Background paper: **Comparative analysis of bus technologies for fleet renewal**

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List of acronyms

A-S-I	Avoid, shift, improve
BEB	Battery electric bus
CAPEX	Capital costs
CH4	Methane
CNG	Compressed natural gas
CO2	Carbon dioxide
CO	Carbon monoxide
dBA	A-weighted decibel
EM	Electric traction motor
FAME II	Faster Adoption and Manufacturing of Hybrid and Electric Vehicles Scheme (in India)
FCEB	Fuel cell electric buses
GHG	Greenhouse gases
HEV	Hybrid electric vehicle
HVAC	Heating, Ventilation, Air-conditioning Systems
HY	Hybrid propulsion system
LFP	Lithium-ion battery using lithium iron phosphate as the cathode material
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
ICE	Internal combustion engine
IMC	In motion charging
NMC	Lithium-ion battery using nickel manganese cobalt as cathode material
NOx	Nitrous oxides
OPEX	Operating costs
PHEV	Plug-in hybrids electric vehicle
PM	Particulate matter
SORT	Standardized on road test cycle
TCO	Total Cost of Ownership
TTW	Tank-to-wheel
VOCs	Volatile organic compounds
WTW	Well-to-wheel

Introduction and scope

Cities and urban agglomerations around the world are experiencing a rapid growth of urbanization. This increasing urban population is in urgent need of efficient and well-developed mobility options including an inclusive public transport network, especially in developing and emerging countries. The economic growth in the last few decades, rising aspirations, and falling cost of private vehicle ownership has significantly increased private car ownership and usage especially in developing economies, leading to several urban problems such as air pollution, accident-related fatalities, and urban sprawl.

Cities and economies around the world are starting to realize the fallacy of this trajectory of growth and going through a fundamental re-examination to achieve a paradigm shift in urban mobility. One of the approaches that is being adopted is known as A-S-I (Avoid/Reduce, Shift/Maintain, Improve). "Avoid" strategies are targeted towards reducing the need to travel, or reducing the lengths travelled. "Shift" measures are focused towards encouraging people to use more sustainable public transport and active transport modes. "Improve" measures are targeted towards vehicle, fuel, and operational efficiency of transport systems, which will be the focus topics of this paper.[1]

By investing heavily into urban public transport, both buses and metros, city governments around the world are trying to decouple the trend of private vehicle ownership from economic growth. Metros or urban railways are capital intensive and usually require a long development cycle compared. In comparison, urban bus systems are flexible, less costly, and much easier to implement in a short span of time. Administrations are recognizing the importance of a decent quality of bus operation to address issues of convenience, inclusion, social equity, and justice. Developing transport nodes, in the longer term, are becoming the agents of changes in land-use planning and population densification, facilitating the delivery of "Avoid" strategies. Consequently, the number of transit buses is rapidly increasing. Several countries are setting ambitious service level benchmarks to achieve urban bus densities. For a meaningful comparison, this study will focus on a standard 12m transit bus with an average capacity of ca. 80 passengers as this is the major type of transit bus operating worldwide.

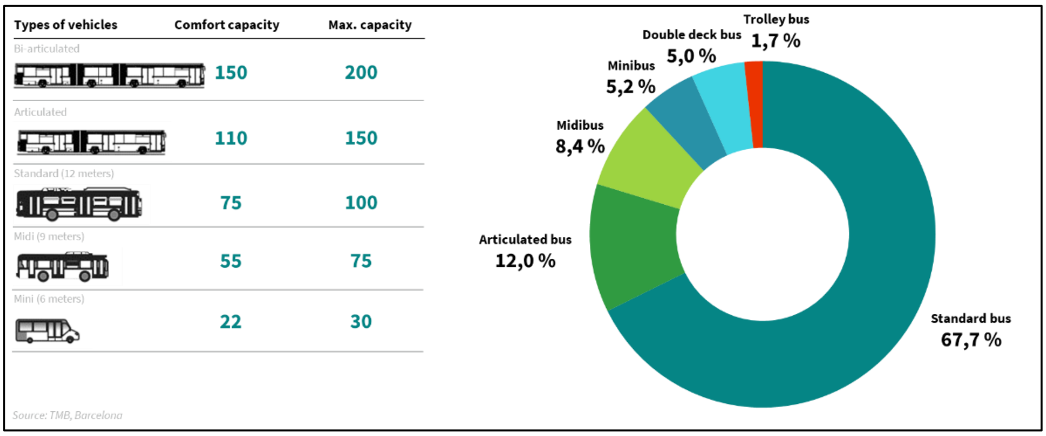

Figure 1: Capacity and market share by bus types

[1] SUTP (2019) Sustainable Urban Transport: Avoid-Shift-Improve (A-S-I) https://www.transformative-mobility.org/assets/publications/ASI_TUMI_SUTP_iNUA_No-9_April-2019.pdf

Though highly space efficient and with much lower emission footprint per capita as compared to private cars, road-based public transit has historically been primarily based on fossil-fuel based internal combustion engines. A few Eastern European countries, which used electric driven trolley buses, were the exception until a big push by the Chinese government for the adoption of electric buses in the last decade. Fulfilling the mobility needs of the citizenry with conventional bus technologies has raised concerns about air and noise pollution, as well as detrimental consequences for climate change. A shift towards sustainable solutions and alternative drive technologies addresses pollutant emissions and consequent air quality issues. It helps to reduce the negative impacts on climate, health and the economy that arise with increasing urbanization. Poor air quality impacts public health which inordinately affects the poorer segments of urban settlements.

Bus fleets must be renewed on a regular basis (ca. every 10 to 18 years but varies significantly), transit agencies typically are active adopters of alternative fuel options as they naturally try to lower their fuel costs and employ more efficient fuel options.[2] Many of the large developing countries like India and China are also significantly dependent on the imported fossil fuels exposing them to currency exchange linked market risks.

Currently, many bus propulsion technologies are available on the market, and choosing the most suitable and sustainable option is crucial for transit agencies to increase their efficiency and make public transport more environmentally friendly. There is no one-size-fit-all kind of solution for cities yet and transit agencies pick and choose a propulsion technology based on their local needs and operational expectations.

For transit agencies and other relevant stakeholders to be able to make fully informed decisions, for or against a specific technology for their bus fleet augmentation or renewal, a multitude of criteria needs to be evaluated. These criteria include capital expenditures, operating costs, greenhouse gas, air and noise emissions, operation criteria like driving range, maintenance while enabling social aspects such as inclusiveness and accessibility.

This report is to serve as a reference document for transport operators, policy makers and urban planners aiming to introduce, renew or expand bus fleets. The report gives an overview of different transit bus technologies and provides necessary background knowledge about strengths and weaknesses, as well as suitable deployment contexts for different technologies. The goal of this report is to enable decision makers to take informed decisions about bus fleet procurement while considering local conditions, technological developments, and their contribution to climate protection.

This overview is structured in six parts:

1. Technology – This section provides a broad overview of various propulsion technologies available around the world, such as internal combustion engine, electrical motor, and hybrid propulsion systems.
2. Operation – This section covers the operational aspects of various propulsion technologies, such as passenger capacity, range, refuelling/recharging, etc.
3. Maintenance – This section covers the engineering and maintenance aspects of various propulsion technologies, such as reliability, skills, spare parts, etc.

[2] Traffic21 Institute, "Which Alternative Fuel Technology is Best for Transit Buses?", 2017 https://www.cmu.edu/traffic21/pdfs/alternative-fuels-policy-brief-buses_web.pdf

4. Environmental impact – This section provides a comparison of emissions and environmental footprint of different bus technologies, considering noise and air pollution, and especially, GHG emissions.
5. Financial aspects – This section convers the financial performance as well as the financial frameworks for different bus technologies, considering capital and operational costs in vehicles and infrastructure.
6. Conclusion – This section provides a summary and an outlook on the deployment of bus technologies

Technology

Fundamentally, three types of propulsion systems are used in transit buses. These are the Internal Combustion Engine (ICE) Propulsion System, the Electric Traction Motor (EM) Propulsion System and the Hybrid (HY) Propulsion System. Each type can be divided into further sub-categories depending on the kind of fuel being used and the alignment of the components in the propulsion system. The following chapter provides an overview of the different options.

