEB target for greenhouse gas (GHG) emissions, which is equivalent to a 30% reduction in its GHG emissions compared to the average Euro III diesel bus of the same total passenger capacity. LCEBs also need to meet Euro V or better emissions standards.

Of the 990 low carbon buses part-funded through rounds one to three of the Green Bus Fund between 2009 and 2012, 912 have been diesel hybrid vehicles. During 2013 grants were offered through round four of the Green Bus Fund for a further 151 diesel hybrid vehicles.

There are no diesel hybrid articulated buses currently operating in the UK, but Wrightbus have developed a hybrid version of their Streetcar articulated bus, with a fleet of 50 in service on two BRT routes in Las Vegas, USA. European vehicle manufacturers offering diesel hybrid articulated buses include Mercedes, Solaris, Van Hool and Volvo.

Figure 2.17: Volvo 7900 Articulated Parallel Hybrid Bus

Source: Volvo Bus

Operators' concerns about battery life on hybrid buses have been addressed by manufacturers typically offering a five year warranty on the vehicle battery pack with the option of monthly contract payments to cover any form of battery repair or replacement until the end of the vehicle's lifecycle. Unlike a pure battery electric bus the battery of a hybrid bus is continually or frequently recharged by the engine, avoiding the battery becoming discharged to a degree that will compromise its performance and economic life.

It is probable that hybrid drivelines will become increasingly common in the near future for urban buses; however there will also be also be a mix of vehicle types including pure electric vehicle technology. Hybrid vehicle technology is thus a potential feature of vehicles powered by both diesel and a range of alternative fuels, rather than a unique sub mode in its own right.

A case study of the introduction of a fleet of 20 diesel hybrid articulated buses in Flanders, Belgium is included in **Appendix A**.

2.6 Plug-in Hybrid Technology

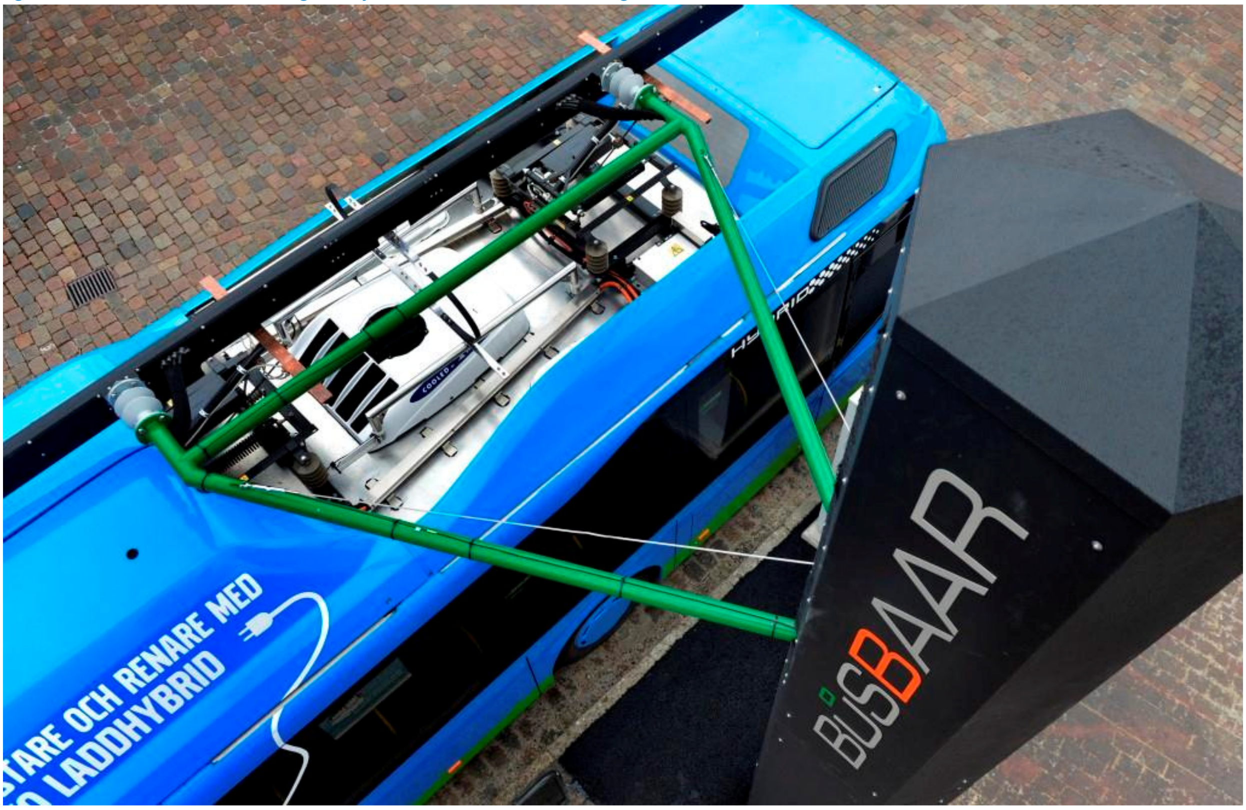
The latest development in hybrid passenger vehicle technology is the plug-in hybrid bus. The Volvo 7900 plug-in hybrid bus commenced field testing in Gothenburg in May 2013. This vehicle is a development of the existing Volvo 7900 parallel hybrid vehicle with a pantograph type collector installed on the roof to enable the battery to be charged directly from the electricity grid. The plug-in bus also has a larger battery package, making it possible to drive for approximately 7 km at a time using electricity only. Current field tests involve top-up charging of the batteries for between six and ten minutes at each terminus. The three vehicles currently operation in Gothenburg are 12m rigid buses, but Volvo Bus have published a product roadmap indicating that an 18m articulated version of the 7900 plug-in hybrid bus is also planned.

Figure 2.18: Volvo 7900 Plug-in Hybrid Bus

Source: Volvo Bus

Volvo claim that the plug-in technology will facilitate the reduction of fuel consumption and carbon dioxide by 75 to 80% compared with current diesel buses, with total energy consumption reduced by approximately 60%. Production for European markets including Sweden, Germany and the UK is planned for late 2015.

Figure 2.19: Volvo 7900 Plug-in Hybrid Bus: Detail showing roof mounted current collector



Source: Opbrid

2.7 Converging Technology

Our research has identified an emerging trend since 2009 for the convergence of technology across the sub modes considered in this study such that some sub mode choices are becoming increasingly blurred. Examples of this trend include:

- A trend towards the adoption of hybrid drivelines as the norm for urban buses. Volvo Bus has announced plans to cease the production of conventional diesel powered city buses from 2014.
- Convergence between a modern trolleybus with fast charging capability to reduce or eliminate the need for overhead wires and a battery electric vehicle with fast charging capability to provide the range sufficient for all day operation, leading to a dual mode electric bus.
- Convergence between a trolleybus with an auxiliary internal combustion engine and a plug-in hybrid with fast charging capability from an overhead charging station, capable of operating on electric power over a substantial proportion of an urban bus route.

- The multi-propulsion platform concept for urban public transport vehicles enabling a vehicle with the same basic structure and many common design features to be configured in various versions such as a trolley, internal combustion hybrid, fuel cell hybrid or full electric bus.

- The future potential for vehicles to be built with one form of propulsion module but with provision for conversion to a different form of propulsion halfway through their life where the life of the vehicle platform significantly exceeds the life of the original propulsion system and there is an opportunity to take advantage of more efficient alternative propulsion technologies which have become proven in service since the vehicle was originally built.

3 Comparison of Sub Modes

3.1 Vehicle Characteristics

This section discusses and compares the typical vehicle characteristics of a range of current products identified for each sub mode. This information has been sourced from trade brochures and technical specifications, supplier presentations and press material. It should be noted that there are variations in vehicle specifications within each sub mode and these will change to suit different local requirements and duty cycles, and as technology develops. A summary table providing vehicle specification and performance data for selected vehicle types within each sub mode appears at the end of this section, with further detailed information in **Appendix B**.

To aid comparison between sub modes we have as far as possible used specification data for single deck single-articulated vehicles circa 18m in length. The exception is battery electric vehicles as the largest battery electric buses currently available are rigid vehicles 11 to 12m in length and no production battery electric articulated bus currently exists. However, manufacturers' published roadmaps for future product development indicate that such vehicles are likely to become available in the near future and plans have been announced for the operation of 18m battery electric buses in Braunschweig, Germany and Barcelona, Spain commencing during 2014.

3.1.1 Propulsion System

The propulsion systems for the seven sub modes under consideration range from pure electric systems (trolleybus, battery electric) through hybrid systems with conventional and/or electric final drive to the wheels (standard diesel hybrid, plug-in diesel hybrid and fuel cell hybrid) to an internal combustion and conventional gearbox (CNG bus).

3.1.2 Performance

All sub modes are potentially capable of achieving similar maximum speeds of circa 70-80 kph (43-50 mph) but differences in acceleration and braking performance between sub modes will impact on overall journey times and are therefore a factor that should influence sub mode choice.

The trolleybus, particularly where fitted with super-capacitors to aid rapid acceleration, stands apart from the other sub modes in terms of potential to achieve the highest commercial speed of operation. A vehicle powered from overhead wires can use this performance to the full without compromising its range and this will be particularly beneficial on routes with significant gradients.

Technical data for the fleet of super-capacitor equipped Solaris articulated trolleybuses operating in the town of Eberswalde, Germany quotes the maximum acceleration rate of these vehicles as 1.4 m/s^2.

A pure battery electric bus has the potential to achieve similar acceleration and braking performance to a trolleybus, with maximum torque available from a standing start, but the full use of this potential is likely to compromise vehicle range and battery life unless frequent opportunities for top-up charging are available.

Technical data for the fleet of 12 Siemens-Rampini battery electric buses operating in Vienna, Austria quotes the maximum speed of these vehicles as 62 kph (39 mph). This is unlikely to compromise the commercial speed of the city centre route for which these vehicles were specifically designed, but would be a limiting factor on routes where there is potential to operate at higher speeds.

All sub modes other than the CNG bus have electric final drive to the wheels and thus the potential to employ regenerative braking.

3.1.3 Propulsion Noise and Vibration

The availability of quantitative information from independent sources to inform a comparison of noise emissions for each sub mode is limited.

Diesel buses typically produce noise at levels between 80 and 90 decibels, depending on vehicle and engine size, with new vehicles at the bottom end of this range. There is a maximum permitted sound level of 89 dBA for UK buses with more than 12 seats within the Road Vehicles (Construction and Use) Regulations (as amended) 1986. CNG vehicles are typically slightly quieter than diesel buses at around 75 decibels.

There is evidence from London and Stockholm that both diesel hybrid and gas buses are likely to offer noise reduction benefits relative to conventional diesel buses.

- Transport for London report a 3 dBA reduction in perceived noise levels for their hybrid bus fleet compared with current diesel buses.
- The City of Stockholm reports that their biogas buses generate 3-5 dBA less noise than their diesel buses.

Vehicles with entirely electric drivelines and no internal combustion engine still generate some transmission noise but are typically quieter again than diesel hybrid and gas buses. A range of 60 to 70 decibels is reported for a trolleybus. The absence of an internal combustion engine and conventional gearbox should also contribute to a reduction in vibration.

Recorded noise levels from the operational trial of a battery electric bus in Rotterdam are:
- Internal <67dB
- External <73dB

Table 3.1 summarises this information and places each of the sub modes on a qualitative scale from highest to lowest.

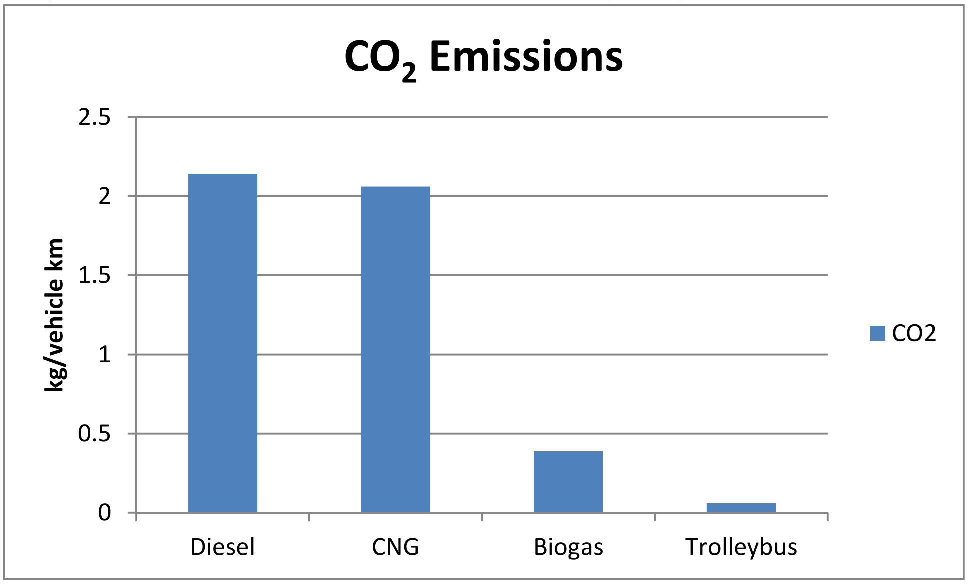
Table 3.1: Noise Comparison of Sub Modes

Noise emissions	Sub mode
Highest	Diesel
	Diesel hybrid
	CNG
	Plug-in hybrid
	Fuel cell hybrid
Lowest	Battery electric Trolleybus

3.1.4 Emissions

Figures 3.1 to 3.3 provide a comparison of the emissions performance of articulated buses powered by diesel, fossil CNG, biogas and electricity (trolleybus). This data was presented by the Zürich public transport operator VBZ at a recent European workshop and represents the results of a system analysis undertaken to compare the performance of vehicles using different propulsion systems on the same two routes under consideration for conversion to trolleybus operation. Fuel cell and diesel hybrid buses were not included in the evaluation.

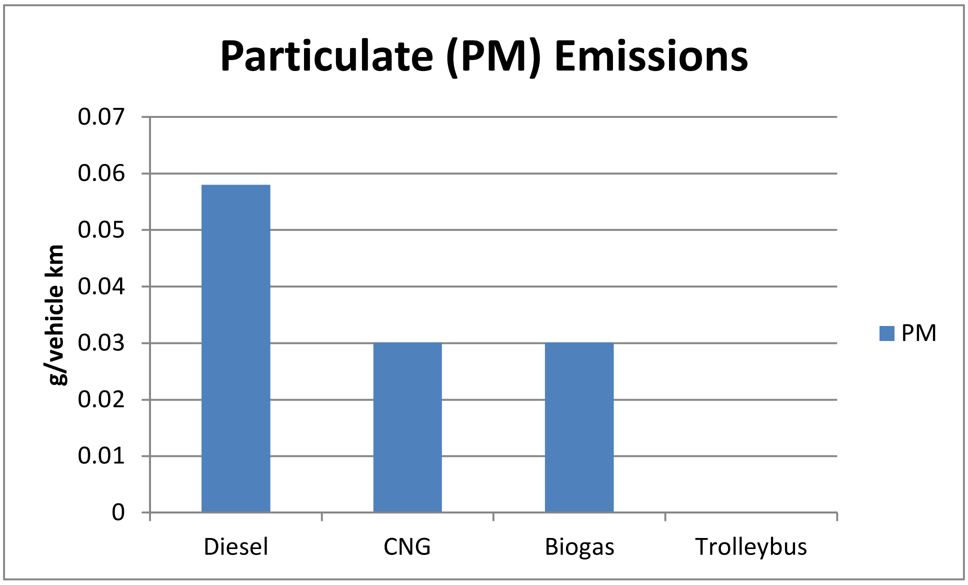
Figure 3.1: Comparison of CO_2 Emissions from 18m Articulated Bus (Zürich)



Source: VBZ

The CO_2 emissions comparison demonstrates the beneficial impact of using biogas compared with fossil fuels. In this case the CO_2 emissions for the trolleybus are only 15% of those for the biogas bus, but this reflects the use of 100% renewable electricity from hydropower by the trolleybus. The CO_2 emissions performance of both biogas bus and the trolleybus will vary significantly according to the energy pathway.