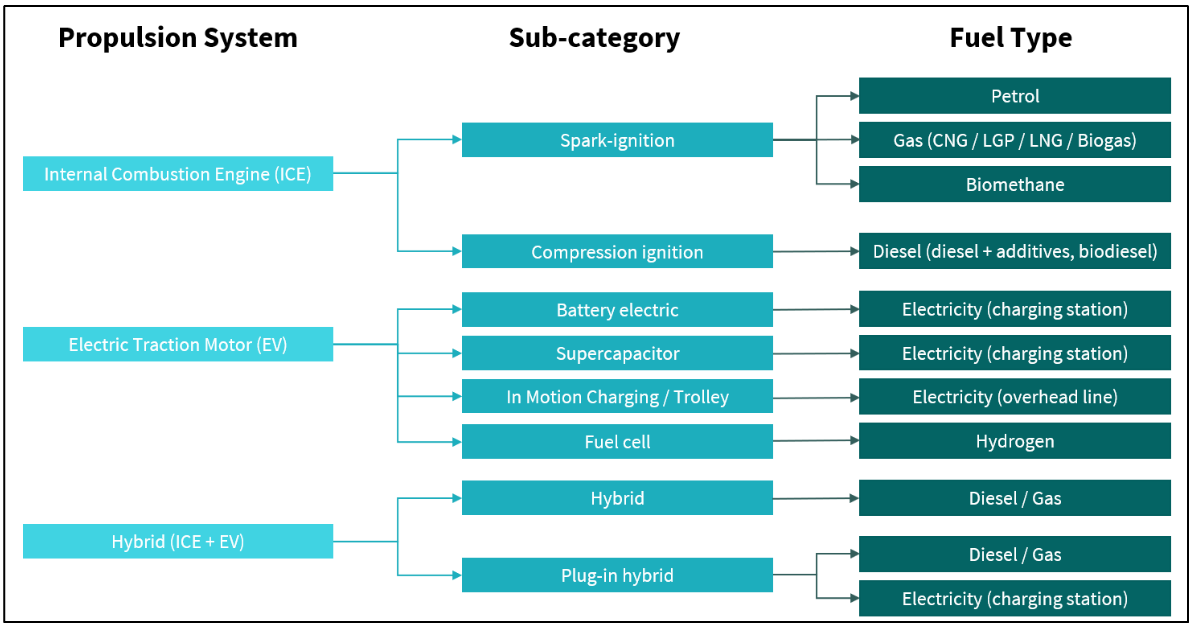

Figure 2 Overview of technologies (Own source)

Internal combustion engine (ICE) propulsion systems

An ICE is a heat engine in which the combustion of the fuel occurs in a combustion chamber that creates high temperature which in turn expand the gases, creating a high pressure. This applies direct force typically on a piston, generating kinetic energy which is then used to propel the engine.

Besides the engine, another important part of the ICE powertrain is the transmission / gearbox which is a torque and speed converter that adapts the traction output of ICE to the traction requirement of the bus. These transmission systems can be manual (in older vehicles) or automatic (in newer vehicles).

The two most common types of ICE are spark-ignition engines and compression ignition engines. Different spark-ignition engines can be run with petrol or Compressed Natural Gas (CNG) or Liquefied Petroleum Gas

(LPG) while the compression ignition engines are run with diesel. In the following, the different ICE types are explained in more detail based on the fuel type they run on.

Diesel buses

Compression engines running on diesel produced from crude oil is the most widespread bus technology prevalent around the world. Compression engines running on diesel have been the preferred choice for buses (and heavy-duty vehicles in general) as their operation has lower costs than the petrol counterparts. The costs are lower mainly due to the diesel motor being more fuel efficient and the diesel fuel containing between 10% and 15% more energy than gasoline[3]. Diesel buses are available in all shapes and sizes; ranging from smaller 9m buses to longer 18m articulated buses, they are also widely seen as single decker buses as well as double-decker buses, which comprise most of the fleets in cities like London, Singapore, and Hong Kong.

Instead of conventional diesel, buses can also be powered with biodiesel, a renewable fuel produced from vegetable or waste oils. Often, vehicles are powered by a blend of diesel and biodiesel (e.g., B20 = 20% biodiesel, 80% diesel). The origin, production and composition of the diesel and biodiesel fuel has significant consequences for the costs and emissions calculations of diesel buses. The availability of biodiesel is also a hurdle towards its sustainable deployment as it contributes to crop-competition and expansion of crop areas, which will be further discussed in chapter 4 on environmental impact.

Gas buses

Gas fuels such as compressed natural gas (CNG), liquefied natural gas (LNG) and liquefied petroleum gas (LPG), just like diesel, are derived from petroleum. LPG is the third most common vehicle fuel after petrol and diesel.

CNG and LNG are both methane derived from oil and gas fields. CNG is stored under pressure, whereas LNG is cooled into liquid state for storage. LPG is a mixture of by-product from petroleum refinement such as butane and propane.

Both forms of natural gas require special safety tanks onboard. They are cheaper to operate as compared to diesel when local sources and a distribution network are available. Approximately 11% of global bus fleet runs on Natural Gas[4].

Instead of natural gas, buses can also function with biogas, which is a renewable fuel produced from organic materials/waste that is broken down by gasification or microbial activity[5]. This process removes carbon dioxide, moisture and hydrogen sulphide and therefore becomes biomethane. It is claimed that biogas technology produces up to 84% less greenhouse gases than diesel and can reduce fuel costs by up to 30% (Sustainable passenger vehicle solutions, n.d.). It can also be liquefied or compressed. As with biodiesel, the availability, origin, and production can have an impact on the cost, emission calculations and overall sustainability.

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[3] Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy, "Fueleconomy.gov" accessed February, 2023, www.fueleconomy.gov

[4] Union Internationale des Transports Publics (UITP) , "Global Bus Survey 2019", 2019, https://www.uitp.org/publications/global-bus-survey/

[5] Clean Fleets Project, "Clean Buses – Experiences with Fuel and Technology Options", 2014, https://www.ajsosteniblebcn.cat/clean-buses_31741.pdf

Electric motor propulsion systems

The EM propulsion system uses a traction motor system powered by electricity that comes from a battery, overhead line, supercapacitor, or a fuel cell. As there is no combustion within the bus, there is no discharge of any gases at the tailpipe. Electric motors, unlike ICE, do not need a transmission / gearbox system as they can match the output torque requirements by simply adjusting the motor speed. An electric motor can also output the torque rotation in reverse direction, which allows them to recover energy through regenerative braking.

Battery electric buses

A basic battery electric (BEB) drivetrain consists of an on/off-board charger, a traction battery converter, an auxiliary battery converter, and a motor drive. The power is stored in batteries and electricity is generated through an ion-exchange process (electrolysis) on-board, which is then directly fed to power the traction motor. The power storage system or batteries can be recharged by reversing the ion-exchange process. Batteries have become mainstays as fuel storage units and utilised in a wide range of bus types. Due to cost, degradation over the lifecycle, and the amount of research that is going into the topic, batteries are considered the crucial component in the BEB. They are available in different chemistries and configurations, but they are primarily Lithium-ion based. In a battery system, dozens or typically hundreds of single cells are connected in series, forming a string.

The current global fleet of BEBs is estimated at approximately 700,000 units of which 98% of the fleet is in China. Bloomberg NEF forecasts that there will be 1.7 million BEBs on roads by 2030.[6]

In motion charging (IMC), Trolley buses

Trolley buses use in motion charging (IMC) systems through pantographs that connect to overhead wires. IMC allows these electric buses to run on smaller and lighter batteries, which leads to reduced overall weight and battery resources. To capitalize on the advantages of IMC an overhead wire network needs to be set up along the relevant routes. Traditionally, trolley busses were most common in the Eastern European countries. Only a few of such systems are left now as the massive deployment of the diesel buses, more flexible in terms of route due to not requiring overhead lines, after 1945 reduced their market share strongly. Nowadays, due to more efficient batteries, the flexibility of electric trolley buses has increased as the buses have a higher range when disconnected from the overhead wires. IMC systems are seeing a revival mainly in high-frequency, high-demand corridors (e.g., BRT applications) with high daily mileage and hilly terrain. [7]

Supercapacitor buses

Supercapacitor buses are a type of electric bus which stores electrical charge in electric double-layer capacitors instead of batteries. They operate in a similar manner to BEBs but have much lower range. They can quickly be fully charged using a plug-in charger or a pantograph charger in ca. 5 minutes and give a mileage range of 5-10 kms per charge. These buses are generally deployed in predictable routes, often as feeder shuttles in e.g., airports. Even though a few trials are ongoing in China, Hong Kong, and Europe, they are yet to catch on and hence not discussed further in this report.

[6] BloombergNEF, "Electric Vehicle Outlook 2022", 2022, https://about.bnef.com/electric-vehicle-outlook/

[7] Union Internationale des Transports Publics (UITP) , "Infrastructure for in motion charging trolleybus systems", 2021, https://cms.uitp.org/wp/wp-content/uploads/2021/07/Knowledge-Brief-IMC.pdf

Fuel cell electric buses

Hydrogen is another fuel used to power EM propulsion systems. However, unlike other electric buses, the power is generated on-board using fuel cells and hydrogen as fuel. Like the fuel on conventional buses, compressed hydrogen is carried on-board in tanks and fed into fuel cells where they react with oxygen and generate electricity. The only discharge in this process is pure water. These tanks can be refilled similar to conventional ICE buses through a flexible hose and nozzle connected directly to the vehicle's tank. As hydrogen is stored under high pressure in the vehicle tank, typically 350 bar, the refuelling station additionally requires other components such as a compressor. The drivetrain, however, is that of electric buses.[8]

Hydrogen as a fuel is attracting a high degree of interest in the public transit sector. Hydrogen, despite not being a primary source of energy like fossil fuel, can be used as an energy carrier, like electricity, and as a means of storage, like batteries. The biggest issue with hydrogen is that although plentiful, it does not occur in a natural state but must be produced either through electrolysis or using an industrial process. Both processes have a very low efficiency compared to other the production of other types of fuel. Hydrogen is also flammable and bulky compared with many other fuels.

In the last few years, the share of hydrogen fuel cell electric buses (FCEB) in the bus market has grown. Presently, hydrogen buses are still in a pilot stage and not produced or deployed at large scales. Currently, an estimated number of 35,000 fuel cell electric vehicles (FCEBs) exist worldwide, mostly light duty passenger vehicles, with buses having a 14% share.[9] FCEBs are growing exponentially with Japan's fleet of FCEBs projected to reach 200,000 by 2025 and China setting an ambition of 1 million FCEBs by 2030.

Hybrid systems

As the name suggests, hybrid propulsion systems combine both ICE and electric motor propulsion systems to optimize the positive qualities of both the systems. ICEs are optimized at constant speeds whereas electric motors are ideal for variable speeds. Each of the engine types is tapped accordingly for the vehicle propulsion needs making hybrid buses more efficient that their ICE counterparts. The drivetrains can be sequenced in many ways and the three most common ones, the non plug-in, the parallel plug-in and the series plug-in hybrid are shown in figure 3 below.

As there are two type of propulsion systems on-board, the weight of the vehicle increases, which in turn requires a higher amount of energy to drive the vehicle. This can be partially offset by the higher efficiency of the combined propulsion system. Yet studies from ICCT have shown that the real-world fuel consumption from hybrid vehicles is on average three to five times higher than what is specified in test procedures due to higher use of the ICE mode.[10][11]

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[8] Fuelcellbuses.eu, "Hydrogen refuelling concepts", accessed February 2023, https://www.fuelcellbuses.eu/category/concepts

[9] International Energy Agency (IEA), "Fuel cell electric vehicles stock by region and by mode", 2020, https://www.iea.org/data-and-statistics/charts/fuel-cell-electric-vehicles-stock-by-region-and-by-mode-2020

[10] ICCT, "Real-world usage of plug-in hybrid vehicles in Europe", 2022, https://theicct.org/publication/real-world-phev-use-jun22/

[11] Keramydas et al., "Real-World Measurement of Hybrid Buses' Fuel Consumption and Pollutant Emissions in a Metropolitan Urban Road Network", 2018, https://www.mdpi.com/1996-1073/11/10/2569

In a conventional parallel hybrid, both, the ICE as well as the electric motor can drive the axle directly. Both engines are connected to the power transmission which enables the vehicle to be powered either by one or both engines simultaneously.[12] The parallel hybrids are fundamentally operating on a dual-power system.

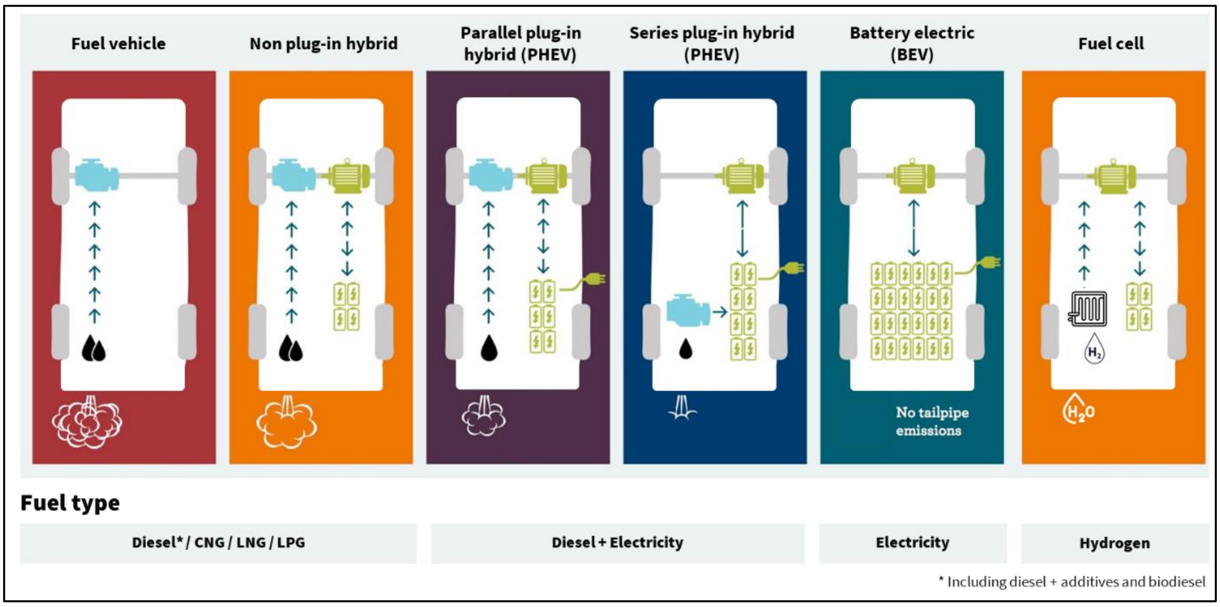

Figure 3: Main types of powertrains

In a series hybrid system, the ICE and drive axle are not directly linked: The ICE powers a generator that charges the vehicle batteries which in turn power an electric motor that drives the vehicle. The ICE is not directly connected to the transmission. This allows the vehicle engine to run the whole time at constant speed with maximum efficiency. The battery balances the constant output to the engine based on vehicle's demand. The series hybrid drivetrain is fundamentally an electric one where fossil fuel is used only for power generation for storage into batteries.

Blended or series-parallel hybrids are a combination of series and parallel hybrids that allow power paths to the wheels by either electrical or mechanical means.

Hybrid buses can be further differentiated between conventional (HEV) and plug-in hybrids (PHEV). In conventional systems, electricity is generated by on-board diesel engines and stored in the batteries for use by electric motors. On the other hand, in the plug-in system the batteries are charged from an external electric power source, thereby reducing the dependence on diesel as a fuel.

Hybrid buses usually involve diesel fuels. Although there are other forms of hybrid engines without electricity (e.g., diesel-hydrogen hybrids), they are very few in numbers and still in experimental stages. Hence, the focus of this report will be on diesel-electric hybrids. Hybrid buses are a proven technology that have reached high market maturity as the technology has been on the market for more than 20 years[13]. They are a suitable compromise that takes advantage of positive characteristics of both electric propulsion as well as ICE

[12] Benz, M., "TechView Report Electric Buses", *Fraunhofer MOEZ*, 2015, https://www.imw.fraunhofer.de/content/dam/moez/de/documents/Working_Paper/Working_Paper_Electric_Buses.pdf
[13] Grütter, J., "Real World Performance of Hybrid and Electric Buses", 2015, https://slocat.net/wp-content/uploads/legacy/u13/report_hybrid_and_electric_buses.pdf

propulsion. The vehicle is still primarily driving on fossil fuels, but the electric engine results in significantly less fuel consumption than diesel buses.

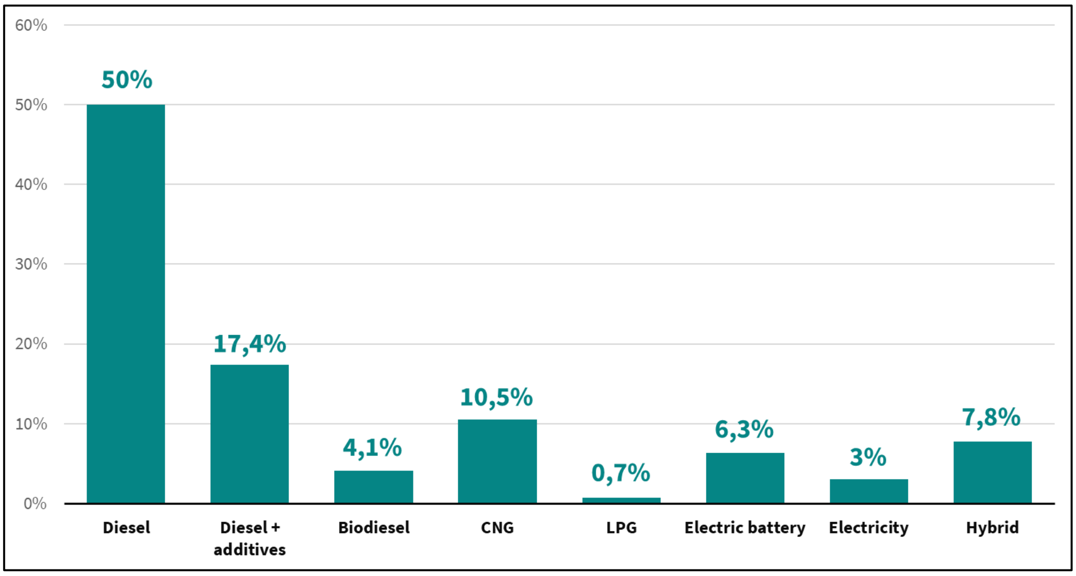

Figure 4 Market share of different vehicles based on fuels from the UITP Global Bus Survey 2019

Figure 4 shows the market share of the different propulsion systems based on the fuels they apply. Although the share of alternative bus technologies has been increasing for some years, approximately 70% of buses worldwide are still primarily reliant on diesel and over 60% of these buses are already on vehicle emission standard Euro IV or above.[14]

[14] Union Internationale des Transports Publics (UITP) , "Global Bus Survey 2019", 2019, https://www.uitp.org/publications/global-bus-survey/

Operations

When operating transit buses in urban areas there are many different factors that affect the performance and overall suitability of a certain technology. This chapter will take a closer look at the role that external factors such as driving pattern, climatic conditions, altitude and gradeability play in operation. Internal factors such as fuel efficiency, range, refuelling / recharging, and passenger capacity will also be assessed.