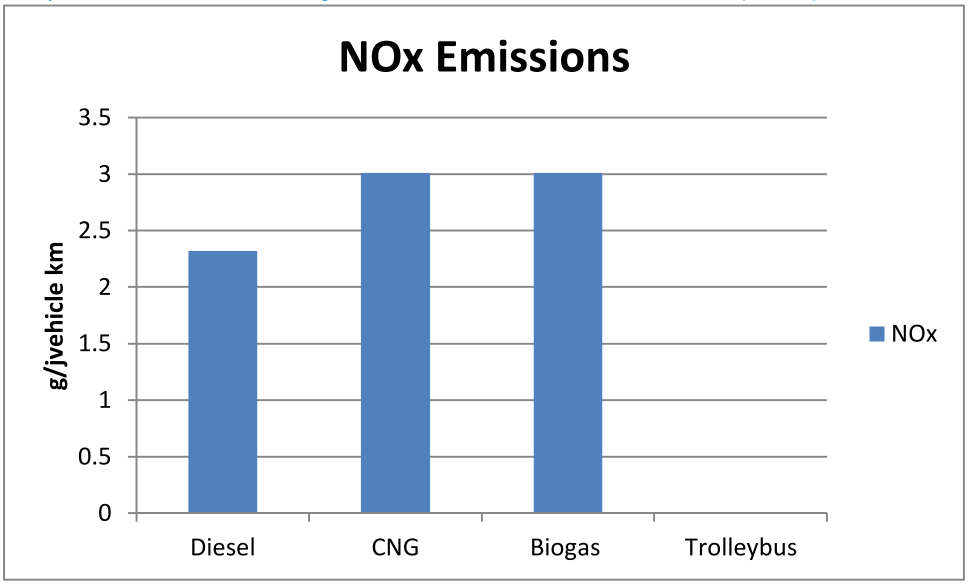
Figure 3.2: Comparison of Particulate Emissions for 18m Articulated Bus (Zürich)



Source: VBZ

The comparison of particulate emissions demonstrates the beneficial impact of using CNG or biogas compared with diesel, but also highlights the fact that the trolleybus produces zero emissions.

Figure 3.3: Comparison of Oxides of Nitrogen Emissions for 18m Articulated Bus (Zürich)



Source: VBZ

The comparison of oxides of Nitrogen (NOx) emissions shows that in this case NOx emissions for CNG and biogas are higher than for diesel, although this is at variance with data from vehicle manufacturers showing NOx emissions from CNG engines relative to diesel engines of the same Euro standard. Again the zero emissions performance of the trolleybus is highlighted.

A literature search conducted for an independent study comparing emissions for all of the sub modes under consideration for NGT revealed a report for the Low Carbon Vehicle Partnership entitled '*Preparing a low CO_2 technology road map for buses'* (Ricardo plc, July 2013).

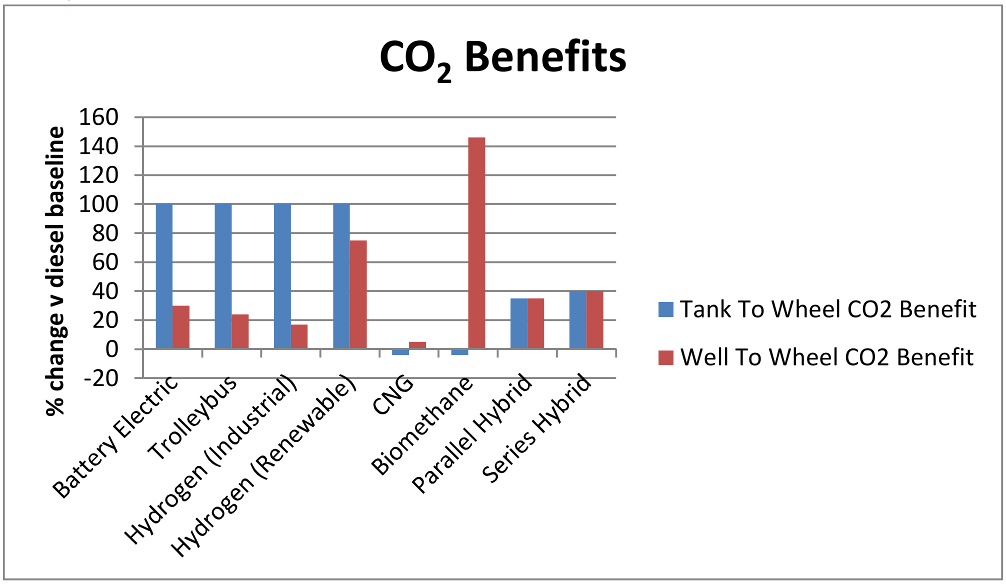
The purpose of this study was to identify the low carbon technologies for UK urban buses that could achieve greenhouse gas savings of greater than 2% relative to a Euro V diesel bus baseline, and to develop a technology roadmap to illustrate when these technologies are likely to be deployed into the bus market.

The study considers CO_2 benefits in terms of both well to wheel and tank to wheel emissions.

- The well to wheel (WTW) CO_2 emissions of a particular activity captures the CO_2 emitted during fuel/electricity production, distribution and vehicle use;
- Tank to wheel (TTW) or tailpipe CO_2 emissions refers to CO_2 emissions directly from the vehicle as a result of combustion of fuel.

The Ricardo report includes a comparison of potential WTW and TTW CO_2 emissions relative to the diesel bus baseline for all of the powertrain technologies and alternative fuels relevant to the sub modes under consideration. This is summarised in Figure 3.4.

Figure 3.4: Comparison of Well to Wheel and Tank to Wheel CO_2 Benefits of Alternative Fuels v Diesel Baseline



Source: Preparing a low CO_2 technology roadmap for buses, Ricardo plc, July 2012

The key points from this comparison are:

- Battery electric, trolleybus and fuel cell buses can all deliver a 100% reduction in TTW CO_2 relative to the diesel baseline, but WTW benefits vary significantly with the fuel type and energy pathway.
- The potential WTW CO_2 benefits for the battery electric and trolleybus sub modes depend on electricity production methods. The reductions of 24% for trolleybus and 30% for battery electric are based on the current UK grid mix (164 g CO_2eq/MJ). These figures could be improved significantly through the use of electricity from renewables or future decarbonisation of the UK grid.
- The higher potential reduction in WTW CO_2 for battery electric relative to trolleybus is not explained, but is presumed to derive from assumed higher energy efficiency for the battery electric vehicle.
- The WTW CO_2 benefits for a hydrogen powered fuel cell bus are lower than the electrically powered sub modes unless the hydrogen fuel is formed through the electrolysis of water powered by renewable electricity.
- The use of fossil CNG offers only marginal reductions in WTW CO_2 emissions relative to a diesel bus and may generate an increase in TTW CO_2 emissions.
- The use of biomethane has the greatest potential to deliver a reduction in WTW CO_2 emissions relative to diesel bus. The 146% reduction assumes the use of biomethane produced by anaerobic digestion in a dedicated plant, using animal/agricultural waste as a feedstock.
- The potential CO_2 benefits of hybrid buses are derived from a reduction in diesel fuel consumption and thus the WTW and TTW reductions are the same?
- Series hybrid technology is considered to offer greater potential for regenerative braking than parallel hybrid technology.

3.1.5 Passenger Capacity

All of the sub modes under consideration other than battery electric are currently available as single deck single-articulated vehicles circa 18m in length. Pure battery electric buses are not currently available in an 18m articulated form.

The potential passenger capacity of each of the sub modes is therefore similar as all involve the use of vehicles with similar external dimensions and useable internal passenger space. However, in practice the additional unladen weight of battery electric and fuel cell vehicles relative to the other sub modes may impose some greater limitations on total passenger capacity to ensure that the maximum gross vehicle weight remains within legal limits. These are likely to be in the form of a reduction in the number of permitted standing passengers. There is also the possibility of the interior space within battery electric buses being compromised by the space taken up by battery packs, but solutions adopted to mitigate this include mounting battery enclosures over the front wheel arches and on the roof of vehicles.

It is difficult to clearly identify variations in passenger capacity between similar vehicle designs from different manufacturers as the capacities quoted in manufacturers' brochures are often based on different door and seating configurations, with the provision of fewer seats increasing the overall capacity of the vehicle by providing more space for standing passengers. Capacity information for selected vehicle types within each sub mode is provided in **Appendix B**, but it should be noted that these figures may not represent directly comparable seating layouts or calculate standing capacity on the same basis.

In summary, 18m articulated battery electric and fuel cell vehicles are likely to have a lower potential total passenger capacity than the other sub modes due to the additional weight of their propulsion systems, but passenger capacity will not be a determining factor between trolleybus, diesel hybrid and CNG.

3.1.6 Ride Quality

The ride quality of the vehicle is taken to be the interaction between the vehicle and the road surface and includes the suspension system, tyres etc. of the vehicle. The overall passenger journey experience is influenced by both the ride quality and the noise and vibration of the vehicle, as well as other factors such as seating and on-board facilities. It should be noted that the noise and vibration of the various modes is included in section 3.1.3.

The trends for development of common vehicle platforms with alternative power / fuel options and move towards electric hybrid drivelines for diesel and gas powered vehicles is expected to result in a convergence between the level of ride quality offered by the alternative sub modes under consideration.

The use of common vehicle platforms and suspension components across sub modes means that ride quality is more likely to be influenced by the infrastructure on which the vehicles are operating than the characteristics of the vehicle itself.

We have not identified any significant differences in vehicle-related ride quality between the sub modes under consideration, excluding issues of noise and vibration which are dealt with in section 3.1.3.

3.1.7 Dimensions

The maximum authorised dimensions for buses that can travel freely on UK roads are:
- Width – 2.55m
- Length – 18.75m
- Height – 4.57m

Table 3.2: Maximum authorised length for buses operating on UK roads

Class of vehicle	Maximum length (metres)
Bus with two axles	13.5
Bus with three axles	15.0
Articulated bus	18.75

Source: The Road Vehicles (Construction and Use) (Amendment) Regulations 2003

Full size buses of all sub mode types considered in this study are typically built to widths of between 2.49m and 2.55m.

Rigid single deck buses of all sub mode types other than battery electric vehicles are most commonly built to a length of 12m or just under on two axles or between 13.5m and 15m on three axles.

Articulated single deck buses of all sub mode types other than battery electric vehicles are typically between 17.9m and 18.75m in length.

The longest battery electric buses currently in production are 12m in length. The UK-built Optare Versa EV is slightly shorter at 11.1m. Pure battery electric buses are not currently available in 18m articulated form.

The main area where the dimensions of vehicles vary between the sub modes considered in this study is overall height. This is due to differing requirements for the mounting of equipment on the roof of the vehicle.

Trolleybuses require roof-mounted electrical equipment including the trolley poles. On fuel cell hybrid buses the hydrogen tanks, super-capacitors (where fitted) and in some cases, the fuel cell system itself, are roof-mounted. CNG buses require roof-mounted tanks to carry methane in sufficient volume to give them the necessary range. The Volvo plug-in hybrid has roof-mounted pantograph charging equipment and some designs of standard hybrid bus also have roof-mounted electrical equipment. Pure battery electric buses may be fitted with a roof-mounted battery enclosure, but where this is not the case will be similar in height to the equivalent diesel buses.

Table 3.3: Typical single deck vehicle heights by sub mode

Sub mode	Overall height range (m)
Trolleybus	3.400 – 3.685
Diesel hybrid	2.754 – 3.280
Plug-in hybrid	TBC (but expected to be similar to trolleybus)
Fuel cell hybrid	3.200 – 3.688
Battery electric	2.820 – 3.250
CNG	3.356

Source: Manufacturers' technical specifications

3.1.8 Weight

The weight of the vehicle has an overall impact on propulsion efficiencies. In short the greater the vehicle weight the greater effort is required to move the vehicle and therefore the overall efficiency of the vehicle will be less than for a lighter weight option. Therefore a lighter vehicle weight is generally beneficial to energy consumption. However depending upon the bus mode it may be beneficial to trade some extra weight for a more energy efficient propulsion option.

The maximum gross vehicle weight limits for buses operating on UK roads are 18,000 kg for a rigid bus with two axles and 26,000 kg for an articulated bus with three axles.

Any bus type approved or otherwise certified for use in the UK will have a maximum legal passenger capacity that reflects these limits and the unladen weight of the vehicle. Fuel cell and battery electric buses typically have higher unladen weights than the other sub modes under consideration. This may adversely affect passenger capacity relative to other sub modes, but differences are likely to be in the form of a reduction in the number of permitted standing passengers.

The 12m BYD ebus battery electric vehicles for London are type approved at an unladen weight of 13,800 kg, of which the traction battery packs account for 3,024 kg. These vehicles are certified for 21 seated and 41 standing passengers, a total of 62. This is nominally less than the legal maximum capacity of a comparable 12m diesel bus, but the practical capacity of both vehicles in terms of physical space available is closer to 50.

The first generation of 12m Mercedes Citaro fuel cell buses for London operating during the CUTE project had an unladen weight of 14,000 kg. The 12m VDL SB200 fuel cell hybrid buses currently operating in London are significantly lighter at 10,350 kg unladen, in part because their improved fuel efficiency has enabled the number of hydrogen tanks to be reduced, but still considerably heavier than the equivalent diesel-powered SB200.

The 18m APTS Phileas fuel cell hybrid articulated bus has an unladen weight of 20,590 kg. This compares unfavourably with less than 17,000 kg for a typical diesel powered 18m articulated bus. The Phileas buses operating in Cologne in three door configuration have a total passenger capacity of 96 (37 seats, 1 wheelchair space, 58 standing). This is at the bottom end of the expected range for an 18m articulated bus and suggests that the passenger capacity may be compromised by the weight of the propulsion system.

3.1.9 Additional Equipment

A wide range of additional equipment is available for original fitment by vehicle manufacturers across all sub modes. This includes, but is not limited to the following items:

- Air conditioning/air chill to drivers cab area;
- Air conditioning/air chill throughout vehicle;
- Double glazing;
- Radio/media player/public address system;

- On-board Wi-Fi system;
- Leather (or ‘E-Leather’) seats;
- High back coach-style seats;
- Wiring loom for on-board display screens/electronic signage/next stop display (potential for audio next stop announcements);
- Integrated CCTV systems covering both exterior and interior of vehicle.

3.2 Operations

The service pattern and frequency is assumed to be the same for all sub modes and the comparison is thus limited to considering the impacts of differences in vehicle performance, capacity and charging requirements on fleet size. The baseline service pattern and frequency are assumed to be as calculated below, generating a combined peak vehicle requirement (PVR) of 15.

Bodington to Stourton

- 12 minute headway
- 72 minutes round trip time + 2 x 5 minute layovers rounded to headway = 84 minutes
- PVR for 12 minute headway is 84/12 = 7

Holt Park to Stourton

- 12 minute headway
- 86 minutes round trip time + 2 x 5 minute layovers rounded to headway = 96 minutes
- PVR for 12 minute headway is 96/12 = 8

The fleet size for battery electric vehicles will need to be higher than for all other sub modes to allow for the additional time that will be required within duty cycles for recharging on arrival at each terminus. The scheduled layover time included in the cycles set out above cannot be relied upon for recharging. Assuming 10 minutes is required for recharging at each terminus in addition to 5 minutes recovery time, the operating cycles would be:

Bodington to Stourton

- 12 minute headway
- 72 minutes round trip time + 2 x 5 minute layovers + 2 x 10 minutes for recharging rounded to headway = 108 minutes
- PVR for 12 minute headway is 108/12 = 9

Holt Park to Stourton

- 12 minute headway
- 86 minutes round trip time + 2 x 5 minute layovers + 2 x 10 minutes for recharging rounded to headway = 120 minutes
- PVR for 12 minute headway is 120/12 = 10

Based on the above assumptions the battery electric sub mode would require an additional 4 vehicles (combined PVR of 19 compared with baseline of 15) to provide the same level of service as the other sub modes.

The plug-in hybrid sub-mode will also require recharging on arrival at each terminus to ensure it can operate in zero emission mode on sensitive sections of route on every journey. However, in this case it is assumed that only 7.5 minutes is required for recharging at each terminus in addition to 5 minutes recovery time. With this assumption, the operating cycles would be:

Bodington to Stourton

- 12 minute headway
- 72 minutes round trip time + 2 x 5 minute layovers + 2 x 5 minutes for recharging rounded to headway = 96 minutes
- PVR for 12 minute headway is 96/12 = 8

Holt Park to Stourton

- 12 minute headway
- 86 minutes round trip time + 2 x 5 minute layovers + 2 x 5 minutes for recharging rounded to headway = 108 minutes
- PVR for 12 minute headway is 108/12 = 9

Based on the above assumptions the plug-in hybrid sub mode would require an additional 2 vehicles (combined PVR of 17 compared with baseline of 15) to provide the same level of service as the other sub modes.

In addition, the fleet size for a catenary free electric bus may need to be higher than for a trolleybus with OLE if additional stops are required for charging on route, or the dwell time at existing stops has to be increased relative to that required for boarding and alighting only with other sub modes to allow sufficient time for charging. However, if it is assumed that the performance of the catenary free electric bus operating in Shanghai can be replicated or bettered in Leeds, such that vehicles can run for a distance of approximately 1.5 km between each recharge, the fleet size for a trolleybus with OLE and a catenary free electric bus should be the same.

3.3 Power Usage and Efficiency

Table 3.4 shows the power source or fuel type for each of the sub modes.

Table 3.4: Power Source/Fuel

Sub Mode	Power source / Fuel
Trolleybus with OLE	Electricity
Catenary Free Electric Bus	Electricity
Fuel Cell Hybrid	Hydrogen
Diesel Hybrid	Diesel
Plug-in Hybrid	Diesel/Electricity
Battery Electric	Electricity
Compressed Natural Gas (CNG)	Biomethane from waste

3.3.1 Energy Conversion Efficiency

Tables 3.5 and 3.6 present the results of the desk research undertaken into the relative energy conversion efficiency of each of the sub modes. Our research has found directly comparable energy efficiency data for some but not all sub modes. In order to present data for all sub modes the figures presented come from a range of sources and thus may not represent directly comparable vehicles or operating conditions.

The energy consumption of vehicle heating, ventilation and air conditioning (HVAC) systems can represent a significant proportion of the total vehicle energy consumption and thus data for vehicles operating in warm or cold climates will not be comparable with that for vehicles operating in more temperate conditions requiring less use of HVAC systems.

For comparison purposes data has been presented in a common unit of kWh per 100km distance travelled.

Table 3.5 compares the energy efficiency of 12m rigid buses. Data from three sources, including an independent test, indicates that the battery electric bus is the most energy efficient sub mode, followed by the trolleybus. However, all of the electrically powered sub modes are significantly more energy efficient than the hybrid sub modes, which are in turn almost twice as efficient as the sub modes powered by internal combustion engines. CNG buses are the least energy efficient of all the sub modes and less efficient than a conventional diesel bus which is included for comparison.

No data has been found to verify the energy savings that can be achieved by fitting super-capacitors to a trolleybus, but we have conservatively assumed savings of 10% relative to a modern trolleybus operating on a fully wired system with regenerative power feedback to the OLE. Applying this assumption to the Landskrona data for a 12m trolleybus gives an estimated energy efficiency of 162 kWh/100km for a 12m trolleybus with super-capacitors.

Table 3.5: Energy Efficiency Comparison for 12m Buses

Sub-mode	Energy Efficiency (kWh/100km)	Source	
Trolleybus	180	Trolleybus Landskrona	Operator
Trolleybus (with super-capacitors)	162	Mott MacDonald	Estimate
Fuel Cell Hybrid	269	First London	Operator
Diesel Hybrid	283	Volvo Bus	Manufacturer
	380	e-Busz (Rotterdam)	Operational test
Plug-in Hybrid	260	e-Busz (Rotterdam)	Operational test
Battery Electric	119	TNO	Independent test
	130	BYD (London)	Manufacturer
	140	e-Busz (Rotterdam)	Operational test
	140	Volvo Bus	Manufacturer
Compressed Natural Gas (CNG)	655	Volvo Bus	Manufacturer
Diesel	500	Volvo Bus	Manufacturer

Table 3.6 compares the energy efficiency of 18m articulated buses. The broad picture is similar to that for the 12m buses, with the electrically powered sub modes being the most efficient, followed by the hybrid modes with the fuel cell hybrid performing marginally better than the diesel hybrid and CNG again being the least energy efficient of all the sub modes and less efficient than a conventional diesel articulated bus.

There is no data for the plug-in hybrid and battery electric sub modes in this table as no production 18m articulated vehicles currently exist for these sub modes.

Table 3.6: Energy Efficiency Comparison for 18m Articulated Buses

Sub-mode	Energy Efficiency (kWh/100km)	Source	
Trolleybus	264-402	ATM Milan	Operator
	230	VBZ Zürich	Operator
	195	Arnhem	Operator
Trolleybus (with super-capacitors)	338-343	BBG Eberswalde	Operator
Fuel Cell Hybrid	504	ELTIS (Cologne)	Operator
Diesel Hybrid	523	CIVITAS (Ghent)	Operator
Plug-in Hybrid	No data	-	-
Battery Electric	No data	-	-
Compressed Natural Gas (CNG)	735	ELTIS (Frankfurt am Oder)	Operator
Diesel	624	CIVITAS (Ghent)	Operator

The Eberswalde data is from a test of two vehicles over a whole day of operation on 11 January 2013 in temperature conditions of -3°C. The energy used for heating of the vehicles was between 133 and 140 kWh/100km. If the heating energy is deducted from the total, the propulsion energy efficiency is within the range 199 to 209 kWh/100km. This is similar to the Arnhem and Zürich figures. The Zürich trolleybus system has significant gradients which will impact on power consumption.

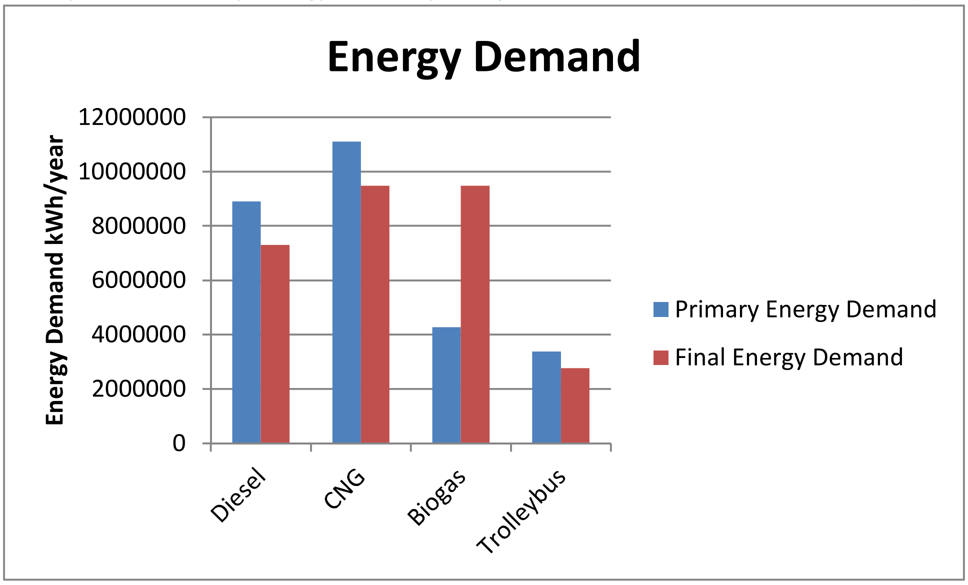
Table 3.7 and Figure 3.5 provide a comparison of the energy efficiency of articulated buses powered by diesel, fossil CNG, biogas and electricity (trolleybus). This data was presented by the Zürich public transport operator VBZ at a recent European workshop and represents the results of a system analysis undertaken to compare the energy demand of fleets of vehicles using different propulsion systems on the same two routes under consideration for conversion to trolleybus operation.

Table 3.7: Primary and Secondary Energy Efficiency Comparison for 18m Articulated Bus Fleets (Zürich)

Sub-mode	Primary Energy Demand (kWh/year)	Final Energy Demand (kWh/year)
Diesel bus	8,908,200	7,298,256
Gas bus (fossil gas)	11,100,600	9,487,733
Gas bus (biogas)	4,271,400	9,487,733
Trolleybus	3,376,800	2,772,000

Source: VBZ

Figure 3.5: Primary and Secondary Energy Efficiency Comparison for 18m Articulated Bus Fleets (Zürich)



Source: VBZ

The final energy demand figures represent the secondary energy consumed by the vehicles. This is the same for fossil gas and biogas. The primary energy demand figures represent the energy contained in the raw fuels, and other forms of energy received as input to systems. The use of biogas significantly reduces primary energy demand relative to diesel and fossil natural gas, but the trolleybus sub mode has both the lowest primary and final energy demand. It should be noted that this analysis is based on the use of 100% renewable electricity generated from hydropower by the trolleybus.

In summary the best performing sub modes in terms of energy efficiency are the electrically powered sub modes of battery electric and trolleybus. As there is no data from the same source to directly compare battery electric and trolleybus the apparent superiority of the battery electric sub mode over the trolleybus should be treated with caution. The difference between the performance of the battery electric and trolleybus sub modes based on the data in Table 3.5 is within the range that can be accounted for by differences in duty cycles and climatic conditions. There is also anecdotal evidence that battery electric vehicles are most energy efficient at low speeds and may not perform as well as the data suggests on more demanding duty cycles with higher cruising speeds and requiring higher acceleration rates.

The already good energy efficiency of trolleybuses and the relatively low historic cost of electricity have until recently provided few incentives to further optimise the energy efficiency of the traditional trolleybus. The consensus amongst experts attending the Clean Fleets workshop held in Bremen on 11/12 December 2013 was that in the same operating conditions any difference between the energy efficiency of a pure battery electric bus and a modern trolleybus employing the latest efficient electric drive technology and fitted with a battery and super-capacitors is likely to be negligible.

While high energy efficiency is generally desirable from a sustainability perspective, this may be considered less important in the case of the CNG sub mode which is assumed to be powered by biomethane produced from waste. As the primary energy source in this case is a renewable resource, the low efficiency of the energy conversion process may be of lesser concern if the cost of biomethane for transport use is lower than alternative fuels.

However, another way of looking at this is to consider alternative uses of biomethane produced from waste. A study by Volvo Bus has shown that it is far more energy efficient to use biomethane to generate electricity and then to use the electricity to power vehicles than to upgrade biomethane for transport use and use it to power vehicles directly. This provides a compelling case to use biomethane for electricity generation rather than as a transport fuel, especially if this results in a reduction in the well to wheel emissions of electric vehicles as a result of a higher proportion of the electricity they consume being generated from renewable sources.

Table 3.8: Energy Efficiency Comparison of Alternative Biomethane Pathways

Biomass > Gasification > Biogas > Gas Bus	Biomass > Gasification > Biogas > Electricity > Electric bus
Well to tank efficiency 54%	Well to tank efficiency 39%
Tank to wheel efficiency 17%	Tank to wheel efficiency 75%
Well to wheel efficiency 9%	Well to wheel efficiency 29%

Source: Volvo Bus

The figures in Table 3.8 indicate that the detour via electricity generation turns out to be more favourable in terms of overall wheel to wheel energy efficiency.

3.4 Infrastructure Requirements

3.4.1 Impact of Vehicle Characteristics on Infrastructure

An assessment has been made of how typical vehicle characteristics for each of the sub modes may impact on infrastructure requirements.

The "multi propulsion platform" is an emerging approach to vehicle design based on the principle of a common vehicle design that can be configured in various environmentally-friendly versions such as a trolleybus, hybrid systems (diesel-electric and CNG-electric), fuel cell hybrid or full electric bus.

The Van Hool ExquiCity vehicle is an example of this concept. This vehicle has been ordered as a trolleybus for Geneva, a biogas powered hybrid for Malmo and a diesel hybrid for Metz.

The impact of the "multi-propulsion platform" approach to vehicle design is likely to be a convergence of sub mode vehicle characteristics, particularly those impacting on general route corridor infrastructure requirements such as vehicle dimensions, swept paths, turning circles and boarding heights.

The main area where vehicle characteristics directly impacting on infrastructure requirements will vary between sub modes is the overall height of vehicles. Trolleybuses, fuel cell hybrid buses and CNG buses are all typically fitted with roof mounted equipment. Some, but not all battery electric and diesel hybrid bus designs have roof-mounted battery enclosures.

3.4.2 Power Source/Fuel Supply

Table 3.9 shows the power source or fuel supply assumed for each of the sub modes from an infrastructure perspective.

Table 3.9: Power Source/Fuel Supply

Sub-Mode	Power source / Fuel supply
Trolleybus with OLE	Electricity from grid supply
Catenary Free Electric Bus	Electricity from grid supply
Fuel Cell Hybrid	Hydrogen delivered to depot by tanker
Diesel Hybrid	Diesel delivered to depot by tanker
Plug-in Hybrid	Diesel delivered to depot by tanker and electricity from grid supply
Battery Electric	Electricity from grid supply
Compressed Natural Gas (CNG)	Natural gas from grid supply
Biogas (CBG)	Biogas injected into grid at point of production

For the purpose of this study it has been assumed that:
- Electricity is from grid connections;
- Hydrogen and diesel are from commercial sources and delivered to the depot by tanker;

- Methane is from a gas grid connection to the depot
- Biomethane is injected into the gas grid at the point of production to offset the use of methane from the grid to fuel vehicles at the depot;
- Power supply to a conventional trolleybus is from an electrified overhead catenary system;
- Power supply to a catenary free electric bus is from charging points at bus stops and termini;
- Power supply to a battery electric bus is via overnight recharging at the depot with top up charging at termini;
- Electrical power supply to a plug-in hybrid bus is via charging points at termini and selected bus stops.

3.4.3 Right of Way

Both on-highway and segregated right of way sections of route will need to be capable of accommodating the geometric and clearance requirements of each sub mode. The trolleybus sub modes will require greater clearances than the other sub modes to allow for the OLE or overhead charging points at bus stops. The battery electric and plug-in hybrid sub modes will require space and clearances sufficient for the installation of charging equipment at termini and for the plug-in hybrid potentially also at selected bus stops.

3.4.4 Stops and Termini

The basic stop requirements for all sub modes will be similar and will reflect the vehicle dimensions, swept path, platform height required to achieve level boarding and passenger numbers to be accommodated.

Where sub modes require the provision of charging points at bus stops, the design and location of the charging point and feeder power supply will require careful consideration to maintain space for passengers and ensure their safety.

In the event of the use of inductive vehicle charging technology involving power transmission from a coil buried in the road, suitable sites for bus stops that are free of existing underground services will be required.

The design of termini for the trolleybus with OLE, catenary free electric bus, battery electric and plug-in hybrid sub modes will require special consideration. Trolleybuses will be able to turn around using auxiliary traction battery power to obviate the need for a turning loop with OLE. Charging points at termini should be designed to allow a bus to overtake a bus that is in the process of being recharged.

Where the NGT service frequency exceeds the recharging time required, for example at the Stourton terminus, it will be necessary to provide two charging points that can be used simultaneously and independently.

3.4.5 Overhead Line Equipment

The trolleybus with OLE sub mode will require an electrified overhead catenary system for power supply to the vehicles. OLE will be required over the majority of the NGT alignment, but not all of it, to the extent that vehicles have the capacity to operate off-wire on traction battery and super-capacitor power.

The capital, maintenance and renewal costs of the OLE are significant but should be weighed against the energy cost savings from use of electric traction power relative to liquid and gaseous fuels. A trolleybus powered by electricity from an OLE system also offers proven levels of performance and reliability that the catenary free electric bus and battery electric sub modes cannot currently match.

The standard trolleybus current collection system consists of two parallel overhead wires with crossings and switches. The trolleybus has two poles, one collector is connected to the overhead power supply wire and the second to the overhead return wire. The trolleybus connects to the overhead wires via a wheel or shoe on the end of the poles, with the wires running in grooves to give a positive connection. Where there are turnouts and crossovers the trolleybus OLE requires frogs to be installed in order to ensure the trolleybus pole follows the correct route with the vehicle.

Figure 3.6: Streetscape with OLE, Lyon

Source: commons.wikimedia.org

There is potential for OLE to be suspended from fixings installed on properties located on each side of the roadway, but where building fixings cannot be accommodated, it will be necessary to use support poles, either with cantilevers or span wires to the traction power lines. These should normally be sited at the back of footway in order to minimise the risk of them being struck by errant vehicles. Where footway widths are of the minimum desirable values then checks need to be made to ensure that further local narrowing due to the siting of poles does not produce unacceptable pinch points.

Where alignments are fully segregated from general traffic, provision should be considered for centre poles between the opposing alignments. However, in some circumstances side poles and span wires may be more appropriate.

Route selection for trolleybuses must consider the headroom required to accommodate the OLE. The Office of the Rail Regulation's (ORR's) Guidance on Tramways, Railway Safety Publication 2, sets out the minimum clearances required. These are also applicable to the OLE of a trolleybus system. Where there are level differences adjacent to the routes, they should be highlighted as it may be necessary to install screening or barriers to prevent access to the wires.

Catenary free electric bus technology offers the potential to reduce overhead wires to short sections, optimally located at bus stops, to act as charging points. Charging points for all of the electrically powered sub modes are discussed below.

3.4.6 Charging Points

For efficient catenary free operation, charging points to top up the super-capacitors on-board the buses are required at regular distance intervals in the catenary free areas. These charging points can be advantageously located at bus stops and may be in the form of either:

- A short length of overhead catenary pick-up wires fed from the traction power underground cable supply network.
- A ground based supply using inductive transfer of power installed under the road surface at the optimum location for the trolleybus (e.g. Bombardier Primove system).

By locating charging points at bus stops, the traction power supply feeding arrangement and other equipment can be incorporated into the bus stop infrastructure and shelter design and the charging time can be matched with the dwell time of the trolleybus at the stop, typically 20-30 seconds. The trolleybus supply poles can be automatically raised and lowered to suit this charging period.