Driving pattern

One of the distinct characteristics of transit buses is that moving around cities requires frequent acceleration and braking. This could be due to frequent bus stops which are usually spaced 500 metres to a kilometre apart or due to the road junctions. In mixed stream traffic, transit buses also must vary their speeds frequently due to traffic congestion. This has a direct impact on the operating performance of buses and the resultant fuel consumption. A technology selection for the transit buses should take these characteristics, which may differ from city to city, into account.

In case of ICE propulsion systems, the gear/transmission needs to be constantly changing to cope with shifts in acceleration and braking. An ICE would keep running even when the bus is stationary. A transmission system would normally control how the energy produced in the ICE is transmitted into the drivetrain. Braking also means a loss of kinetic energy which is often dissipated through heat in ICEs.

Propulsion systems with electric motors, in contrast, fit very well for frequent acceleration and braking conditions. They do not require a transmission / gear system and their speed is controlled directly by the amount of energy produced by the electric motors. Electric, Hybrid and Fuel Cell buses can also be fitted with regenerative braking systems whereby the energy generated during braking is fed back into the energy storage system (usually batteries) on-board. This can make these types of buses more efficient for transit bus operations that involve frequent acceleration and deceleration.

In case of modern hybrid buses, ICE is normally not directly connected to the driving wheels and can operate in the optimal stationary mode, producing energy for traction motors. When hybrid systems are being designed, it is important to determine the optimal characteristics of ICE, ensuring its minimum fuel consumption, which affects their cost and performance.

Climatic conditions

The general climatic conditions affect the bus operations significantly and have a major bearing in the bus technology selection. All city buses, regardless of fuel source, experience some loss of range in extreme weather. These range losses are mainly related to changes in efficiency of the powertrain or to measures used to ensure passenger comfort, such as the use of heating, ventilation, air-conditioning (HVAC) systems.

Internal combustion engines run slightly more efficiently in cold and less efficiently in hotter ambient temperatures. EMs on the other hand, see a significant deterioration in their performance in cold weather and a smaller deterioration in hot weather. The optimal energy consumption of a BEB takes place at an ambient temperature of 20°C to 25°C. A US study found that in cold temperatures (between -5 and 0° C) the range of battery-electric buses decreases by up to 38% and up to 23% for fuel cell powered buses. [15]

Increases or decreases in ambient temperature above certain thresholds lead to the more frequent use of cooling or heating, which reduces the amount of energy that is available for the movement of the vehicle independent of the vehicle powertrain technology. In cities requiring intensive air-conditioning or heating inside the buses, up to 50% of the fuel or battery charge may be used by auxiliaries which then would have significant impact on the range that can be delivered on a single charge.[16] [17]

Altitude

The performance of an ICE deteriorates with altitude (cities higher than 2000 mean above sea level), which leads to an increase of fuel consumption and tailpipe emissions gases. [18] The fuel consumption can increase by roughly 10% for a 1,500-meter altitude gain. Fuel cell performance slightly degrades affected by altitude due to lower air pressure.[19] Electric buses on the other hand do not exhibit any significant constraints related to altitude.

Gradeability

ICE buses operate quite well in a flat environment and engines are optimized for the energy consumption at that level. Even though the engines are powerful enough to provide traction to negotiate rolling terrains or steep climbs, the fuel consumption (and consequent tailpipe emission) increases significantly. The engines also become noisier when they are climbing steep gradients. On downhills, the gravitational force assists the movement, but any energy dissipated during braking actions are often lost or wasted.

EM buses on the other hand can accelerate and climb hills as well or better than diesel and natural gas vehicles. They're much quieter in doing so too. Most EMs are also fitted with mechanisms to capture the braking energy and feeding it back to the drivetrain or storage systems. Such regenerative braking systems can capture nearly 30% of the energy dissipated, which can offset higher energy consumption required for climbing a gradient. The weight of the batteries on the BEB does act as a handicap while moving up slopes, therefore, there is large potential for combining BEB with the trolley ICM technology in hilly terrain. This combination would allow to downsize the batteries and lower the weight, while providing a charging opportunity while moving up the slopes.[20]

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[15] Henning, M., et al., "An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses", 2019, https://www.researchgate.net/publication/337290433_An_Analysis_of_the_Association_between_Changes_in_Ambient_Temperature_Fuel_Economy_and_Vehicle_Range_for_Battery_Electric_and_Fuel_Cell_Electric_Buses

[16] Bartłomiejczyk et al., "The reduction of auxiliaries power demand: The challenge for electromobility in public transportation", 2019, https://www.sciencedirect.com/science/article/pii/S0959652619346463

[17] Basma et al., "Comprehensive energy assessment of battery electric buses and diesel buses", 2019, https://core.ac.uk/download/pdf/222875995.pdf

[18] Giraldo et al., "Real emissions, driving patterns and fuel consumption of in-use diesel buses operating at high altitude", 2019, https://www.sciencedirect.com/science/article/abs/pii/S1361920918311428

[19] Albrecht et al., „Zukuenftige Kraftstoffe fuer Verbrennungsmotoren und Gasturbinen", 2013, https://www.ufop.de/files/8913/8384/3541/20131107_FVV-Kraftstoffstudie_LBST.pdf

[20] Union Internationale des Transports Publics (UITP) , "Infrastructure for in motion charging trolleybus systems", 2021, https://cms.uitp.org/wp/wp-content/uploads/2021/07/Knowledge-Brief-IMC.pdf

Hybrid buses perform quite well as far as gradeability is concerned as they are fitted with both a fossil fuel engine and electrical drivetrain. The electrical system in a hybrid bus is also equipped with a regenerative energy capture mechanism for braking. Nevertheless, the weight of carrying both propulsion systems is a clear handicap.

Fuel efficiency

Fuel efficiency is a direct indicator of cost of operations as well as environmental impact caused by the buses. Many countries have developed a Standardized Testing Mechanisms such as the "Standardized On Road Testcycle" (SORT) in Europe[21], which allows comparison of fuel efficiency on a like to like basis.

Energy consumption can vary considerably by driving cycle and hence, route characteristics such as road type, number of stops per kilometre, and average speed should be considered when evaluating potential alternative transit bus technologies. For buses with ICEs such as diesel, hybrid, and CNG, energy consumption tends to increase with higher stop and go operations requiring frequent acceleration/deceleration. These buses will consume less fuel per kilometre when deployed on routes with higher average speeds and fewer stops than on routes with high levels of congestion or low-speed, stop-and-go driving conditions:[22]

In one of the US studies using 40-foot Xcelsior buses (which the bus manufacturer New Flyer makes in diesel, diesel-hybrid, natural gas, and battery electric versions), fuel efficiencies in the standardized tests were as follows[23]:

- diesel bus: 2.05 kms per litre of diesel (48.78 l/100kms)
- diesel-hybrid bus: 2.48 kms per litre of diesel (40.32 l/100kms)
- natural gas bus: 1.90 kms per litre of diesel equivalent (52.63 l/100kms)
- battery electric bus: 1.26 kWh per km; equivalent to 7.99 kms per litre of diesel eq. (12.52 l/100kms)

Table 1: Energy consumption for alternative powertrains[24]

Bus technology	Commuter/suburban operation	Medium-speed urban operation	Low-speed urban operation
Diesel-electric hybrid	+2%	-20%	-21%
CNG	+5%	+11%	+23%
Battery electric	-67%	-75%	-73%

This case showed that BEBs can be four times more energy efficient than diesel or natural gas buses. The actual on-road fuel efficiency, however, depends on the specific route, including the vehicle's speed, number of stops, and terrain; passenger load; auxiliary uses of energy, e.g., air conditioners or heaters; and the inherent efficiency of the engine or electric motor.

[21] Union Internationale des Transports Publics (UITP), "SORT protocol", 2021, https://unece.org/sites/default/files/2021-05/Session%203.1%20-%20UITP%20-%20A.%20Kerkhof%20-%20C.%20Martin.pdf
[22] ICCT, "South Africa's Green Mobility Flagship Project: Leeto La Polokwane", 2021, https://theicct.org/publication/south-africas-green-mobility-flagship-project-leeto-la-polokwane/
[23] O'Dea, J., "Electric vs. Diesel vs. Natural Gas: Which Bus is Best for the Climate?", 2018, https://blog.ucsusa.org/jimmy-odea/electric-vs-diesel-vs-natural-gas-which-bus-is-best-for-the-climate/
[24] ICCT, "Low-Carbon Technology Pathways For Soot-Free Urban Bus Fleets In 20 Megacities", 2017, https://theicct.org/publication/low-carbon-technology-pathways-for-soot-free-urban-bus-fleets-in-20-megacities/

Due to their poor energy efficiency chain, FCEB have a very high primary energy demand and are, according to Doppelbauer (2019), not as environmentally friendly as often believed: Only 15-30% of the hydrogen energy is finally used at the FCEB drivetrain due to the elaborate production process. As hydrogen must be stored under extremely low temperatures or extremely high-pressure, high-energy amounts are required to create these storing conditions. Research is moving towards more efficient storage solutions such as the solid-state hydrogen storage systems based on light metal hydrides or hydride composites.[25] This value resembles the energy efficiency of diesel buses (20%[26]). In comparison, 69-80% of the used electrical energy remains for the propulsion of a BEB[27]. The huge loss of efficiency could be a decisive difference between BEBs and hydrogen buses.