Figure 3.7: Trolleybus Charging Point at Bus Stop, Shanghai

Source: Mott MacDonald

It is essential to consider the operating range of vehicles between charging points and position charging points accordingly, taking into account:

- Distances between bus stops;
- Known traffic ‘bottleneck’ areas, that could cause potentially excessive delays between charging points;
- Road junction technology and priorities for trolleybus operation, e.g. traffic light priority;
- Road gradients; and
- The need to cater for traffic diversions for road works and for special city events.

The unit capital cost of charging stations for a catenary free electric bus system is estimated to be in the region of €200,000.

The plug-in hybrid and battery electric sub modes will also require top-up charging stations, but only at termini or other locations where sufficient time (at least 5 minutes) is available within duty cycles for recharging. Without super-capacitors the vehicle batteries cannot be charged sufficiently rapidly to make charging during normal bus stop dwell times a practical proposition.

Figure 3.8 shows the footprint and clearances required for an overhead fast charging station with its own power supply designed for top-up charging of the batteries on a plug-in hybrid or battery electric bus with a roof mounted pantograph current collector. The unit cost of this type of charging station is estimated to be similar to that for a charging station for a catenary free electric bus system at around €200,000. However, the overall cost of charging infrastructure for these sub modes will be significant lower than for a catenary free electric bus due to the smaller numbers required.

Figure 3.8: Overhead Charging Station for Plug-in Hybrid Bus, Gothenburg

Source: Opbrid

Where longer opportunities for top-up charging of battery electric vehicles exist, for example by removing vehicles from service at termini in rotation outside peak periods, the use of a manual plug-in charging station will be a viable option. Figure 3.9 shows the manual plug-in charging station installed at the Coventry Memorial Park park-and-ride site for top-up charging of the Optare Versa EV battery electric vehicles used to operate the park-and-ride service. This equipment can charge the vehicle batteries to full capacity in less than two hours. The reported cost of this equipment was £58,000.

Figure 3.9: ABB Terra 51 Manual Plug-in Charging Station at Park and Ride Site, Coventry

Source: Route One

3.4.7 Substations

The only sub mode requiring conventional traction supply substations is the trolleybus with OLE. It is considered that the charging units for the electric bus and plug-in hybrid bus would not require sub-stations. Evidence from battery electric vehicle systems in the UK has shown that the electricity supply can be taken from an existing sub-station if needed, although in some locations where distances are greater a small sub-station may be required. The traction power supply and associated cabling and switching for a catenary free electric bus system need only be located at bus stops and could be installed in neighbouring properties within close proximity of stops.

There is potential for substations to be disguised as part of the street furniture, or it may be possible to locate them out of sight in neighbouring properties if space permits.

There is potential to incorporate energy storage units within the design of substations. Early tests carried out in Cologne, Germany by Siemens in the 1990s indicated that this was not economically viable, but this is an area that is the subject of ongoing research and tests.

The benefit of a line-side rather than on-board energy storage solution is avoidance of the need to mount heavy equipment on the trolleybus vehicle. The disadvantage is the need for vehicles to be in close proximity to the substation in order to discharge energy to the store. This may not be a problem if the substation can be sited in a location where vehicle braking is likely to occur, but the siting of substations is frequently dictated by other considerations.

3.4.8 Structures

The maximum gross vehicle weight limits for buses operating on UK roads of 18,000 kg for a two axle rigid bus with two axles and 26,000 kg for an articulated bus with three axles would be applicable to the design of new structures for all sub modes.

One requirement specific to the trolleybus with OLE sub mode is the provision at bridges over the trolleybus route of parapets of sufficient height to deny access to the live OLE as required in ORR's *Guidance on Tramways*. This could also apply to the catenary free electric bus sub mode in the event of the provision of an overhead charging point under an over bridge, but it would be preferable to avoid this situation when considering the siting of bus stops and charging points.

Where the OLE for a trolleybus system has to pass under an overhead structure, the change from the standard running height of 5.8m to the height attainable under the overhead structure has to be made at a prescribed rate, which may reduce the speed of trolleybuses through this section. Where routes have significant overhead constraints this may increase the run time for trolleybus relative to other sub modes.

3.5 Depot Requirements

Depot facilities will be required for all sub modes.

All sub modes have the potential to use existing bus garage facilities, but existing facilities will require modification for all sub modes other than the diesel hybrid and plug-in hybrid bus as detailed below.

The size of the depot would be dependent on the particular site configuration; however a site of approximately 1.5 ha should be sufficient to accommodate a fleet of up to 24 buses up to 18.75 m in length, the associated maintenance and staff facilities and staff car parking.

The battery electric and plug-in hybrid sub modes will require depot facilities with a larger vehicle parking area to accommodate the increased fleet size relative to the other sub modes, with maintenance facilities also sized accordingly.

Table 3.10: Depot site size required by sub mode

Sub mode	Fleet size	Depot area required
Trolleybus with OLE	20	1.3 ha
Catenary Free Electric Bus	20	1.3 ha
Fuel Cell Hybrid	20	1.3 ha
Diesel Hybrid	20	1.3 ha
Plug-in Hybrid	22	1.3 ha
Battery Electric	24	1.5 ha
Compressed Natural Gas (CNG)	20	1.3 ha

The depot infrastructure requirements that are specific to individual sub modes are as follows:

3.5.1 Trolleybus

The depot infrastructure required to support the operation of a trolleybus fleet will include the provision of some OLE within the depot site and facilities to enable work to be undertaken safely on roof-mounted electrical equipment.

The extent of the OLE required for trolleybus movement within depot areas and workshops will depend on the vehicle specification. If vehicles are specified with auxiliary battery power units the extent of the OLE installation required at the depot can be reduced that required for vehicle maintenance and testing.

The provision of OLE in stabling areas should be considered to provide power for vehicle auxiliary systems, e.g. heating, and ensure vehicles can leave the depot with their traction batteries fully charged.

A catenary-free trolleybus system would require a charging point in the form of a short section of OLE or a ground-based pick-up system providing sufficient power to enable vehicles to reach the charging point at the bus stop or terminus closest to the depot.

3.5.2 Fuel Cell Hybrid

The depot infrastructure required to support the operation of a fleet of fuel cell hybrid buses will include:
- Hydrogen storage and filling station facilities;
- Workshop facilities with additional safety features.

The primary hazards associated with operating and maintaining hydrogen vehicles are:
- The fuel itself, which is flammable;
- Storage of fuel at high pressure;
- Voltages associated with hybrid power systems.

Although existing hydrogen refuelling stations have demonstrated an excellent safety performance, hydrogen refuelling projects are often subjected to regulation and safety standards that are far more stringent than any other transport fuel due to the lack of extensive historic safety records.

It should be noted that hydrogen is classified as a hazardous substance under the Planning (Hazardous Substances) Act 1990. That Act provides that the presence of or above the controlled quantity of a hazardous substance on, over or under land, requires hazardous substances consent in accordance with the Planning (Hazardous Substances) Regulations 1992.

The controlled quantity of hydrogen as set out in Schedule 1 Part B of the regulations is 2 tonnes.

In addition to the Planning (Hazardous Substances) Regulations 1992, the Control of Major Accident Hazards (COMAH) Regulations 1999 and 2005 apply to larger installations involving the storage of 5 t or more of hydrogen.

Any practical hydrogen filling station will be over the 2 t threshold for hazardous substances consent and a commercial one is likely to be nearer to 5 t.

It is likely that the need to comply with these regulations will impose constraints on the location and design of a depot for hydrogen powered buses that will not apply to the other sub modes considered in this study.

In addition to the cost of providing the depot infrastructure and safety features required to support the operation of hydrogen powered buses, obtaining the required approvals for the use of hydrogen storage and fuelling facilities can be a lengthy and cost intensive process which can, in some cases, take more than one year to complete.

On-site production of hydrogen through electrolysis is possible, but the majority of existing refuelling stations for hydrogen powered bus applications rely on the delivery of hydrogen to site by tanker. Hydrogen may be delivered in liquid or gaseous form, but in the former case dispensing equipment to vaporise and compress the hydrogen will be required on site.

The hydrogen is typically stored at pressures of 400 to 500 bar, enabling buses to be refuelled by the cascade method, with the hydrogen held at 350 bar within the tanks on the buses.

Hydrogen storage tanks located within a depot environment should be within a secure compound and positioned at least 20 m from any occupied buildings.

Figure 3.10: Hydrogen Fuelling Station, Cologne

Source:

The additional safety features likely to be required in buildings used for the maintenance of hydrogen powered buses include:

- Hydrogen detection alarms within workshop areas;
- Automatic forced venting of building if 40% of lower flammable limit reached;
- Automatic venting whenever a bus enters workshop;
- Buses grounded by attaching cable prior to fuelling and maintenance; and
- Pressure release pipe attached to hydrogen tanks prior to work on vehicles.

Buses are normally plugged into an electrical supply when not in use to prevent the risk of frost damage to proton exchange membranes within the fuel cells. An electrical supply will therefore need to be provided to all bus parking areas within the depot.

3.5.3 Diesel Hybrid and Plug-in Hybrid

A depot to support the operation of a fleet of diesel hybrid buses will require the following sub-mode specific infrastructure:

- Diesel storage tank and fuelling equipment;
- Facilities for the maintenance and replacement of traction batteries.

Integrated diesel tank units incorporating bunding etc. will be required to mitigate the environmental risks associated with storage of liquid fuels.

The normal mode of operation of diesel electric hybrid buses is for the diesel engine to be used to charge the battery, rather than for the battery to be charged directly using plug-in recharging points. There is thus no need to provide plug-in recharging points within vehicle parking areas for overnight recharging.

The use of plug-in hybrid vehicles with roof-mounted charging equipment will additionally require fall arrestor equipment to allow staff to work safely when maintaining this equipment.

3.5.4 Battery Electric

Battery electric vehicles will require the installation of sufficient manual plug-in recharging points within vehicle parking areas to recharge the entire fleet overnight. Such ‘slow’ recharging points are typically capable of fully charging a bus within a period of six hours.

Figure 3.11: Manual Plug-in Overnight Charging Point at Depot, Coventry

Source: Route One

The cost of the three manual recharging points installed at the Travel de Courcey depot in Coventry for the Optare Versa EV battery electric buses used on the Coventry South park-and-ride service is reported to be £108,000, a cost of £36,000 per vehicle.

Current limitations on the range of battery electric buses are such that on all but very low mileage duties, opportunity fast-charging facilities will be required at termini to allow for top-up charging between journeys without the need for buses to return to the depot.

3.5.5 CNG / CBG

A depot to support the operation of a fleet of buses powered by CNG will require the following sub-mode specific infrastructure:

- Gas refuelling station – self-contained modular units available;
- Gas mains supply to refuelling station;
- Workshop safety features – gas monitoring equipment; roof venting.

On-site CBG or CNG storage is typically at pressures up to 250 bar, with refuelling either by compressor or pressure cascade system via a gas tight nozzle.

Figure 3.12: Typical CNG Fast Filling Station

Source: Gas Vehicle Alliance

The principles for the siting of a gas refuelling station within a depot environment are the same as for a liquid fuel refuelling station. The land area required is relatively small. For many applications a standard shipping container with a footprint of 6 m x 2.5 m will accommodate the compressor and control equipment, with the potential to mount storage cylinders on top of the container.

Table 3.11: Comparison of Sub Modes - Summary

	Diesel Bus	Trolleybus (with OLE)	Catenary Free Electric Bus	Plug-in Hybrid	Standard Diesel Hybrid	Fuel Cell Hybrid	Battery Electric	CNG (Biomethane from waste)
Vehicle capital cost (18m bus)	£280,000	£650,000	£680,000	£470,000	£420,000	£1,600,000	~£500,000 to £550,000 (no 18m vehicle)	£300,000
Technology maturity	Mature	Mature	Unproven	Incremental development of existing hybrid vehicle technology	Mature	Unproven	No 18m vehicle	Mature
Energy efficiency (12m bus)	500 kWh/100km	180 kWh/100k	162 kWh/100km (estimated 10% saving v standard trolleybus)	210 kWh/100km (estimate for electric power over 50% of route)	283kWh/100km	269kWh/100km	140kWh/100km	655kWh/100km
Fuel cost	TBC	TBC	TBC	TBC	TBC	TBC	TBC	TBC
Range	≥500km	Unlimited	Unlimited	As diesel bus	As diesel bus	370km	150-250km without recharging	Similar to diesel bus
Service availability	~90%	Similar to diesel bus	Limited evidence but some concerns about reliability of super-capacitors in hot weather conditions	Similar to diesel bus	Similar to diesel bus	55-80% (diesel equivalent availability expected for next generation vehicles)	Similar to diesel bus	Similar to diesel bus
Refuelling/ recharging time		N/A	~20 seconds	6-10 minutes for top-up charging at termini	As diesel bus	TBC	Full charge 2-6hrs Potential for rapid top up charging	Similar to diesel bus
TTW CO_2 emissions	Benchmark	-100%	-100%	-60%	-35-40%	-100%	-100%	-1%
WTW CO_2 emissions	Benchmark	-24%	-24%	-35%	-35-40%	-17-94%	-30%	-143%
Propulsion system durability	Engine: typical life 7 years	Auxiliary traction battery: typical life 5 years Other propulsion system components likely to last for whole life of vehicle	Auxiliary traction battery: typical life 5 years Super-capacitor: typical life 8 years Other propulsion system components likely to last for whole life of vehicle	Engine: typical life 7 years Battery: typical life 5 years	Engine: typical life 7 years Battery: typical life 5 years	Fuel cell: typical life 10,000 to 15,000 hours or 5 years Battery life uncertain but likely to be worse relative to trolleybus and diesel hybrid	Battery life in heavy duty application uncertain but likely to be worse relative to trolleybus and diesel hybrid	Engine: typical life 7 years
Infrastructure requirements and cost	Depot with diesel refuelling infrastructure and workshop	Overhead line equipment over whole route and at depot Sub-stations for power supply	Overhead line equipment (or alternative charging system) at bus stops and depot only Sub-stations for power supply	Top-up charging points at termini	As diesel bus	Hydrogen refuelling infrastructure at depot and hydrogen delivery network Workshop safety measures	Charging points at depot and termini Potential for rapid charging at bus stops	Gas refuelling infrastructure at depot Gas mains supply to refuelling station Workshop safety measures
Summary	Do-minimum option. In absence of NGT scheme the majority of bus services on NGT corridors expected to continue to be operated by diesel buses.	Proven and energy efficient option to deliver NGT operations with zero adverse on-street emissions. Overhead wires provide benefits of a sense of 'permanence' associated with fixed track systems to be set against cost and visual impact.	Catenary free electric bus technology currently insufficiently proven and presents unacceptable risk to scheme delivery	Has capability to operate on electric power for distances of up to 7 km, enabling operation with zero adverse on-street emissions in sensitive areas. Vehicles, including 18 m articulated version, expected to be in full commercial production by late 2015.	No capability to operate solely on electric power but offers reduced CO_2 emissions and local air quality benefits. A mature technology with market traction, providing a lower cost alternative option that would make a limited contribution to the scheme objectives.	Immature technology that remains uneconomic for commercial use. Electric propulsion offers more cost effective, proven and energy efficient options to deliver NGT operations with zero adverse on-street emissions.	Unsuitable for NGT due to insufficient range and capacity of current production vehicles and the performance and technology risks involved in use of unproven battery powered 18 m articulated buses and fast charging technology.	Performs best in minimising well to wheel CO_2 emissions of NGT vehicles but low energy efficiency and unable to operate 'adverse emission free' over any part of route. Biomethane is more energy efficient when used to generate electricity

Table 3.12: Summary of vehicle characteristics for single deck articulated buses

Sub Mode	Trolleybus	Diesel hybrid bus	CNG bus	Fuel cell hybrid bus	Battery electric bus *
Seating capacity	48(+2)	47	42(+1)	37(+1)	38
Total passenger capacity	142	158	150	96	59
Door configuration	3 (2+2+2)	3 (2+2+2)	3 (2+2+2)	3 (2+2+2)	1
Length (m)	18.70m	17.94m	18.08m	18.49m	11.10m
Width (m)	2.55m	2.55m	2.55m	2.49m	2.51m
Height (m)	3.42m	3.08m	3.36m	3.20m	2.82m
Unladen Weight (kg)	18,225	not specified	not specified	20,590	8,110
Gross Vehicle Weight (kg)	28,000	29,000	29,000	27,000	12,500
Minimum turning circle (m)	11.965	11.966	11.966	12.000m	not specified
Maximum operating gradient (%)	15	>13	>13	>13	>13
Power source	Overhead line	Diesel	CNG or CBG	Hydrogen	Mains electricity
Power output	250kW (TBC)	220-260kW	223kW	240kW	120kw
Auxiliary power options (Yes/No)	Yes (traction batteries/super-capacitors or diesel motor / generator)	Yes (traction batteries)	No	No	No
Regenerative braking (Yes/No)	Yes	Yes	No	Yes	Yes
Currently available in UK	Not currently produced in right hand drive configuration for UK market	Yes	Yes (12m rigid bus only)	Yes (12m rigid bus only)	Yes (12m rigid bus only)
Vehicles considered in this assessment	Hess Swisstrolley III Solaris Trollino 18 Van Hool AG300T	Mercedes Citaro G Hybrid Solaris Urbino 18 Hybrid Van Hool AG300H Volvo 7900 Articulated Hybrid Wrightbus Streetcar RTV	MAN Lions City G Volvo 7900CNG Articulated	APTS Phileas	BYD ebus Optare Versa EV Solaris Urbino 12 Electric *

* Data for Optare Versa EV 11m rigid bus. No articulated battery electric bus currently available.

4 Whole Life Cost Assessment

4.1 Capital Costs (Capex) – Vehicle Costs

Based on market data the cost of an articulated trolleybus with traction batteries and super-capacitors, and powered by OLE, is taken to be £650,000. It is assumed that the trolleybus would include for traction batteries and super-capacitors to allow the vehicle to benefit from regenerative braking, and therefore save on energy usage, and for use as an auxiliary power unit. The costs of a catenary free electric bus would be slightly higher due to the costs of the recharging pantographs and that it would likely be a bespoke system, therefore the cost is taken to be £680,000.

Based on market data the cost of a double decker hybrid vehicle is £240,000 and the cost of an articulated hybrid vehicle is £420,000. This therefore gives a range of £240,000 to £420,000 for the cost of a hybrid vehicle depending on the configuration.

As Volvo Bus does not plan to commence commercial manufacture of articulated plug-in hybrid vehicles until late 2015, there is no cost information currently available for these vehicles. Based on current market data the cost for a standard 18m articulated hybrid vehicle is £420,000 (based on Gent tender price). It is assumed that an articulated plug-in hybrid vehicle would have a larger battery pack than a standard hybrid vehicle and therefore an extra over cost of £20,000 for the larger battery has been factored in. In addition a plug-in hybrid vehicle would require roof mounted pantograph charging equipment which is taken to cost an additional £30,000. This gives a total cost of £470,000 for a plug-in hybrid vehicle.

It should be noted that the Volvo Bus design approach to the plug-in hybrid vehicle is to minimise the cost of charging equipment on the vehicle in favour of including additional equipment at the charging station. Therefore the costs included for the charging equipment above seem sensible. The current cost of a complete replacement battery pack for the Optare Versa EV battery electric bus is £56,000; it is therefore considered that the additional cost of a larger battery for plug-in hybrid will be no more than £15,000 to £20,000.

A cost estimate for a rapid charging station of €150,000 to €200,000 has been sourced. Taking the mid-point of the cost estimate for the charging station and assuming that the cost of the charging equipment on the vehicle is no more than 20% of the cost of the charging station, that gives us an estimate of €35,000 (circa £30,000) for the on-vehicle charging equipment.

The plug-in hybrid vehicle does not include for super-capacitors as the diesel-electric hybrid driveline provides both the acceleration necessary to pull away from stops and signals, and regenerative braking. The vehicle battery is charged directly via the roof mounted pantograph without the need for super-capacitors.

Articulated fuel cell hybrid buses have been built in very small numbers for demonstration projects but are not in commercial production. The cost of an 18m articulated fuel cell hybrid bus is estimated to be £1,600,000 based on the unit cost of €1,860,000 for the two APTS Phileas vehicles of this type currently operating in Cologne, Germany quoted in a case study of this project.

An articulated battery electric vehicle is not currently commercially available. The cost of an 18m articulated battery electric bus has been estimated at £500,000 to £550,000.

Based on market data a cost of circa €350,000 (£300,000) has been sourced for an articulated CNG powered bus. This is based on an order for two MAN Lion's City CNG 18m articulated buses purchased by the Transport Company of Gdynia, Poland in January 2013.

According to the International Association of Public Transport (UITP), in 2006 a CNG powered 12m bus was about 15-20% more expensive than a comparable diesel powered bus. Recent Green Bus Fund awards to UK operators to contribute 50% of the additional cost of CNG buses versus equivalent diesel buses indicate that the current cost differential remains similar. In relative terms a CNG bus is more expensive than a comparable diesel bus but cheaper than a hybrid. In that context the above figure looks sensible relative to the hybrid cost provided above.

Table 4.1 summarises estimated vehicle fleet capex for each sub mode based on the above cost estimates and taking account of the impacts of differences in vehicle performance and charging requirements on fleet size as discussed in section 3.2.

Table 4.1: Vehicle Capex by Sub Mode

Sub-Mode	Total Capital Cost of Vehicle Fleet
Trolleybus with OLE	£13,000,000
Catenary Free Electric Bus	£13,600,000
Fuel Cell Hybrid	£32,000,000
Diesel Hybrid	£8,400,000
Plug-in Hybrid	£10,340,000
Battery Electric	£13,200,000
Gas (CNG/CBG)	£6,000,000

4.2 Capital Costs (Capex) – System Costs

The trolleybus with OLE would require the following infrastructure:

- Provision of Overhead Line Equipment (OLE) with associated traction poles and catenary supporting wires;
- Sub-stations along the route to provide power to the OLE system. For the NGT system this is estimated to number 10 sub-stations;
- Depot to be sited close to the route alignment, within the operating range of the vehicle using auxiliary battery power unless OLE is provided between the route alignment and depot; and
- Facilities to store, maintain and replace traction batteries and super-capacitors.

The catenary free electric bus would require the following infrastructure:

- Charging points will be required and it is assumed that these are integrated into the stops and at each terminus. It is therefore estimated that 30 charging points would be needed for the NGT system;

- It is assumed that sub-stations will be required to provide power to the charging points where existing sub-stations are either not available or are located too far from the route alignment. It is assumed that five would be required for the NGT system;
- Charging points for all vehicles stabled at the depot;
- The depot could be sited away from the alignment of the route as long as the distance between the depot and the alignment is within the operating range of the vehicle between charging points;
- Facilities to store, maintain and replace traction batteries and super-capacitors; and
- There may be some costs associated with the diversion of statutory undertakers' equipment if parallel feed cables are required between the charging points.

The diesel hybrid sub mode would require the following infrastructure;

- Facilities to store, maintain and replace traction batteries at the depot; and
- Diesel storage and refuelling facilities at the depot.

The plug-in hybrid sub mode would require the following infrastructure;

- Charging points could be provided along the route to allow the vehicle to operate in electric propulsion mode and emission free in sensitive areas. It is assumed that charging points will be provided in the following locations; giving a total of eight charging points;
  - Stourton park and ride site – two charging points (to allow two vehicles to charge at a time)
  - Bodington park and ride site – one charging point
  - Holt Park terminus – one charging point
  - Additional charging points could be included either side of the City Centre to ensure that emission free operation could be ensures, however this would require a vehicle lay-over to top up the batteries although this could be accomplished via a flash charge.
- It is assumed that sub-stations will be required to provide power to the charging points where existing sub-stations are either not available or are located too far from the route alignment. It is assumed that a sub-station would be required at each charging location, giving a total of eight sub-stations. It is assumed that the sub-stations would be half the size of the sub-stations to be provided for the trolleybus scheme;
- There may be some costs associated with the diversion of statutory undertakers' equipment if parallel feed cables are required between the charging points.
- Charging points for all vehicles stabled at the depot;
- Facilities to store, maintain and replace traction batteries at the depot; and
- Diesel storage and refuelling facilities at the depot.

The following facilities would be required for the fuel cell hybrid sub mode;

- Facilities for storage of compressed Hydrogen and refuelling at the depot;
- A system for delivery of hydrogen fuel to the depot;
- Workshop facilities with additional safety features to maintain the fuel cells and hydrogen tanks; and.
- An electrical supply to all vehicles stabled at the depot.

The battery electric vehicle would require the following facilities;

- It is considered that charging points would be required at the termini only and therefore charging points would be required at the following locations;

  - Stourton park and ride site
  - Holt Park terminus
  - Bodington park and ride site (as 50% of services will terminate here)
- It is assumed that sub-stations will be required to provide power to the charging points. It is assumed that a sub-station would be required at each charging location, giving a total of three sub-stations.
- Charging points for all vehicles stabled at the depot; and
- Facilities to store, maintain and replace traction batteries would be required at the depot.

A Compressed Natural Gas (CNG) bus powered by biomethane from waste would require facilities for storage of compressed gas and refuelling at the depot. However gas storage facilities would not be needed if the gas is sourced directly from the grid and an offset of natural gas is achieved by injecting biomethane into the gas grid at the point of production. Gas monitoring equipment and roof venting would be required within vehicle workshop areas.

4.3 Operational Costs (Opex)

4.3.1 Staff Costs

The management and supervisory structure for the system is expected to be similar for all sub modes.

It is assumed that the vehicle fleet will be the subject of a time-based system of scheduled preventative maintenance and thus the number of skilled engineering staff required will largely be a function of fleet size and inspection intervals. Responsibility for the roadworthiness of the vehicle fleet and adherence to vehicle maintenance systems and standards should be vested in one person regardless of the vehicle propulsion system in order to ensure compliance with Operator Licensing requirements.

The differences between the sub modes in respect of requirements for skilled vehicle maintenance staff will generally be in relation to the level of specialist training required and the mix of mechanical and electrical / electronic engineering skills required within the fleet engineering function, rather than headcount.

The plug-in hybrid and battery electric sub modes will require additional driving staff in proportion to the increase in the peak vehicle requirement for these sub modes to allow for charging time within operating cycles. The plug-in hybrid will thus require around 13% more driving staff than the trolleybus, fuel cell hybrid, diesel hybrid and CNG sub modes. This will increase to 27% for the battery electric bus.

4.3.2 Fixed Costs

The main area of variation in fixed costs between the sub modes is in respect of repair and maintenance costs.

Evidence gained from the operation of a fleet of 20 fuel cell buses by BC Transit in Whistler, Canada since 2009 indicates that repair and maintenance costs for these vehicles have proved to be higher than the conventional diesel buses they replaced.

Evidence from the City of Stockholm indicates that repair and maintenance costs for CNG buses are marginally higher than those for comparable diesel buses within the current Stockholm fleet.

There is limited evidence available regarding the repair and maintenance costs of diesel hybrid buses relative to conventional diesel buses, but commentators have suggested that repair and maintenance costs for a diesel hybrid are likely to be within the range 10% to 20% higher than a comparable diesel vehicle.

Repair and maintenance costs for a plug-in hybrid vehicle are likely to be similar to a standard diesel hybrid as both of these sub modes share the same driveline, with the main difference being the roof mounted pantograph charging equipment on the plug-in hybrid.

Electric propulsion systems have fewer moving parts compared with internal combustion engines and arguably should require less maintenance, but it has proved difficult to find quantitative evidence to support this. Comparisons of vehicle maintenance costs per km for a trolleybus relative to a diesel bus range from 88% (Edmonton, Canada) to 129% (Poland).

In a presentation by the Zürich public transport operator VBZ at a recent European workshop a statement was made that maintenance costs for the Zürich trolleybus fleet over the lifetime of the vehicle are lower relative to comparable diesel buses, but this was not quantified and may be influenced by spreading the trolleybus maintenance costs over a longer service life relative to the diesel bus.

There is as yet little experience of the operation of full size battery electric buses from which to draw conclusions about repair and maintenance costs for this sub mode. Some commentators have suggested costs similar to a diesel hybrid at 10% to 20% higher than a comparable diesel vehicle. However, there is anecdotal evidence from the operator of the Optare Versa EV battery electric vehicles employed on a Park and Ride service in Coventry that the labour cost of scheduled preventive maintenance on these vehicles is lower than for a comparable diesel bus simply because there are fewer items to be checked.

"The buses are serviced every 21 days like the rest of the Travel de Courcey fleet. However, there is less to do as there is no engine or gearbox, no filters – none of the items that normally have to be checked with a diesel bus."

Other fixed costs such as motor insurance, vehicle excise duty, operator licences, annual MOT test and ticketing equipment are expected to be the same on a per vehicle basis for all sub modes but will be higher for the plug-in hybrid and battery electric sub modes in proportion to the increase in fleet size required.

4.3.3 Variable Costs

The main area where variable operating costs differ between the sub modes is the cost of power / fuel. In the UK context any cost comparison needs to take into account the partial rebate of fuel duty paid to the operators of registered local bus services in the form of Bus Service Operators Grant (BSOG).

BSOG is currently paid at the following rates:

- Diesel: 34.57 pence per litre
- Natural gas used as road fuel (including biogas): 18.88 pence per kg

The effect of BSOG is to reduce the cost of fuel for the diesel hybrid, plug-in hybrid and CNG sub modes and to make the use of electric power less attractive relative to other markets.

Table 4.2 shows a comparison of power/fuel costs for 12m buses based on the following assumptions:

Trolleybus and battery electric:

- Power consumption 1.8 kWh / km
- Cost of electricity 15 pence per kWh

Diesel hybrid bus:

- Fuel consumption 2.21 km / litre
- Cost of diesel net of BSOG 70.56 pence per litre

Plug-in hybrid bus:

- Assumed to run for 50% of route on electric power and 50% in diesel hybrid mode
- Fuel consumption 2.72 km / litre
- Cost of diesel fuel net of BSOG 70.56 pence per litre
- Cost of electricity 15 pence per kWh

CNG bus:

- Fuel consumption 3 km / kg
- Cost of gas net of BSOG 77.12 pence per kg

Table 4.2: Comparison of Power / Fuel Costs by Sub Mode

Sub-Mode	Estimated Power / Fuel Cost per 100km
Trolleybus	£27.00
Fuel Cell Hybrid	TBC
Diesel Hybrid	£31.93
Plug-in Hybrid	£26.47
Battery Electric	£27.00
Gas (CNG/CBG)	£25.71

Overnight charging of battery electric buses will enable use of off peak electricity at reduced cost.

4.4 Maintenance

A trolleybus system would require maintenance of the traction power system, to include the OLE system, sub-stations and the on-board traction power system. For the OLE system this would include for items such as inspection of building fixings, visual inspections by a foot patrol and access platforms and inspection of the electrical isolation system. For the sub-stations the maintenance would include inspections through the year, monitoring of stray current, testing of the AC breaker and impedance testing. The maintenance of the traction power system on the vehicle would include inspection and testing of the batteries and super-capacitors, maintenance of the heating and cooling systems for the batteries and super-capacitors, maintenance of the pantograph system and high voltage contactors and regular replacement of the OLE shoes. In addition there would be the standard maintenance items for the vehicle, such as tyres, CCTV, passenger heating and cooling systems and GPS. There would also be the daily cleaning of the vehicle as well as graffiti removal and repair of damage / vandalism.

The catenary free electric bus and plug-in hybrid bus would have similar maintenance requirements to the trolleybus except the OLE system would not be present and instead maintenance of charging points would be required. This would be higher for the catenary free electric bus sub mode as there would be a greater number of charging points (integrated into the stops) and a greater number of sub-stations. In addition the maintenance of the on-board pantograph equipment may be more onerous than for the trolleybus with OLE as the pantograph has moving parts and rises to make contact with the charging point.

The battery electric bus will have system maintenance costs for the charging points at termini and the associated sub-stations only.

The diesel hybrid bus, fuel cell hybrid bus and CNG bus will have no maintenance costs for OLE, charging points or sub-stations. There will be sub mode specific maintenance requirements for the vehicle propulsion systems (diesel engine, electric motor, traction batteries, fuel cell and gas engine) plus the standard maintenance items for the vehicle, such as tyres, CCTV, passenger heating and cooling systems and GPS. There would also be the daily cleaning of the vehicle as well as graffiti removal and repair of damage / vandalism.

For all sub modes, in addition to the maintenance of the main transit system, maintenance activities would also be required for other items such as fences, drains, ditches, embankments and cuttings. As well as tree pruning, grass cutting, vegetation removal, patching of the highway and litter picking. In addition standard maintenance activities would be required at the traffic signals, NGT stops and at the depot.

4.5 Renewals

Renewal requirements for each sub mode are assumed to be as follows:

4.5.1 Trolleybus

Vehicle renewals

- Vehicle refurbishment every 6 years;
- Replacement of traction batteries every 5 years;
- Replacement of super-capacitors every 8 years;
- Vehicle fleet replacement every 12 years.