Range

The energy density of diesel is much higher than that of batteries. This is particularly relevant since city buses are required to run for the entire day. Average public transport operator runs buses for about 150 to 300 km a day (approx. 50,000 to 100,000 kms a year). Transit buses have a more energy-intensive driving cycle due to traffic, more turning and stopping compared to intercity buses, e.g., conventional diesel buses, in most cases, with a full tank would give the daily range of far over 300km before needing to refuel, giving them a high level of operational flexibility. In case of refuelling, it is relatively a simple process and buses can be refuelled at any gas station.

Hybrid, natural gas, and hydrogen buses also have a similar range in transit service with between 320-500km before refuelling[28]. The route flexibility of hydrogen buses is therefore comparable to diesel buses.

The daily operating cycle of a BEB is heavily dependent upon the number of batteries included in the vehicle and the charging concept. According to the National Academies of Sciences, Engineering, and Medicine (2020), the actual operating battery range of BEBs is likely less than 250km with a single charge due to operational reserve that needs to be maintained. If BEBs are run on similar requirements as diesel buses (long distances on single charge) the biggest challenge is to range. There are examples around the world where replacing a route operated by diesel buses with BEBs required an increase in number of buses for operating the same frequency. There are approaches that help avoid the increase such as introducing opportunity charging or ICM as well as shortening or adapting the routes.[29]

Refuelling / Recharging

ICE buses and hydrogen fuel buses are fuelled at the refuelling stations. Regular gas stations are ubiquitous and do not require much explanation. Hydrogen fuel stations are specialist facilities with cryogenic handling and storage of the fuel in case of liquid hydrogen and high-pressure systems in case of compressed hydrogen.

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[25] Helmholtz-Zentrum hereon, „Hydrogen Storage Materials", accessed March 2023, https://www.hereon.de/institutes/hydrogen_technology/materials_design/hydrogen_storage/index.php.en
[26] Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), „Elektromobilität - was bringt sie mir? Faktencheck für heute und die Zukunft", 2018, https://www.kea-bw.de/fileadmin/user_upload/Kommunaler_Klimaschutz/Wissensportal/Mobilitaet/BMU_elektromobilitaet_2018.pdf
[27] Doppelbauer, M., „Strategiepapier elektrische Pkws - aktueller Stand und zukünftige Entwicklung", 2019, https://www.eti.kit.edu/img/content/Strategiepapier%20Elektroautos%20Stand%202019-10%20V1.5.pdf
[28] National Academies of Sciences, Engineering, and Medicine, "Guidebook for Deploying Zero-Emission Transit Buses", 2021, https://nap.nationalacademies.org/catalog/25842/guidebook-for-deploying-zero-emission-transit-buses
[29] ICCT, "Preparing To Succeed: Fleet-Wide Planning Is Key In The Transition To Electric Buses", 2020, https://theicct.org/preparing-to-succeed-fleet-wide-planning-is-key-in-the-transition-to-electric-buses/

Hydrogen fuel stations are much less common than Diesel or CNG, e.g., When rolling out FCEBs the infrastructure investment for these stations needs to be considered.

Several options are available for the recharging of BEBs. These are rapid charging and slow charging stations and both types are either implemented in the depot, at terminals or on the way (opportunity charging). Most commonly, buses are charged when they return to the depots or maintenance facilities for overnight parking. This gives sufficient time before the start of the morning service to fully charge through a slow charger overnight. Also, during the daytime between the morning and evening peaks, when service levels are reduced and buses are returned to the depot for parking, BEBs can be charged during the day. Buses using this slow-charging method require a large enough battery capacity (200-300 kWh) on board to run an average daily distance of 200-300km. If fast charging solutions are implemented, the batteries can be smaller as the charging times are shorter and can be more frequent. An analysis of charging strategies for BEB would exceed the scope of this paper. Nevertheless, decision makers need to consider that the charging strategy always should be adapted to the specific use case and include analysis on the bus model ranges available, route requirements, charging infrastructure networks and a business case.

Passenger capacity

Finally, the passenger capacity is a central topic that can vary between the bus technologies. The energy density of various fuels affects how much space needs to be devoted to its storage within the bus. A 12-meter diesel bus can provide a maximum capacity of approximately 80-100 passengers. Most models from other bus technologies allow similar numbers as the storage space of gases such as hydrogen and CNG can be steered based on the pressure. The batteries of BEBs can be quite voluminous depending on the chemistry and are either accommodated in the floor, or the roof or in the back. Choosing a larger battery and with that a longer range, it may take away certain amount of passenger capacity from BEBs. In Asian cities where the buses routinely run at peak capacity, this may mean that additional fleet may be required to service the same number of passengers.

Maintenance

Maintenance activities are critical for a successful delivery of a well-functioning bus operation. Bus breakdowns during operations could create significant customer relationship issues in milder cases and may jeopardize passenger and staff safety in extreme cases. Retrieval and redeployments may also be quite disruptive and costly. Especially when deploying innovative technologies, the behaviour of components over their lifecycle might be less well recorded as it is the case in market proven technologies. A lot of emphasis during technology selection, therefore, must be placed on the engineering and maintenance aspects. BEBs and FCEBs are still new technologies, and it must be considered that early adopters will face some maintenance challenges that are not because of the technology itself but solely due to the stage of the innovation cycle.

Reliability

"The business of a transport operator is to move people, and therefore they require high reliability in their work instrument".[30] Reliability and maintenance needs are thus crucial for transit agencies as bus schedules might be disrupted and additional buses are required to replace broken buses.

In addition to the long driving range, conventional diesel buses are characterized by high levels of reliability of over 90% of the time.[31] and availability due to the dominance and the technological maturity of fossil fuel which gives them a strong advantage over alternative technologies as these are not as well-researched and thus present higher risk for transit agencies.[32] Moreover, most alternative technologies require qualified staff and high expertise, especially CNG and LNG buses where specific safety measures are necessary due to the high-pressure tanks. As a result, natural gas buses have slightly higher maintenance costs (+15%) than diesel buses.[33] The maintenance costs of hybrid buses can be compared to those of diesel buses.[34]

In the long run BEBs are expected to be more reliable than the ICE counterparts due to having fewer moving parts inside the vehicle. Apart from tyres and wipers, there's no oil change, no complex exhaust system and even braking is largely done by the engine itself, sparing the mechanical brakes. During the market ramp up we are currently seeing that maintenance costs are reported to be similar as there are currently fewer spare parts available and not all mechanics are skilled well enough to repair electric buses.[35] BEBs were known to have a lower reliability rate than diesel buses in the early days of the technology[36]. When assessing the reliability and maintenance of BEBs it is also important to consider the charging stations as part of the deployed technology. Especially, high power fast chargers are a product that is seeing a lot of innovation and is more complex in operating and maintaining than the slow charging stations. As the roll-out of BEBs and charging infrastructure is moving ahead rapidly, so are the advancements regarding reliability.

[30] C40 Cities Finance Facility (CFF), "Evaluation of Electric Buses for Eje 8 Sur", 2018, https://cff-prod.s3.amazonaws.com/storage/files/0UfjGtaTa9DvErsxOvtsRUqWyVhy8223rwzGhclQ.pdf
[31] TRANSfer Project, "New Drive Technologies for Public Bus Fleets in International Cooperation", GIZ, 2016
[32] C40 Cities Finance Facility (CFF), "Evaluation of Electric Buses for Eje 8 Sur", 2018,
[33] TRANSfer Project, "New Drive Technologies for Public Bus Fleets in International Cooperation", GIZ, 2016
[34] Grütter, J., "Assessment of Low Carbon Bus Technologies for Vietnam", 2016
[35] ICCT, "South Africa's Green Mobility Flagship Project: Leeto La Polokwane", 2021, https://theicct.org/publication/south-africas-green-mobility-flagship-project-leeto-la-polokwane/
[36] Meishner, et al., "Technical and economic comparison of different electric bus concepts based on actual demonstrations in European cities", 2019, https://d-nb.info/1216637784/34

Trolleybuses and hybrid buses are reported to have a similar reliability as diesel buses (>90%), which is the result of the well-known and long-established technology, same as with the diesel technology.[37]

Safety

The protocols on keeping people, assets, and infrastructure safe during maintenance activities has been improved a lot over the past decades and most risks associated with ICEs are known and hence well-managed. Diesel buses due to their long history have through a series of incremental improvements and finally what we have is a relatively robust vehicle, nevertheless, accidents do happen. CNG/LNG/LPG require storing fuel at high pressure or cryogenic temperatures, both the states of matter which could potentially cause safety issues due to explosions. Fuel handling therefore requires staff training and certification on a consistent basis.

There have been single incidents with lithium-ion batteries on board of BEBs where overheating or physical impact has led to fires and explosions. This can be avoided if the batteries are handled with expertise. People handling the maintenance must be extremely careful in having clear procedures in place to ensure battery packs are not exposed. The maintenance team must have expertise regarding specific types of batteries, as lithium batteries are available with different cathode materials (e.g., LFP, NMC, etc.) which have different sensitivities.

FCEB have the same issues as CNG/LNG/LPG where the liquified hydrogen is present in cryogenic conditions in high pressure. This makes maintenance of these vehicles very specialized jobs. Bus operators must instil a training or certification process for the maintenance staff.

BEBs / Hybrids and FCEBs are, however, new technologies and some of the specific safety issues are still being discovered. For example, despite having very high standards of safety norms, in a recent incident a fire destroyed 25 BEBs in Stuttgarter Straßenbahnen (SBB)'s depot in Gaisberg on 30 September 2021. As a safety precaution, SBB has taken all buses of the suspected model out of service. There have also been incidents of "thermal runway" where one battery cell heats up unreasonably and ignites the adjacent cells in the battery pack. Water/humidity intrusion in the battery pack is another suspected cause of fires/explosions and most modern BEBs are extensively tested to obtain IP68 certifications, which is highest level of compliance against water intrusion.

On an overall basis, the number of safety incidents on BEBs are lesser than ICE buses. FCEBs are even more novel a concept and their risks will be known as they become more mainstream.

Technological advances (sensors, IoT, communication and computing) have created much safer systems by enabling platforms for real-time vehicle health monitoring systems and fault detection and correction systems. BEBs are part of new technology and a big part of battery management and charging management relies on these technological advances. Most of the ICE bus stock in the world is what is referred as the legacy stock. Because of this reason, ICE buses are mostly less high-tech as compared to BEBs.

Staffing and skills

The maintenance requirements for gas vehicles are in line with diesel vehicles. The use of NG/LPG buses and HDVs is not expected to have any impact on the resources required in terms of workshops and technicians.

[37] Clean Fleets Project, "Clean Buses – Experiences with Fuel and Technology Options", 2014, https://www.ajsosteniblebcn.cat/clean-buses_31741.pdf

Workshops can be refitted to install gas detectors, upgrade ventilation etc. to meet international standards for handling NG/LPG vehicles. No increase in vehicle mechanics is envisaged, although mechanics would be required to undergo retraining.

The adoption of new technologies such as BEBs and FCEBs will require a complete shift in fundamental skillset in the frontline staff. Even though from a driving perspective, there are no major changes apart from the interfaces with the on-board equipment and indicators, from a maintenance point of view there is a major shift from a mechanical propulsion system in ICE vehicles to a high voltage electrical propulsion system.

Having said this, the maintenance of BEBs is less onerous as compared to ICE buses due to less parts and simpler drive train. BEBs are generally also more digitalized and introduced in combination with advanced asset management strategies such as predictive maintenance platforms. These intelligent platforms further improve the productivity and reduces the need for manual inspections and interventions. Traditional diesel/LNG/LPG vehicles can also be moved to these platforms but in practice, most of those are still operated using manual or outdated IT platforms.

Being a new technology, FCEBs are also highly digitalized and equipped with advanced sensors and IoT devices. This makes their maintenance very efficient and like BEBs except that hydrogen storage (at high pressure or at cryogenic temperatures) and fuel cell maintenance require specialized staff and related skills.

From a maintenance activity point of view, there are systems or subsystems that are generally agnostic to the bus technology adopted. Components such as doors, windows, seats, radios, fareboxes, camera systems, multiplex systems, air system (except compressor drive), power steering (except pump drive) and brakes (except regenerative braking).

On the other hand, systems that are unique to each technology require deep technical skills to be developed or adapted within the maintenance teams. These components are the propulsion system, energy storage, HVAC, alternator, and the fuelling/charging system.

Both BEBs and FCEBs use electric powertrains. From the maintenance perspective, there is a risk associated with working on high voltage systems that can cause an electrocution and could be fatal. The maintenance staff therefore need specialised high voltage system training, certification and are required to wear Personal Protective Equipment (PPE), such as, insulated gloves, goggles, non-slippery insulated boots and "hot sticks" (a long, insulated pole that can be used to separate a person under electric shock from contact). BEBs are normally de-energised during routine maintenance activities but in activities where they need to be "live", floor areas or the zones must have adequate warnings for safety.

Depot layouts

For ICE, FCEB, and trolley electric buses, where the refuelling is typically done outside of the parking bays, there are two distinct functions in a bus depot - parking and maintenance. At the end of the duty cycle, the operator would, after basic inspections, refuelling and washing, park the buses at assigned or available parking spot. Maintenance teams, based on their preventive maintenance cycle, will take possession of the designated vehicles, and drive them to maintenance pits or bays. Once the maintenance is completed, these buses are driven back to parking bays for operators to put in service. As there are no activities at the parking bays where buses spend most of their time in the depot these spaces can be designed very efficiently and closely spaced. Apart from hydrogen storage and refuelling facilities, the FCEB depot layout is quite like ICE depots.

Apart from parking and maintenance, BEB depots also do another important function – depot charging. In most cases this is integrated within the parking, but space needs to be created to accommodate the charger installations. Buses while charging should also be well spaced for safety reasons. In case, charging is done separately (such as by using high-capacity overhead chargers), extra space is needed to accommodate the vehicle charging and movements in and out of these charging areas. Operators who are transitioning from ICE to BEB need to account for this capacity reduction and replanning of depot layouts, especially in intercity depots, where space is limited. The main hurdles for setting up cost and energy efficient depot charging infrastructure is the upgrade of power connection to the depot site, coupled with local production of power (e.g., through PV) and storage options. BEB technology requires operators to redesign their current depot layouts.

Spare parts

In any automotive system, more the parts, more the points of failure. The ICE buses comprise of several components which includes the engine, gearbox, and a drivetrain. On the other hand, BEBs are much simpler with just the traction motor and the drivetrain as key driving components. BEBs do not have an exhaust system, their braking systems are simpler (traction motor can also be used for speed control) and do not require oil changes. Hence, BEBs have significantly fewer parts than traditional ICE buses. This translates directly into the inventory of spares required to keep a smooth operation. Less spares also mean, less obsolescence and hence less overall wastage.

Assessment of environmental impacts

In the light of climate change, increasing pollution and noisy inner cities, it is important to consider the environmental impact when renewing bus fleets. Depending on the deployed technology, tailpipe emissions can expulse greenhouse gases (GHG), that contribute to the acceleration of climate change, and further pollutants into the atmosphere. In urban areas, noise pollution lowers life quality which also plays a factor when selecting a specific bus type.

Air pollution

Transit buses are important contributors to local air pollution as they are typically circulating in densely populated areas. The production of local air pollutants such as Nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOC), particulate matter (PM), and sulphur dioxide (SO2) can negatively impact the human health and environment. Air pollutants might therefore influence the decision-making process in cities already experiencing high levels of air pollution.

Especially in the case of ICE buses, the combustion inevitably results in a cocktail of exhaust gases such as carbon oxides, sulphur oxides and nitrogen oxides in addition to others. Many of these gases, when inhaled, can cause significant damage to human health. One in six deaths worldwide are linked to air pollution, three times more deaths than from AIDS, tuberculosis, and malaria combined and 15 times more than from all wars and other forms of violence. [38] Many of the pollutants also stay in the atmosphere for a long time and may locally cause acid rain and globally, increase the heat retention of the atmosphere, which then leads to climate change.[39]

Diesel buses in general produce high levels of air pollutant emissions, although these vary depending on the emission standards. Buses with old vehicle emission standards such as Euro IV and its predecessors are responsible for high levels of NO2 particle emissions. Due to large investment and efforts in the development of efficient filter and catalyst technology in the last years, the level of air pollutants was effectively reduced in modern Euro V/VI buses[40]. Nevertheless, these buses still emitting higher tank to wheel levels of air pollutants than the other technologies. Euro VI standards achieve a 90% to 98% reduction in particulate mass, particulate number, and black carbon emissions as compared to Euro V and is the best available control technology for emissions from ICE. Biodiesel has the potential to reduce the PM10 emissions significantly, while it might increase NOx emissions of buses compared to conventional diesel fuel.[41]

Since 2014, Europe has mandated Euro VI standards, which are significantly cleaner with much less emissions as compared to earlier Euro buses. Over a period, the tailpipe emissions of diesel buses are also reducing drastically. A comparison of particulate matter (PM) and NOx for different Euro standards is shown below. These reference figures may vary in actual applications depending on the vehicle operation and maintenance characteristics.

[38] The Lancet Commission, "Pollution and health: a progress update", 2022, https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(22)00090-0/fulltext

[39] European Public Health Alliance, "The invisible killer, Air pollution in Europe", 2018, https://epha.org/wp-content/uploads/2018/07/Clean-air-briefing.pdf

[40] TRANSfer Project, "New Drive Technologies for Public Bus Fleets in International Cooperation", GIZ, 2016

[41] Clean Fleets Project, "Clean Buses – Experiences with Fuel and Technology Options", 2014, https://www.ajsosteniblebcn.cat/clean-buses_31741.pdf

At the time of the publication of this paper the European Commission is working on the Euro VII standard.[42] The new standard will confront many OEMs the decision if it is worthwhile to further invest into the research and development of Euro VII ICEs or directly go for BEB technology. Some OEMs have already made this decision in favour of BEBs for transit buses.[43]

LNG and CNG buses only negligibly reduce TTW air pollutant emissions compared to modern diesel buses.[44] The air pollution in urban centres cannot be improved much by using Natural Gas Buses even though PM emitted from CNG vehicles tends to be much lower, and NOx is comparable to that of Euro VI vehicles. However, the extraction and transfer of the gas may lead to their leakage into the atmosphere and cause even more global warming than CO2 due to the 34 times higher global warming potential of methane.