System renewals

- Overhead line equipment and ancillaries will require the following renewals:
  - Overhaul of the switchgear per substation, assumed 1 AC and 5 DC breakers per substation to be renewed every 15 years;
  - Assumed 50% of power cable (250m per substation) to be renewed every 20 years;
  - Renewal of stray current detection and monitoring equipment every 15 years;
  - Assumed 50% of the contact wire and droppers to be renewed every 17 years.
- On-route renewal works:
  - Resurfacing of 100% of all new carriageways every 20 years;
  - Renewal of pre-cast concrete paving on new carriageway every 15 years;
  - Renewal of 50% of Kassel kerbs every 25 years;
  - Renewal of 10% of concrete and granite kerbs every 5 years;
  - Renewal of 25% of all drainage every 20 years;
  - Assume all new signals (8 per junction) and bus gate signals to be replaced every 15 years.
- Renewals works at the stops include the following:
  - Re-patching of the platform surface every 25 years;
  - Re-painting of stop equipment cabinets every 4 years;
  - Replacement of air conditioning in equipment cabinets at 7 year intervals;
  - Every 10 years, replacement of passenger information displays;
  - Every 15 years all lighting and stop furniture are due to be replaced;
  - Every 20 years NGT trolleybus shelters to be replaced.

4.5.2 Plug-in Hybrid Bus

Vehicle renewals

- Vehicle refurbishment every 6 years;
- Replacement of traction batteries every 5 years;
- Vehicle fleet replacement every 12 years.

System renewals

- Replacement of charging stations and ancillaries every 24 years;
- On-route and at stop renewal works as per trolleybus.

4.5.3 Battery Electric Bus

Vehicle renewals

- Vehicle refurbishment every 6 years;
- Replacement of traction batteries every 5 years;
- Vehicle fleet replacement every 12 years.

System renewals

- Replacement of charging stations and ancillaries every 24 years;
- On-route and at stop renewal works as per trolleybus.

4.5.4 Diesel Hybrid Bus

Vehicle renewals

- Vehicle refurbishment every 6 years;
- Replacement of traction batteries every 5 years;
- Vehicle fleet replacement every 12 years.

System renewals

- On-route and at stop renewal works as per trolleybus.

4.5.5 Fuel Cell Hybrid Bus

Vehicle renewals

- Vehicle refurbishment every 6 years;
- Replacement of fuel cell stack every 5 years;
- Replacement of super-capacitors every 8 years;
- Vehicle fleet replacement every 12 years.

System renewals

- On-route and at stop renewal works as per trolleybus.

4.5.6 CNG Bus

Vehicle renewals

- Vehicle refurbishment every 6 years;
- Vehicle fleet replacement every 12 years.

System renewals

- On-route and at stop renewal works as per trolleybus.

4.6 Sensitivity for Staff Wages and Future Power / Fuel Costs

All modes will be sensitive to increasing staff costs resulting in an increase in operating costs; however those modes that require more staff to operate the system will be most vulnerable. In terms of the power or fuel costs of the different modes those based on a hydrocarbon or diesel fuel source for all or part of their power requirements will be the most sensitive in terms of fuel price increases due to the volatility in the price of crude oil, which then feeds through to the unit cost of diesel.

Vehicles which are based upon drawing their power from the national grid, such as electric buses and trolleybuses are likely to experience less sensitivity to changing prices and there will be the opportunity to enter into agreements with power companies for the bulk supply of electricity.

The cost of biomethane will be most sensitive to supply and demand within the UK and locally. It may be possible to secure a long term supply from a local source at a relatively stable price.

5 Environmental Comparison of Sub Modes

This section presents the results of a strategic appraisal of the potential environmental and health effects associated with each sub mode. The purpose of this appraisal is to identify the key environmental and health differentiators for each sub mode and consider their significance at each stage of the life-cycle: construction, operation and decommissioning.

5.1 Approach

5.1.1 Previous studies

A number of internal documents have been reviewed as part of this assessment, including:

- The "Transit Mode Options – Quantified Environmental Benefits" report (236834/RPT15B, October 2009) which considered the environmental issues for a Trolleybus, Hybrid Bus and a Diesel Bus on both a generic basis and in the Leeds-specific context.
- The 'EIA Scoping Report' (312694/EST/RPT53/C, March 2013), which identifies the technical environmental disciplines that will be considered in the Environmental Impact Assessment (EIA); and
- The draft "Sustainability Appraisal Report" (RPT054, Revision A July 2013), which assesses the economic, environmental and social impacts of the NGT scheme.

5.1.2 Scope of Environmental and Health Appraisal

The appraisal was conducted using a strategic comparison technique - comparing the performance of each sub mode against a range of indicators. A holistic approach was adopted through consideration of the indicators at each stage in the proposed lifecycle, thus considering the full life-cycle of the different sub modes.

Only the individual sub mode technologies have been considered in this appraisal as there are a myriad of technology combinations to consider.

5.1.3 Assumptions

The assumptions for the purposes of this environmental and health appraisal are consistent with those presented in section 1.4 of this report.

During the appraisal, assumptions were made that were specific to each sub mode and the associated infrastructure. These are as follows:

Trolleybus with Overhead Line Equipment

- Powered by electricity from Overhead Line Equipment (OLE); and
- Incorporating an electric motor with electricity taken from overhead wires along the route.

Catenary Free Electric Bus

- Incorporates an electric motor, energy recovery (regenerative breaking) and storage function;

- Super-capacitors, which store energy through a physical process in on-board batteries;
- 20 seconds is assumed for full recharge of the super-capacitors; and
- MV electrical supply to depot.

It is also important to note that both an OLE trolleybus and a catenary free electric bus have a regenerative braking system.

Battery Electric

- Incorporating traction batteries which recharge at the depot and termini.
- Charging points to be provided at the termini.

Depot Infrastructure:

- MV electrical supply to depot;
- Electric recharging points; and
- Takes 6 hours to recharge.

Fuel Cell Hybrid

It is assumed that all necessary permits will be obtained for the vehicle, depot and supporting infrastructure. However, this has been identified as being a lengthy (1 year) and potentially costly process.

The necessary infrastructure and technology that is assumed to be required for this sub mode is stated below:

Depot infrastructure:

- Hydrogen storage and filling stations required;
- Filling station likely to be over 2t threshold for hazardous substances consent;
- Workshops will be required plus necessary safety features to achieve planning/permitting (Forced venting, alarms, grounding etc.);
- Hydrogen delivery will be by tanker in gaseous form; and
- Hydrogen will be held at 350 bar within the tanks on the buses.

Standard Diesel Hybrid

Depot infrastructure:

- Assumed similar depot requirements as for diesel vehicles; and
- Assumes no charging stations along the route.

Plug-in Hybrid

Depot infrastructure:

- Assumed similar depot requirements as for diesel vehicles with additional electric charging points; and
- Assumes additional Bůsbaar or similar fast charging stations along the route.

Compressed Natural Gas / Biogas

It is assumed that all necessary permits will be obtained for vehicle, depot and supporting infrastructure.

Depot Infrastructure:
- Gas refuelling station – self-contained modular units available;
- Gas mains supply to refuelling station;
- Workshop safety features – gas monitoring equipment; roof venting;
- Assumed storage at pressures up to 250 bar;
- Refuelling by compressor or pressure cascade system via a gas tight nozzle; and
- Principles for siting of the gas refuelling station same as for liquid refuelling station.

5.1.4 Indicators

Having established the assumptions and boundaries/exclusions in the appraisal process, the next step was to identify the key environmental and health indicators that influence the sub mode technology selection. The following potential environmental and health indicators were identified as significant for the proposed scheme following consultation with environmental and transportation specialists. Indicators that were considered at each of the project stages were:
- Health and safety;
- Technology risk;
- Cultural heritage;
- Noise and vibration;
- Green House Gas (GHG) emissions;
- Air pollutants (excluding GHG e.g. PM10);
- Climate resilience;
- Education and training;
- Social acceptance; and
- Wellbeing.

Each of the above indicators was considered at the three life-cycle stages (construction, operation and decommissioning. The appraisal has been conducted only where significant differences in performance have been identified (i.e. the key differentiators). The appraisal Table 5.1 below provides a commentary specific to each stage of the life-cycle for the key differentiators.

5.2 Appraisal

Table 5.1: Key Justifications

Construction Indicator	
Construction Health & Safety	The sub modes that do not require any additional infrastructure e.g. hybrid vehicle technology perform well against this indicator as the quantity of construction activity needed is less. Electric vehicle technology involves construction practices that require working at height during construction that do not perform well against this indicator. This can be mitigated to acceptable levels through standard health and safety practice.
Wellbeing/Noise & Vibration/Air Pollutants/GHG/Cultural Heritage	The sub mode options that would create higher levels of particulate matter, dust, noise and visual impact during construction (those requiring additional infrastructure e.g. OLE electric, CNG and Hydrogen fuel cell hybrid) perform poorly against this indicator due to the level of infrastructure required for each mode. These subsequent impacts will then have an effect on the health and wellbeing of the general public and construction workers.
Climate Mitigation	Sub modes that required a higher energy use to construct (e.g., fuel cell hybrid, CNG and those with a high level of infrastructure required perform poorly than those where little or no additional infrastructure is required (e.g. diesel hybrid).
Technology Risk	Emerging sub mode technologies such as fuel cell hybrids perform poorly against this indicator compared to well established technologies such as OLE electrified trolleybus where construction techniques have been well known for decades.
Education & Training	The sub modes that did not require any specialist construction methods or additional infrastructure perform less well than OLE and catenary free as the latter sub modes would provide more opportunities for specialist skills training.
Operation Indicator	
User Health & Safety	The fuel cell hybrid was considered the worst performing sub mode for this indicator due to the highly combustible nature of the compressed Hydrogen carried on the vehicle and stored at the depot.
Climate Resilience	Sub modes may be affected by climate in different ways e.g. OLE may be at higher risk of extreme weather events such as wind and extreme temperature, especially in exposed areas such as Belle Isle, so may not perform as well as those sub modes with built in flexibility e.g. modes that do not rely on additional infrastructure that can be affected by climatic events.
Green House Gas Emissions	As illustrated in Figure 3.4, CO_2 emissions, the electrically powered sub modes and the Hydrogen fuel cell hybrid perform well in terms of Tank to Wheel emissions, offering some of the greatest savings. The composition or source of energy generation for electrified vehicles is one of the greatest opportunities to reduce carbon emissions. For example, as illustrated in Appendix A, the Zurich trolleybus scheme in Switzerland performs significantly better than electric power in the UK as Grid energy in Switzerland is largely powered by renewable energy.
Social Acceptance	Sub mode technologies that move away from diesel fuel performed well against this indicator. Emerging technologies performed poorly due to the potential for perceived technology risks to affect acceptance by users and non-users.
Air Pollutants	As illustrated, the trolleybus performed exceptionally well on air pollutants due to the lowest emissions in operations. The diesel hybrid performed poorly having the highest air pollutants e.g. PM10 at street level.
Technology Risk	Electrified OLE trolleybus performs best against this indicator as it is the sub

	mode that is the most well trialled technology that will meet the necessary performance requirements for the scheme. The least well performing sub mode was the fuel cell hybrid as this is the least well trialled technology at the proposed scale.
Noise	Electric vehicles performed well against this indicator due to reduced noise disturbance in operation, with diesel internal combustion engines performing poorly.
Decommissioning Indicator	
Demolition Health & Safety	Decommissioning activities associated with less well known technology were considered as posing a higher risk to demolition Health & Safety, particularly Hydrogen fuel cells due to the unknown nature of disposal. Similarly to the indicator of Health and Safety in Construction, the sub modes that involved the demolition of additional infrastructure were assessed as performing poorly against this indicator as a greater level of decommissioning is required.
Waste/Materials	There are more opportunities for recycling of materials that arise from the demolition of the OLE and catenary free infrastructure than with an option that has no infrastructure to be removed. In addition decommissioning of traction batteries associated with the trolleybus, battery electric and hybrid sub modes performed poorly against this indicator.
Wellbeing/Noise & Vibration/Air Quality/ Cultural Heritage	The sub mode options that would create higher levels of particulate matter, dust, noise and visual impact during demolition performed poorly against these indicators. Sub modes such as OLE trolleybus performed poorly due to the level of infrastructure that needs to be removed. These subsequent impacts will then have an effect on the health and wellbeing of the general public and demolition workers.

5.3 Summary of Key Environmental Differentiators

The summary below provides an explanation of the key environmental differentiators across the construction, operation and end of life decommissioning of the scheme. A differentiator is an indicator that influences technology selection and design decisions.

5.3.1 Construction

There are two key differentiators between the sub mode options during the construction phase, these are the technology risk posed by each sub mode and the level of additional infrastructure required in construction. There is a variance in the level of certainty of the construction techniques required for each sub mode; electrified trolleybus performed the best and hydrogen fuel cells performed least well.

If large quantities of infrastructure are required this will result in a greater impact on the environment in terms of air quality, noise and vibration, as well as contributing to carbon emissions that have a potential impact on climate change. The need to construct additional infrastructure such as OLE also puts certain sub modes at a higher risk to the impacts of climatic events such as high winds and lightning strikes.

5.3.2 Operation

The fuel source used to power each sub mode and the level of infrastructure associated with the fuel type were the main differentiators between each sub mode. For example those powered by fuels that produce low emissions would have less environmental impact.

The level of resilience to the effects of climate change, such as extreme weather events, was also a significant differentiator between sub modes. This is also reflects the level of infrastructure that needs to be resilient to high winds, heavy rainfall, snow and ice and lightning. The modes that require OLE are most susceptible to climatic events and will require the greatest level of adaptation. Adaptation refers to the initiatives and measures implemented to decrease the vulnerability of the scheme to extreme weather events.

5.3.3 End of Life

The end of life stage refers to the demolition of the scheme. The two key differentiators for the decommissioning phase are the technology risk and the level of infrastructure that needs to be demolished and the associated risks and opportunities. Other sub modes such as the fuel cell and traction batteries within trolleybus, battery electric and hybrid options carry risks in their safe disposal. The level of infrastructure required for the operational phase will also determine the long term effects on the cultural heritage after demolition, for example the OLE fixings on buildings may have a minimal long term effect on the visual quality of the streetscape when they are removed and create minor damage.

5.4 Summary of Key Health Differentiators

5.4.1 Construction

The key health differentiator during construction when comparing the sub modes is the level of infrastructure required to operate each mode. The greater the amount and complexity of the construction required, for example the materials used, and the length of the construction period, the greater the potential impact to have an effect on the health and wellbeing of both the general public and the construction workers. For example the installation of OLE will require working from a height, resulting in a higher health and safety risk. This risk can be safely mitigated through good construction practice. The associated emissions from energy use during construction, dust, noise and vibration levels will also be dependent on the level of construction required. All of these impacts against these performance indicators have been identified as having potential to affect the health and wellbeing of individuals.

5.4.2 Operation

The key health differentiators during operation are the health and safety risks to users, the level of air pollutants such as particulate matter (PM10) and oxides of Nitrogen (NOx) produced by each sub mode and the associated effects from the visual impact effect of each sub mode on the wellbeing of individuals. The level of health and safety risk to users depends on the technology associated with each option and the level of certainty surrounding the technology. Advancements in technology will allow the noise levels of certain vehicle types, including the electrically powered sub modes, to be lower than those powered by internal combustion engines, and this can help to improve wellbeing.

5.4.3 End of Life

The two significant health differentiators between each of the sub modes during decommissioning of the scheme are likely to be the level of infrastructure required and the technology risk. For example the health and safety risk to demolition workers associated with the decommissioning of each technology is a significant factor, which in turn will have a subsequent effect on the health and wellbeing of individuals. Similar to the differentiator during construction, the degree to which this is a significant risk will depend on the level of infrastructure that needs to be demolished and the demolition methods used. This will then also influence the levels of dust, noise and vibration and visual impact, all of which will have an effect on the wellbeing of individuals.

5.5 Environmental and Health Impact Summary

A strategic appraisal of the potential environmental and health effects of the sub-modes has been undertaken. Sub-modes that performed well are the electrified vehicles particularly the OLE trolleybus due to the well trialled nature of this technology. Plug-in hybrid technology also performs well due to the limited additional infrastructure required in implementation.

6 Conclusions

6.1 Fuel Cell Hybrid Bus

Fuel cell technology provides an alternative to all-electric drivetrains for urban bus operations without pollutant exhaust emissions. Although fuel cell technology is arguably now proven through large scale demonstration projects in an operational environment (the latest fuel cell hybrid technology less so), this technology remains immature and uneconomic for commercial use, as demonstrated by the uncertain future for the world's largest fuel cell bus fleet operating in Whistler, Canada after the current five year demonstration programme ends in Spring 2014.