WLTP type-approval values suggest that hybrid vehicles can help lower GHG emissions to a certain degree. It must be considered that the real-world emissions are likely to be far higher as the WLTP values are highly dependent on the optimal usage of the ICE and EV powertrains that cannot always be met in busy cities and challenging topographies. [45] Case studies show hybrid buses (1,23 kg CO_2 per km) do run more fuel efficient than diesel buses (1,59 kg CO_2 per km) but the hybrid technology cannot reach a zero-emission level.[46]

Except for pollutants from abrasion and resuspension, electric and hydrogen buses do not produce any tailpipe air pollution. Replacing a diesel bus fleet with those bus technologies would strongly reduce particle matter, NOx and SO2 emissions. However, just as with GHG emissions, the amount of WTW air pollution is highly dependent on the energy production as upstream air pollution is generated if electrical energy or hydrogen is generated with fossil resources. According to the TRANSfer Project (2016), however, power plants can filter those emissions more effectively than vehicle engines. The pollution created by power plants also is emitted in less critical pollution zones than where buses run. Significant reductions of air pollutants have significant effects on local air quality which results in major health benefits for the population. In general, emission-free bus operation is possible with electric buses and green hydrogen produced from renewable energy sources.

GHG emissions

The production and operation of buses can have negative environmental impacts due to air pollutant and especially greenhouse gas (GHG) emissions: "Common GHGs associated with diesel combustion include carbon dioxide (CO2), carbon monoxide (CO), nitrous oxides (NOx) volatile organic compounds (VOCs), and particulate matter (PM)" besides methane (CH4) in LNG and CNG buses[47]

[42] European Commission," European vehicle emissions standards – Euro 7 for cars, vans, lorries, and buses", 2022, https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12313-European-vehicle-emissions-standards-Euro-7-for-cars-vans-lorries-and-buses_en

[43] Electrive.com, "Daimler Truck calls to accelerate ZEV transition", accessed October 2022, https://www.electrive.com/2022/10/13/daimler-trucks-buses-calls-to-accelerate-zev-transition/

[44] ICCT, "The rapid deployment of zero-emission buses in Europe", 2022, https://theicct.org/wp-content/uploads/2022/09/zero-emission-buses-europe-sept22.pdf

[45] ICCT, "Real-world usage of plug-in hybrid vehicles in Europe", 2022, https://theicct.org/publication/real-world-phev-use-jun22/

[46] 2020 Civitas, "LPA 7.2 – Hybrid buses in the urban bus fleet", 2021, https://civitas.eu/sites/default/files/measure_evaluation_report_lpa7.2_10032021_final.pdf

[47] National Academies of Sciences, Engineering, and Medicine, "Guidebook for Deploying Zero-Emission Transit Buses", 2021, https://nap.nationalacademies.org/catalog/25842/guidebook-for-deploying-zero-emission-transit-buses

The creation of GHG emissions of bus technologies can be determined in many ways:

- "Well-to-Wheel" emissions (WTW) additionally measure the indirect upstream emissions caused by the production of buses and components like batteries as well as the usage and transport of fossil fuels in the production process (Production and Use Phase in the picture below); and
- "Well-to-Grave" emissions that in addition includes emissions related to end-of-life asset disposal (all the phases in the picture below).
- "Tank-to-Wheel emissions" (TTW) that are related to the combustion of fuels i.e., they are the direct emissions caused by the vehicle and its operation ("Use Phase" in the picture below); [48]

These concepts are illustrated in the figure below –

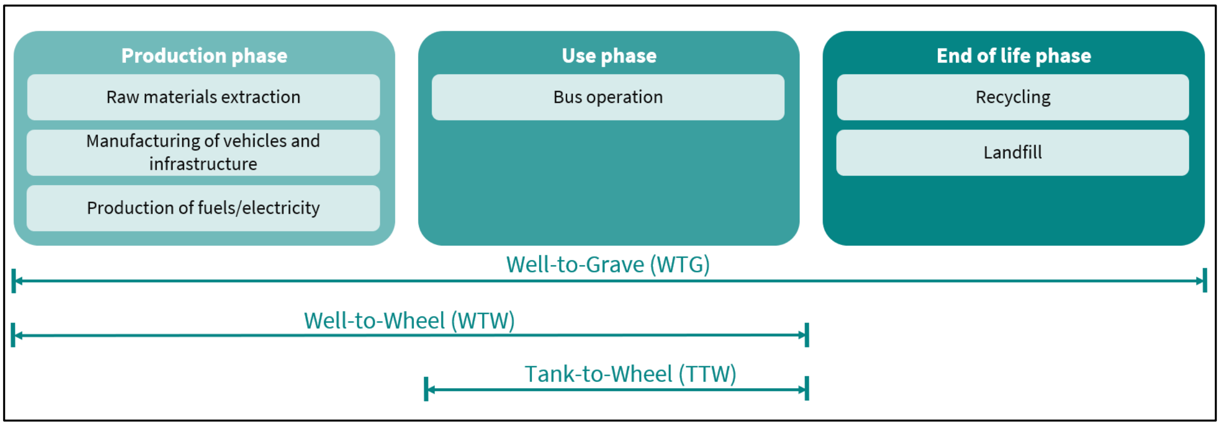

Figure 5: Determination of GHG emissions for vehicles

The terminology above has been developed in context of fossil fuel buses where "well" and "tank" are relevant part of the ecosystem. In BEBs, even though there is no "well" or "tank" involved, the terminology is applied such that "well" implies the energy generation infrastructure and "tank" implies the battery storage systems. Similar analogies are applied for Hydrogen buses.

As the name implies, TTW focuses on the impacts at the vehicle level which is more comparable across the board and simplifies to vehicle technologies. At the vehicle level, zero emission buses fare extremely well primarily because they do not do energy generation like ICE vehicles do. BEBs store the energy generated elsewhere and release when needed and hence are much cleaner at TTW comparisons. Though WTW comparisons depend on location of energy or fuel production, transportation/transmission, and distribution, it is more widely used for comparison of the environmental footprint of various bus technologies.

BEB TTW efficiency is about a factor of 3 higher than ICE buses. In BEBs, energy is not consumed while the vehicle is stationary, unlike ICEs, which consume fuel while idling. However, looking at the WTW efficiency of EVs, their total emissions are even lower than ICE vehicles in countries where electricity generation relies on fossil fuels.[49]

[48] Grütter, J., "Real World Performance of Hybrid and Electric Buses", 2015, https://slocat.net/wp-content/uploads/legacy/u13/report_hybrid_and_electric_buses.pdf
[49] Transport & Environment, "Does an electric vehicle emit less than a petrol or diesel?", 2020, https://www.transportenvironment.org/discover/does-electric-vehicle-emit-less-petrol-or-diesel/

When taking sustainable decisions, it is vital to focus on WTW emissions to account for the totality of GHG emissions throughout a buses' lifecycle. The results for WTW can vary depending different local variables (e.g., energy source used for vehicle production, source of fuels, recycling process, etc.) so a general number is difficult to name for the production phase, which will be discussed below. To start it is helpful to consider that CNG and Diesel run buses are not a solution for complete decarbonisation of the transport sector, as shown in the TTW emissions table below.

Table 2: TTW emissions expressed in equivalent greenhouse gas emissions per kWh of fuel consumed[50]

Technology	TTW in gGHG/kWh
Electric	0
Hydrogen	0
CNG	203
Diesel	270
Biodiesel	0

Being the most used technology, the diesel buses will serve as the baseline for the comparison with other technologies and measurement of potential to mitigate GHG emissions. Diesel vehicles are known for high PM and NOx emissions. NOx is a precursor to the formation of secondary particles and ozone in the atmosphere. Diesel PM consists mainly of black carbon (BC), the second-largest contributor to human-induced warming. Even the cleanest diesel releases very high levels of CO_2 when burned.[51] Some of the GHG impacts of diesel can be mitigated by adopting biodiesel, although the mitigation potential heavily depends upon the origin, availability, and processing of the biofuel. Currently, most biofuels are only used in blends with conventional fuels, the most widespread blend being the B5 consisting of 5 percent biodiesel and 95 percent petroleum diesel. Pure biodiesels, B100, are not widely adopted but could save large amounts of GHG emissions. As mentioned in chapter 2 "Technology", the GHG impact of biofuels also strongly depends on its origin, production, and composition. From an GHG emission perspective it is important to consider that an increase in demand of biodiesel would lead to the need of crop area expansion. This crop area expansion would entail the conversion of fallow land, pastures, or forests into crop land, which sets free GHG emissions as it reduces the carbon storage capability of the land. [52]

In comparison to diesel fuels, buses running on natural gas cannot reduce GHG emissions significantly as LNG or CNG are also non-renewable fossil fuels. In some cases, LNG/CNG buses can even fare worse than diesel engines and produce more GHG emissions, depending on the extraction process and the quality of the gas, as well as the transport distance to the fuelling station and the efficiency of the bus engine.[53] Like biodiesel, the combustion of biogas can be classified as carbon neutral. During the combustion of biogas methane is set

[50] Global Infrastructure Facility (GIF), "GIF Guidance: Clean Technology Options for Buses", 2022, https://documents1.worldbank.org/curated/en/099512112062241767/pdf/IDU020d91b36009f404c5a0b516051b8b9c9efe5.pdf
[51] ICCT, "South Africa's Green Mobility Flagship Project: Leeto La Polokwane", 2021, https://theicct.org/publication/south-africas-green-mobility-flagship-project-leeto-la-polokwane/
[52] Scarlat. N et al., "The Role of Bioenergy in the Bioeconomy", 2019, https://www.sciencedirect.com/science/article/pii/B9780128130568000108?via%3Dihub
[53, 53] Clean Fleets Project, "Clean Buses – Experiences with Fuel and Technology Options", 2014, https://www.ajsosteniblebcn.cat/clean-buses_31741.pdf

free and therefore, GHG emissions are added to the atmosphere. As the methane came from plant matter that initially fixed the amount of GHG emissions from the atmosphere, when regrowing these crops, the same amount again will be removed from the atmosphere, making it a carbon neutral cycle.