The adoption of fuel cell technology for NGT would be the first real world deployment of this technology on such a scale in Europe and presents significant commercial and technology risks. Electric propulsion offers more cost effective, proven and energy efficient options to deliver NGT operations with zero on-street emissions. The benefits of fuel cell technology over other sub modes are thus insufficient to justify taking these risks. Fuel cell hybrid vehicles should therefore be rejected as an option for NGT on the grounds of cost and technology risk.

6.2 Battery Electric Bus

There has been a breakthrough in the real world deployment of production battery electric buses over the last two years, but the limited operational range and passenger capacity of current battery electric vehicles means that they are not yet a practical option for intensive urban bus operations requiring high capacity vehicles and where operating cycles provide limited opportunities for recharging without taking vehicles out of service.

Advances in battery technology providing better acceleration and greater range from fewer batteries have seen the size of commercially available battery electric buses grow from the previous generation of small buses to full size single deck buses of 11 to 12m in length, but the weight of battery packs means that passenger capacity is a limiting factor and no production pure battery electric 18m articulated bus currently exists.

Pure battery electric buses are most efficient when operating at low speeds and may also have a limited maximum speed. They are thus best suited to operations such as city centre and airport shuttle services, where power consumption is lower, routes are typically short, offering frequent opportunities for top-up charging at termini and where the current generation of 11 to 12m vehicles is likely to provide sufficient passenger capacity.

The latest developments in wireless fast charging technology offer the potential to overcome the current range limitations of battery electric buses and to make a battery powered 18m articulated bus a practical option. However, fast charging technology is still at the demonstration project stage and remains unproven in a commercial environment. Concerns also remain about battery life and the impact of degraded battery performance on journey times. A pure battery electric bus has no auxiliary propulsion system that could be used in the event of battery performance becoming degraded. Fitting an auxiliary internal combustion engine to a battery electric vehicle effectively turns it into a plug-in hybrid. This intermediate sub mode is discussed further below.

Pure battery electric vehicles should therefore be rejected for NGT on grounds of unsuitability due to the insufficient range and capacity of the current generation of production vehicles and the technology and performance risks involved in the use of unproven battery powered 18m articulated buses and fast charging technology.

6.3 Gas Bus powered by biomethane from waste

CNG buses are a proven technology that is starting to be adopted in the UK for bus operations. CNG engines are less energy efficient than diesel engines, but CNG vehicles still offer fuel cost savings versus conventional diesel buses, providing a payback on the higher capital cost. CNG vehicles are also quieter than comparable diesel buses by between 3-5 dBA. Well to Wheel (WTW) greenhouse gas emissions for fossil CNG vary from an increase versus diesel to a significant reduction dependent on engine technology and gas pathway. Biomethane of sufficient quality can be used in CNG engines without modification and the use of biomethane from waste assures significant WTW CO_2 reductions (potentially 100%+). Biomethane from waste can be produced locally at a cost divorced from world oil and gas prices.

The balance of evidence indicates that CNG buses are comfortably the cleanest vehicles powered by an internal combustion engine available for urban bus operations, but still produce pollutant exhaust emissions and unlike electric, fuel cell or plug-in hybrid vehicles have no capability to operate in zero emission mode within Air Quality Management Areas or other areas of environmental sensitivity.

Biomethane is potentially attractive as a transport fuel source, particularly where a local biomethane supply chain already exists. However when alternative uses of biomethane is considered it is clear that from an overall energy efficiency perspective the use of biomethane to generate electricity for use to power vehicles is the better option.

The overall environmental merits of a gas bus powered by biomethane from waste as a sub mode for NGT depend critically on the relative importance attached to reducing global CO_2 emissions and improving local air quality. However, having considered the alternative energy pathway of using biomethane from waste to generate renewable electricity and using this to power vehicles, we have concluded that a gas bus powered by biomethane from waste should be rejected for NGT on the grounds of the overall energy inefficiency of this sub mode and the inability of this sub mode to operate without any pollutant emissions in environmentally sensitive areas.

The remaining four sub modes considered in this study are trolleybus (with OLE), catenary free electric bus, diesel (or other internal combustion engine) hybrid and plug-in hybrid.

6.4 Standard Hybrid Bus

A standard diesel hybrid bus offers fuel economy gains, reduced CO_2 emissions, local air quality benefits and a reduction is noise versus a conventional diesel bus. Diesel hybrid propulsion is now a mature technology with considerable market traction. As a result the cost premium versus diesel buses is falling and fuel economy gains may in future provide a commercial payback.

However, unlike all of the other sub modes considered in this study, a diesel hybrid bus still uses a fossil fuel with its price linked to world oil prices, albeit in lower quantities. This exposes NGT to the risk of a long term increase in the cost of fuel relative to other sub modes. The long term security of diesel fuel supplies may also be a concern.

A gas hybrid bus is an alternative to a diesel hybrid bus offering the potential for use of fuel from a renewable source in the form of biomethane. A gas hybrid propulsion system replaces the diesel engine in a hybrid driveline with a spark ignition engine optimised to run on methane. A gas hybrid bus is essentially a new combination of proven technologies. A fleet of 15 gas hybrid articulated buses, to be powered by biomethane, is due to enter service in Malmo, Sweden in the summer of 2014.

One of the major drawbacks of the current generation of both series and parallel hybrid buses is that they have no capability to operate solely on electric power for any significant distance.

6.5 Plug-in Hybrid Bus

The next generation of rapid charging plug-in hybrid buses, as pioneered by Volvo Bus, has the capability to operate on electric power for distances of up to 7 km and thus effectively reduces the diesel engine to the status of an auxiliary power unit. Therefore the major benefit of a plug-in hybrid bus over a standard hybrid is its capability, within limitations, to operate without any pollutant emissions in environmentally sensitive areas.

Plug-in hybrid buses, including an 18m articulated version, are expected to be in full production by late 2015. Although not yet a fully proven technology, the technology risk presented by the use of a plug-in hybrid bus is considered to be significantly lower than for a fuel cell bus or a catenary free electric bus and lower than for a pure battery electric bus as the driveline remains similar to the current generation of parallel hybrids but with the addition of a larger battery pack and roof mounted pantograph charging equipment based closely on existing and well proven heavy rail technology.

The Volvo plug-in hybrid bus does not use super-capacitor technology for recharging. The availability of a diesel engine for use to recharge the battery where necessary ensures that the battery can remain charged at all times to a level that will optimise battery life.

A plug-in hybrid thus offers many benefits of an electrically powered bus without the associated infrastructure costs. As an incremental development of current technology with large scale operational testing already planned prior to full production from 2015 the technology risk associated with this sub mode is considered to be acceptable.

The capability of a plug-in hybrid bus to operate without any pollutant emissions in environmentally sensitive areas provides a compelling reason to prefer a plug-in hybrid over a standard diesel or gas powered hybrid as a sub mode for NGT.

A plug-in diesel hybrid bus, using technology similar to that currently employed in Gothenburg, Sweden, should be taken forward for further consideration as a potential sub mode option for NGT.

6.6 Trolleybus

A trolleybus produces zero on-street emissions, but its overall greenhouse gas emissions are dependent on the source of the electricity used and the availability of electricity from renewables.

Conventional trolleybuses powered by electricity from overhead wires are a very well proven technology that is continuing to advance in performance and energy efficiency through improvements in electric vehicle technology including traction batteries and super-capacitors.

New trolleybuses are increasingly being specified with a traction battery for auxiliary power in preference to a diesel generator and in some cases also with super-capacitors. Improvements in battery technology are increasing the flexibility of trolleybuses to run without wires in historic city centres and other sensitive areas or if diversions from or route extensions beyond wired routes are required. The addition of super-capacitors has been demonstrated to reduce the energy consumption of trolleybuses powered from OLE, but also facilitates catenary free operation, offering the potential to reduce overhead wires to short sections, optimally located at bus stops, to act as charging points.

However, the use of super-capacitor technology for rapid charging at bus stops is still at the demonstration project stage and the completely catenary free operation of trolleybuses remains unproven in a commercial environment within Europe.

A trolleybus with OLE offers benefits in terms of route legibility and a sense of permanence to weigh against the cost and visual impact of the OLE. The use of catenary free electric bus technology would reduce the need for OLE and the associated cost and visual impact but would also reduce the route legibility and sense of permanence provided by the OLE.

Having considered the merits of trolleybuses with OLE and catenary free electric bus technology as potential sub modes for NGT we have concluded that catenary free electric buses, with no OLE other than for charging at bus stops, should be rejected for NGT on the grounds of the unacceptable technology and performance risks involved in reliance on rapid charging using super-capacitor technology as the primary source of traction power for NGT vehicles. However, there is merit in specifying trolleybuses with traction batteries and super-capacitors for NGT to maximise the energy efficiency of the NGT fleet.

6.7 Technology Risk

It can be seen from the discussion of each of the sub modes above that technology risk has emerged as a key differentiator between the sub modes under consideration for NGT and is presented as a significant element of the justification for the rejection of fuel cell hybrid and battery electric vehicles and the entirely catenary free option of trolleybuses for further consideration as potential sub mode options for NGT.

The advocates of new technology may underestimate the risks posed to early adopters. Vehicle manufacturers making decisions about when to introduce new technology to the market will take a more conservative view, recognising that:

- New technology requires proper testing and should be released when it is meeting the expectations of operators and cities within individual local markets;
- Success and competitiveness criteria e.g. availability/reliability, total cost of ownership and environmental performance differ between markets;
- Technology applications should be secured for the applicable climatic conditions and duty cycle before being introduced to the market;
- Where joint demonstration projects with operators or cities form part of the implementation process of the new technology, the technology risks to the project should be assessed, recognised and accepted by all parties;.
- The premature deployment of unproven technology represents a hazard to the overall reputation of electromobility and fuel cell technology for public transport.

Thus the secured implementation of new electromobility and fuel cell technology will not be realised as quickly as some enthusiasts and advocates may hope and it is unreasonable to expect scheme promoters to accept technology risk where the demonstration and advancement of technology is not a scheme objective and proven alternative technologies to deliver the scheme objectives already exist.

This can be summed up in the declared philosophy of the city of Stockholm regarding the adoption of clean vehicle technology for public transport - to use the best available commercial technology now, but support and engage in projects for future technology.

6.8 Summary and Recommendations

The sub modes investigated in this study are:
- Trolleybus (with OLE);
- Catenary Free Electric Bus;
- Standard diesel hybrid;
- Plug-in diesel hybrid;
- Fuel cell hybrid;
- Battery electric; and
- Compressed Natural Gas (CNG) bus powered by biomethane from waste.

We have concluded that fuel cell hybrid, battery electric and CNG buses should be rejected as sub mode options for NGT on the following grounds:

- Fuel cell hybrid - cost and technology risk;
- Battery electric - insufficient range and capacity of the current generation of vehicles and technology and performance risks of battery powered 18m articulated buses employing fast charging technology;
- CNG bus - overall energy inefficiency and inability to operate without any pollutant emissions in environmentally sensitive areas.

Trolleybuses with OLE represent a well proven technology which is continuing to advance as other associated technologies become available, such as super capacitors. They produce zero on-street emissions and offer benefits in terms of route legibility and a sense of permanence to weigh against the cost and prominence of the OLE.

Having considered the merits of trolleybuses with OLE and catenary free electric bus technology as potential sub modes for NGT we have concluded that catenary free electric buses, with no OLE other than for charging at bus stops, should be rejected for NGT on the grounds of the unacceptable technology and performance risks involved in reliance on rapid charging using super-capacitor technology as the primary source of traction power for NGT vehicles. However, there is merit in specifying trolleybuses with traction batteries and super-capacitors for NGT to maximise the energy efficiency of the NGT fleet.

We recommend that the trolleybus with OLE sub mode is taken forward for further consideration as a potential option for NGT.

Plug-in hybrid buses, including an 18m articulated version, are expected to be in full production by late 2015. Although not yet a fully proven technology, the technology risk presented by the use of a plug-in hybrid bus is considered to be significantly lower than for a fuel cell bus or a catenary free electric bus and lower than for a pure battery electric bus. This is because the driveline remains similar to the current generation of parallel hybrids but with the addition of a larger battery pack and roof mounted pantograph charging equipment based closely on existing and well proven heavy rail technology.

Having considered the merits of a plug-in hybrid bus over a standard hybrid bus, the state of development of plug-in hybrid vehicles and the associated technology risk, we have concluded that the capability, within limitations, of a plug-in hybrid to operate without any pollutant emissions in environmentally sensitive areas provides a compelling reason to prefer a plug-in hybrid over a standard diesel or gas powered hybrid and that the technology risk is acceptable.

We recommend that the plug-in hybrid sub mode is taken forward for further consideration as a comparable alternative to Trolleybus for NGT.

Standard hybrid buses have no capability to operate without any pollutant emissions in environmentally sensitive areas, but offer reduced CO_2 emissions, local air quality benefits and a reduction in perceived noise levels. Hybrid buses offer a mature technology with current market traction, providing a lower cost alternative to other modes but at the same time offering benefits upon standard diesel buses.

We recommend the standard hybrid sub mode for consideration as a sub mode for a lower cost alternative option to the NGT scheme.

Table 6.1: Summary of Recommendations

Sub mode	Recommendation	Commentary
Trolleybus (with OLE)	Preferred option	Proven and energy efficient option to deliver NGT operations with zero adverse on-street emissions. Overhead wires provide benefits of a 'sense of permanence' associated with fixed track systems to be set against cost and visual impact. Specification of vehicles with traction batteries and super-capacitors beneficial to maximise energy efficiency and permit catenary free operation within visually sensitive areas.
Plug-in hybrid	Next best option	Has capability to operate on electric power for distances of up to 7 km, enabling operation with zero adverse on-street emissions in sensitive areas. Vehicles, including 18 m articulated version, based on proven technology expected to be in full commercial production by late 2015.
Standard hybrid	Low cost option	No capability to operate solely on electric power but offers reduced CO_2 emissions and local air quality benefits. A mature technology with market traction, providing a lower cost alternative option that would make a limited contribution to the NGT scheme objectives.
Catenary Free Electric Bus	Rejected	Use of super-capacitor technology for 100% catenary free operation currently insufficiently proven and presents unacceptable risk to scheme delivery.
Fuel cell hybrid	Rejected	Commercial application unproven and remains uneconomic for commercial use. Expensive vehicles and technological risk. Electric propulsion offers more cost effective, proven and energy efficient options to deliver NGT operations with zero adverse on-street emissions.
Battery electric	Rejected	Unsuitable for NGT due to insufficient range and capacity of current production vehicles and the performance and technology risks involved in use of unproven battery powered 18 m articulated buses and fast charging technology.
CNG (Biomethane from waste)	Data	Performs best in minimising well to wheel CO_2 emissions of NGT vehicles but low energy efficiency and unable to operate 'adverse emission free' over any part of route. Biomethane is more energy efficient when used to generate electricity, which could be used to power vehicles.

Source: Mott MacDonald

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Appendices

Appendix A. Case Studies

A.1 Operation of Modern Articulated Trolleybuses in Zürich, Switzerland

The Zürich trolleybus system was opened in 1939. The system consists of six lines with a total route length of 54 km (34 miles). It is operated by Verkehrsbetriebe Zürich (VBZ), which also operates the tramway (119 km) and motorbus (324 km) networks.

Minimum service headways on the trolleybus lines range between 5 and 8 minutes. Two of the six lines were previously tram routes.

The key reasons cited by VBZ in favour of the operation of trolleybuses are:
- Proven technology with a highly efficient drive system;
- Capable of handling high traffic flows on routes with challenging topography and gradients of up to 9%;
- No local emissions, making significant contribution to improving quality of life in urban areas;
- Independence from fossil fuels, with the guarantee of stable longer-term energy costs;
- Extended service life of 17 years with a mileage of more than 1.2 million km;
- Lower maintenance costs over the lifetime of the vehicle in comparison to equivalent diesel buses.

The trolleybuses are powered by 100% renewable electricity generated from hydropower.

Articulated trolleybuses have been operated in Zürich since the introduction of a prototype vehicle in 1957, with production vehicles entering services from 1959 onwards. As of November 2013, the Zürich trolleybus fleet stood at 77 vehicles, of which 48 were articulated and 29 bi-articulated. From 2006 onwards the majority of the fleet has been replaced with low floor vehicles manufactured by Carosserie Hess AG, with electrical equipment supplied by Vossloh Kiepe GmbH. Vehicles delivered from 2012 are fitted with a 75kW lithium-ion traction battery for auxiliary power. Scheduled use of the battery is for distances up to 1.5 km with the potential to operate on battery power for up to 10 km.

To further increase the attractiveness and sustainability of public transport in Zürich, VBZ are planning to convert two further routes currently operated by diesel buses (lines 69 and 80) to trolleybus operation. The routes selected for conversion have been chosen because of their challenging topography and passenger growth requiring an increase in vehicle capacity.

Work was undertaken to evaluate the technical, economic and environmental aspects of the use of different drive technologies for the two lines under consideration for conversion, based on a fleet of 21 articulated buses each with an annual mileage of 60,000 km and including consideration of all the required infrastructure costs. The sub modes evaluated were diesel bus, gas bus using fossil CNG, gas bus using biomethane and trolleybus.

Diesel bus was the lowest cost option by a significant margin, but annual operating costs for the gas bus using fossil fuel were similar to those for trolleybus. The environmental benefits of biomethane were recognised, but there were concerns about the future cost of biomethane in the event of demand for this fuel increasing.

The economic evaluation included assessment of the additional financial expenditure in relation to the levels of CO_2 reduction achieved relative to the diesel bus. This highlighted the very poor performance of the gas bus using fossil fuel in this respect.

The evaluation concluded that gas buses were unsuitable from an economic and environmental perspective and would also represent a technological dead end without obvious potential for future traction energy savings.

The preferred option from an operational, energy, environmental and economic perspective was the conversion of lines 69 and 80 to trolleybus operation. The reasons cited to support this conclusion were:

- Trolleybus system has no local emissions and also offers noise reduction benefits;
- Much higher performance and operational development potential including for use of bi-articulated vehicles;
- Electrification sets infrastructure requirements aligned with possible future technological developments e.g. battery electric buses.

Figure A.1: Carosserie Hess / Vossloh Kiepe Swisstrolley4 Articulated Trolleybus, Zürich

Source: VBZ

A.2 Partial catenary free operation of trolleybus with traction battery and super-capacitors in Eberswalde, Germany

Established in 1940, the Eberswalde trolleybus system is the oldest of three trolleybus systems in Germany. The trolleybus network consists of two routes, each around 18 km in length and with a significant common section of route within the West End area and city centre, before diverging to serve separate termini to the north (line 861) and east (line 862). There are three further routes operated by diesel buses.

The trolleybus fleet was renewed between 2010 and 2012 and currently comprises 12 Solaris Trollino 18 AC articulated trolleybuses. 11 of these vehicles have a diesel auxiliary power unit and one, delivered in 2012, has a lithium-ion traction battery with a capacity of 72 kWh. The electrical and electronic equipment is supplied by CEGELEC. The entire fleet is equipped with on-board super-capacitors, enabling the electric energy required for acceleration or heating to be drawn from either the catenary or the super-capacitors.

The 'battery-hybrid' trolleybus can receive power either via the catenary or the battery. Over short distances, for example in the depot, the bus can additionally run on power from the super-capacitors. In test mode this bus was able to run over the full route distance of 18 km, powered only by the battery. In operation, the bus is able to operate catenary free for up to 4 km of the 18 km route.

Under normal operation the maximum continuous distances operated on battery power are 3.1 km on line 861 and 2.9 km on line 862. The concept of operation is that with use of the super-capacitors to capture energy from regenerative braking for use to recharge the traction battery while the vehicle is operating on battery power over the 'catenary free' section of route (the OLE over this section remains in place but is not used by the battery-hybrid vehicle), the state of charge of the battery does not fall below the level of 70% considered beneficial to optimise the life of the battery.

Test results reported by the operator indicate that this has been successfully achieved over a 'catenary free' distance of 2.9 km on line 862. The test results for line 861 show that the battery charge falls just below the 70% threshold after operation over a 'catenary free' distance of 3.1 km.

Monitoring has also been undertaken over an extended period to calculate the savings in energy consumption achieved by fitting super-capacitors to the trolleybus fleet relative to the capital cost of circa 35,000 Euro per vehicle. The results indicate that the payback period for the super-capacitors is within the range 6 to 7 years.

The operator has also investigated the use of super-capacitors as an energy-storage device in a substation. In contrast to on-board super-capacitors, the stored energy in the substation is not bound to a specific vehicle and could release energy to all the vehicles at the same time. However, the conclusion reached was that this would not provide sufficient benefits to justify the cost.

Figure A.2: Solaris Articulated Trolleybus with Traction Battery and Super-capacitors

Source: Barnimer Busgesellschaft mbH

Table A.1: Technical Data for Solaris Trollino 18 AC 'Battery-Hybrid' Trolleybus

Description	Facts and figures
Vehicle	Solaris Trollino 18 AC
Length (m)	18.000
Height (m)	3.490
Width (m)	2.550
Passengers	140 (44 seated)
Wheelbase (m)	5.130 / 6.770
Drive	Cegelec INTEGRA
Energy Storage	Traction battery and super-capacitors
GVW	28,000 kg
ULW	18,225 kg

Source: Barnimer Busgesellschaft mbH

A.3 Operation of Optare Versa EV battery electric bus in Coventry, UK

Table A.2: Facts and figures for Optare Versa EV

Description	Facts and figures
Vehicle	Optare Versa EV
Price	£240,000
Length (m)	11.100
Height (m)	2.820
Width (m)	2.510
Passengers	30
Wheelbase (m)	5.82
Drive	Enova Systems P120 with summation gearbox, 120 kW (161bhp) at 650 Nm (479lbft)
Energy Storage	56 valance lithium ion/magnesium phosphate battery packs
Steering	Power-assisted
Brakes	Discs all around
GVW	12,500 kg
ULW	8,110 kg
Tyres	245/70 R19.5

Source: www.route-one.net

Three battery electric buses operated by Travel de Courcey are employed on the Coventry South park and ride service. The Optare Versa EV vehicles first entered service in Coventry in June 2012 – 14 months later than originally planned.

Charging infrastructure had to be considered and installed. Travel de Courcey contributed £108,000 of their own money towards the infrastructure costs, with additional funding from the Green Bus Fund and Cenex Plugged In.

Three slow recharging points have been installed at the depot – one for each bus. The slow charger is set by a timer to come on at midnight to ensure Economy 7 electricity is used. This takes six hours to charge up the vehicle ready for the next day.

The fast charging station was made in Holland. This is capable of taking the Versa EV batteries to full capacity in less than two hours, thus potentially doubling the vehicles' daily range. The installation proved more costly than originally anticipated because of the remoteness of the electricity substation, some 400 yards away. Limitations on the available power supply means that instead of one 50kVA point (for the fast charger), 2 x 25kVA points are used. This means that each bus has three recharging points, two for the fast charger and one for the slow charger.

All three Versa EV's run during peak times. The vehicles are first recharged after the morning peak using the fast charging point for an hour, a vehicle at a time. A further half hour top-up is done in the afternoon, again one vehicle at a time.

The maximum range is 75 to 95 miles subject to the terrain based on one overnight charge.

The service headway is 15 minutes over a 2.5 mile route. The service runs from 0725 hours to 1810 hours. Each bus consumes approximately £14 of electricity each day. These are effectively zero emission vehicles producing no PM10, nitrogen oxide, carbon monoxide or carbon dioxide.

A.4 Operation of fuel cell-hybrid articulated buses in the Rhineland, Germany

This project aimed to provide an energy efficient and environmental friendly, as well as flexible, public transportation service.

In September 2011, Cologne started using two fuel cell hybrid articulated buses in their daily operations. These vehicles are 18 metres in length. The drivers were required to have special training beforehand to become accustomed to the road behaviour.

The advantages of this vehicle are comfort due to excellent suspension, air conditioning and spacious facilities. The vehicle is easily accessible via wide doors. The hydrogen fuel is sourced as a by-product from the chemical industry in the Cologne region. The vehicle does not emit carbon dioxide. Noise is reduced significantly compared to diesel vehicles.

The range of the fuel cell hybrid bus is lower compared to a conventional diesel bus.

Technical standards have to be improved; including the hydrogen infrastructure in the Rhine-Erft region. The investment costs were around 1.86 million Euro per bus – this equates to six times the cost of a comparable conventional diesel bus.

A.5 Replacement of diesel bus fleet by CNG buses, Frankfurt Oder, Germany

A fleet of 22 CNG buses has been running successfully in Frankfurt Oder for the last 5 years.

The 22 CNG buses cost approximately 6.4 million Euro. The fleet consists of 11 12m rigid and 11 18m articulated buses. The MAN CNG bus utilises a 310 hp CNG turbo engine.

A CNG filling station was built by a local energy provider outside the SVF depot. This consists of a 3-stage bank:

- 250 bar, capacity of 3,200Nm^3/h in 162 bottles;
- 5 fountains (2 for bus, 3 for car);
- 2x350Nm^3/h, hydraulic double acting compressor, public use possible.

The only other costs for infrastructure conversion for CNG buses were special tools and a gas alarm system for the garage.

Refuelling time rose to approximately 8 minutes, but at no extra cost to SVF due to servicing being done in this time. The fuel consumption of the vehicles is within the range 37 - 47 kg CNG per 100km. Emissions are below the requirements of the EEV standard.

A.6 Operation of MAN CNG buses in Norfolk and Suffolk, UK

Anglian Bus, part of the Go-Ahead group, purchased 13 gas powered MAN EcoCity 12m single deck buses in 2012. The EcoCity fleet runs on biogas – a renewable energy source produced from biodegradable waste materials.

The additional cost of the fleet over comparable diesel buses was £624,000. This was funded by a grant from the Green Bus Fund. Before purchasing, it was estimated that a CNG fleet of at least 8 buses would be needed to cover the infrastructure costs.

From four months operation, with a total distance covered of 238,000km, average fuel consumption is 3km/kg, with an approximate forecast of fuel saving of £10,000 per bus per annum compared to the Euro III diesel buses they replaced. Emissions from the EcoCity buses are up to 96% lower than a conventional diesel bus.

Infrastructure costs were approximately £250,000 which includes:

- A gas main extension;
- Enhanced electricity supply; and
- Workshop alterations including non-explosive lighting, roof venting and monitoring equipment.

A.7 Introduction of a fleet of diesel hybrid articulated buses in Flanders, Belgium

The aim of the project was to replace old high floor trolleybuses with a fleet of easy accessible vehicles reaching the highest standards on energy efficiency and to reduce negative impacts such as noise and emissions in the urban area of Gent.

In the summer of 2010, 20 articulated hybrid buses entered service in Gent. These were perceived by the public to be quieter with reduced vehicle emissions.

The hybrid vehicle has regenerative braking; this recuperates braking energy towards energy storage equipment such as super-capacitors (commonly named ‘supercaps’ or ‘ultracaps’) or batteries; this energy is used again while accelerating.

The hybrid vehicle also has enhanced acceleration; because of the assistance of the electricity coming from the energy storage, the diesel motor can be reduced in size compared to classic articulated diesel buses, while having better and seamless acceleration. The ‘downsizing’ of the diesel engine reduces the weight of the engine from approximately 1000 kg to around 450 kg. In comparison, the old trolleybuses were using electricity for braking instead of recuperating electricity, mainly in the electric brake with Foucault-currents.

The hybrid vehicle has improved fuel economy and less exhaust products relative to a conventional diesel bus. Moreover, the diesel motor of a hybrid bus can run over a narrow and optimal number of revolutions per minute range, close to its peak efficiency. The torque curve of the hybrid-bus engine is therefore tailored to frequent steady-state operation, for optimal emissions performance and fuel efficiency.

Appendix B. Vehicle Characteristics

B.1 Trolleybus

Table B.1: General Characteristics of Trolleybus Vehicles

Manufacturer	Hess	Solaris	Van Hool
Vehicle name / model	Swisstrolley III	Trollino 18 AC	AG300T
Passenger capacity	130 (44 seated) to 142	140 (44 seated)	141 (43 seated)
Length (m)	17.976	18.000	17.980
Width (m)	2.550	2.550	2.490
Overall height (m)	3.422	3.490	3.500
Door configuration	4 double	4 double	3 double
Turning circle (m)	11.965	11.500	11.300
Maximum speed	65 kph	70 kph	65 kph
Maximum operating gradient (%)	15	TBC	TBC
Operating acceleration (m/s^2)	1.3	1.4	1.3
Operating deceleration (m/s^2)	1.3	TBC	1.2
Line voltage	DC 600 (+25%;-30%)	DC 600 or 750	DC 600 (+25%;-30%)
Power source	Overhead line	Overhead line	Overhead line
Auxiliary power options	Diesel generator or traction battery	Diesel generator or traction battery; super-capacitors	Diesel generator or traction battery; super-capacitors
Regenerative braking	Yes	Yes	Data
Operational locations	Zurich, Switzerland	Eberswalde, Germany	Geneva, Switzerland

B.2 Diesel Hybrid Bus

Table B.2: General Characteristics of Diesel Hybrid Vehicles

Manufacturer	Solaris	Volvo	Wrightbus
Vehicle name / model	Urbino 18 Hybrid	7900 Articulated hybrid	StreetCar RTV
Passenger capacity	TBC (33 seated)	154 (42 seated)	113 (37 seated)
Length (m)	18.000	18.000	18.699
Width (m)	2.550	2.550	2.520
Overall height (m)	3.250	3.280	2.754
Door configuration	1 single + 3 double	4 double	2 double
Turning circle (m)	TBC	11.966	11.489
Maximum speed	TBC	TBC	TBC
Maximum operating gradient (%)	TBC	TBC	TBC
Operating acceleration	TBC	TBC	TBC
Operating deceleration	TBC	TBC	TBC
Power source	Parallel hybrid drivetrain. Cummins ISB6 diesel engine; Nickel-metal hydride battery	Parallel hybrid drivetrain. Volvo D5K Euro 6 diesel engine; Lithium Ion battery	Diesel engine; battery
Auxiliary power options	N/A	N/A	N/A
Regenerative braking	Yes	Yes	Yes
Operational locations	-	-	Las Vegas

B.3 Plug-in Hybrid Bus

Table B.3: General Characteristics of Plug-in Hybrid Vehicles

Manufacturer	Volvo
Vehicle name / model	7900 Articulated hybrid
Passenger capacity	154 (42 seated)
Length (m)	18.000
Width (m)	2.550
Overall height (m)	TBC
Door configuration	4 double
Turning circle (m)	11.966
Maximum speed	TBC
Maximum operating gradient (%)	TBC
Operating acceleration	TBC
Operating deceleration	TBC
Power source	Volvo D5K Euro 6 diesel engine; Lithium Ion battery
Auxiliary power options	N/A
Regenerative braking	Yes
Operational locations	-

B.4 CNG Bus

Table B.4: General Characteristics of CNG Vehicles

Manufacturer	MAN	Volvo
Vehicle name / model	Lion's City G	7900CNG Articulated
Passenger capacity	up to 150 (51 seated)	150 (42 seated)
Length (m)	17.980	18.084
Width (m)	2.500	2.550
Overall height (m)	3.320	3.356
Door configuration	3 double	3 or 4 double
Turning circle (m)	11.696	11.966
Maximum speed	TBC	TBC
Maximum operating gradient (%)	TBC	TBC
Operating acceleration	TBC	TBC
Operating deceleration	TBC	TBC
Line voltage	N/A	N/A
Power source	CNG	CNG
Auxiliary power options	N/A	N/A
Regenerative braking	No	No
Operational locations	Frankfurt Oder, Germany Gdynia, Poland	-

B.5 Fuel Cell Hybrid Bus

Table B.5: General Characteristics of Fuel Cell Hybrid Vehicles

Manufacturer	APTS
Vehicle name / model	Phileas
Passenger capacity	96 (37 seated)
Length (m)	18.490
Width (m)	2.540
Overall height (m)	3.200
Door configuration	3 double
Turning circle (m)	12.000
Maximum speed	80 kph
Maximum operating gradient (%)	TBC
Operating acceleration	TBC
Operating deceleration	TBC
Power source	Ballard HDE fuel cell
Auxiliary power options	N/A
Regenerative braking	Yes
Currently available in UK	No
Operational locations	Cologne

B.6 Battery Electric Bus

Table B.6: General Characteristics of Battery Electric Vehicles

Manufacturer	BYD	Optare	Solaris
Vehicle name / model	ebus	Versa EV	Urbino 12 Electric
Passenger capacity	62 (21 seated)	59 (38 seated)	68 (35 seated)
Length (m)	12.000	11.100	12.000
Width (m)	2.550	2.510	2.550
Overall height (m)	3.200	2.820	3.250
Door configuration	2 double	1 double	up to 3 double
Turning circle (m)	12.000	TBC	TBC
Maximum speed	70 kph	TBC	TBC
Maximum operating gradient (%)	TBC	TBC	TBC
Operating acceleration	TBC	TBC	TBC
Operating deceleration	TBC	TBC	TBC
Power source	Lithium Iron Phosphate battery packs	Valance Lithium Ion / Magnesium Phosphate battery packs	Lithium ion batteries
Auxiliary power options	N/A	N/A	N/A
Regenerative braking	Yes	Yes	Yes
Currently available in UK	Yes	Yes	No
Operational locations	London	Coventry	-