Due to their partly electric drive technology, hybrid buses do reduce GHG emissions compared to conventional diesel buses and create less negative environmental impacts. As hybrid buses have the potential to save 25-40% fuel, equivalent mitigation of GHG emissions can be directly achieved. Though hybrid buses can be considered low-carbon transport, they cannot completely decarbonize transport because emissions reduction is highly dependent on the extent to which the ICE is used in the hybrid vehicles.[53]

BEBs currently have the highest potential to reduce the most GHG emissions compared to other technologies. When only looking at TTW emissions, BEBs are already an emission-free technology.[54] Due to upstream GHG emissions from electricity production, the WTW emissions of BEBs are dependent on the energy mix of a region or a country: To have low GHG impact, the electrical energy must be produced solely from renewable energy sources. WTW zero-emission BEBs are already possible in some countries like Paraguay, Bhutan, Suriname, or Costa Rica as the weighted emission factor is close to zero since electricity is solely generated by renewable energy sources. Countries like Sweden with a high share of renewable energy in the energy mix can reduce much more GHG emissions than other countries such as Poland or Estonia with a high share of coal-based electricity. There are 13 countries in Asia which have set clear transport emission related emission targets and BEBs would enable a key shift as far as transport sector is concerned.

Even in regions in which the electricity generation is heavily reliant on fossil fuels, the use of electric buses can produce some WTW emissions reductions between 0-25% compared to diesel buses as electric buses have more efficient drivetrains than ICEs. To further reduce GHG emissions, countries and cities should strive for an energy mix that relies on renewable energy. In addition, the production of batteries for BEBs creates significant additional GHG emissions with an average of 110 kgCO2eq/kWh that must be accounted for.[55] The recycling and second life of used batteries, on the other hand, can potentially decrease the CO_2 footprint of BEBs significantly. "E-buses can form part of the circular economy, with bus batteries integrated into renewable grids and used for load balancing and actively recycled after use on buses."[56]

FCEBs do have the potential to diminish GHG emissions significantly in the future. Hydrogen buses may even drive emission-free. However, this is highly dependent on the origin of the hydrogen as only "green hydrogen" produced from renewable energy sources does not generate WTW GHG emissions. Independent of which technology is used for the electrolysis to produce hydrogen, the process is only carbon free if the power used is from carbon free sources (e.g., renewable energy.[57] Currently, there is very little supply of green hydrogen, as only 2% of the worldwide hydrogen production is generated by renewable energy.[58] The highest market share belongs to "Grey hydrogen" which is gained from natural gas or methane and generates high GHG emissions. These emissions are generated in the production phase of the process and the only tailpipe

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[54] Grütter, J., "Assessment of Low Carbon Bus Technologies for Vietnam", 2016

[55] Asian Development Bank, "Sustainable Transport Solutions: Low-Carbon Buses in the People's Republic of China", 2018, https://www.adb.org/publications/sustainable-transport-solutions-peoples-republic-china

[56] European Bank for Reconstruction and Development (EBRD), "Going Electric", 2021, https://www.ebrd.com/infrastructure/going-electric.pdf

[57] Federal Ministry of Education and Research (BMBF), "Wissenswertes zu Grünem Wasserstoff", 2020, https://www.bmbf.de/bmbf/shareddocs/kurzmeldungen/de/wissenswertes-zu-gruenem-wasserstoff.html

[58]TheCityFix by WRI, "Do Hydrogen Fuel Cell Vehicles Make Sense for Cities?", 2020, https://thecityfix.com/blog/hydrogen-fuel-cell-vehicles-make-sense-cities-eleanor-jackson/

emission from the fuel cells in the vehicle, no matter which type of hydrogen, is water which enters the atmosphere in a vaporized form.[59]

If non-renewable energy sources are used in the production of hydrogen, GHG emissions may even surpass those of diesel buses. Other forms of hydrogen (e.g., grey, or blue hydrogen) are not free of emissions as they are obtained by fossil fuels. Although the production of hydrogen does influence overall GHG emissions results, hydrogen buses have the potential to run emission-free.

Technology	Greenhouse Gas Emissions
Conventional Diesel	Highest CO_2 emissions per kilometer. Biodiesel can save up to 70-85% of WTW GHG emissions. Increased demand for biodiesel would lead to expansion of crop areas for production which would then counteract the savings.
Diesel-Electric Hybrid	A 25-40% reduction of GHG emissions is possible, but Diesel-Electric Hybrid Buses are not a viable option to fully decarbonize the transport sector.
Natural Gas	LNG and CNG are non-renewable fossil fuels. They may offer GHG emissions reduction potential in comparison to diesel but can never be emission-free. Biogas can reduce CO_2 emissions if methane emissions are avoided.
Electric Buses	Zero-emission at tailpipe. Potential to become emission-free if electricity, batteries and components are produced solely by renewable energy sources. WTW GHG emissions are dependent on local energy mix. Even in countries dependent on high fossil fuel-based energy mix, GHG reduction of up to 45% possible due to an efficient WTW energy cycle.
FCEV	No tailpipe emissions and may drive emission-free if produced solely with green hydrogen. Currently, only 2% of hydrogen is produced by renewable energy sources. Highly inefficient WTW energy cycle needs to be taken into account.

Figure 6 Assessment of GHG emissions per technology

Noise pollution

According to the World Health Organization[60], traffic noise can have major impacts on the human health and is one of the biggest environmental problems, only surpassed by air pollution. Although noise pollution does not directly account for fatalities, it can cause major health problems like hearing problems, heart diseases or sleep disturbances.[61] The reduction of traffic noise, especially by buses, is a pertinent issue and can fundamentally improve the impact of public transport systems.

While driving at low speeds, most of the noise comes from the vehicle engines before the noise of the tires becomes predominant at speeds over 50km/h[62]. The choice of technology has effects on the noise level of the bus fleet. Quietly running electric buses can significantly reduce noise pollution by 50-65% compared to

[59] Clean Fleets Project, "Clean Buses – Experiences with Fuel and Technology Options", 2014, https://www.ajsosteniblebcn.cat/clean-buses_31741.pdf

[60] World Health Organization (WHO), Regional Office for Europe, "Noise", 2020, accessed March 2023 https://www.who.int/europe/news-room/fact-sheets/item/noise

[61] Transport & Environment, "Electric buses arrive on time. Marketplace, economic, technology, environmental and policy perspectives for fully electric buses in the EU", 2018, https://www.transportenvironment.org/wp-content/uploads/2021/07/Electric-buses-arrive-on-time-1.pdf

[62] Volvo, "Volvo Buses", 2019, accessed in March 2023, https://www.volvobuses.com/en-wa/news/2019/sep/electric-buses-can-address-noise-pollution.html

diesel buses[63], especially when accelerating from or decelerating towards bus stops. Due to their partly electric drive, diesel-electric hybrid buses can also save up to ca. 3 dBA compared to diesel buses.[64] As the decibel scale is logarithmic, a three-decibel reduction would be equivalent to a halving of the traffic level[65]. Hydrogen buses also do produce perceivable engine noise, like electric buses.

In their study on noise reductions, Laib et al. 2018 found that the sound level of BEBs was up to 14dBA lower than conventional diesel buses. The effect, however, diminishes at increasing speed and beyond 50km/h there isn't much difference. When comparing the exterior noises outside, BEBs have 6dBA less noise while departing. They are also much quieter while accelerating compared to hybrid buses. In dense urban environments, where buses are subjected to frequent stop-and-go either at traffic signals or bus stops, the reduced noise pollution of electric buses has significantly positive effects on the human health.

Low noise level of BEBs has some secondary advantages. Noisy diesel buses generally face resistance if parked near residential areas overnight. The early morning commencement of service and consequent revving of the engines can disturb the peace and tranquillity of the neighbourhood. That is why they are parked in industrial areas or in far-flung depots. Zero emission and less noisy BEBs, do not face such resistance and can even be well integrated with Transit Oriented Developments (TODs). This reorganization can save a large amount of dead mileage which can also yield additional emission reduction in conjunction with reduction in operating costs.

[63] C40 Cities Finance Facility (CFF), "Evaluation of Electric Buses for Eje 8 Sur", 2018, https://cff-prod.s3.amazonaws.com/storage/files/OUfjGtaTa9DvErsxOvtsRUqWyVhy8223rwzGhclQ.pdf
[64] Clean Fleets Project, "Clean Buses – Experiences with Fuel and Technology Options", 2014, https://www.ajsosteniblebcn.cat/clean-buses_31741.pdf
[65] Transport & Environment, "Electric buses arrive on time. Marketplace, economic, technology, environmental and policy perspectives for fully electric buses in the EU", 2018, https://www.transportenvironment.org/wp-content/uploads/2021/07/Electric-buses-arrive-on-time-1.pdf

Assessment of financial impacts

It has been clearly demonstrated in previous chapters that bus technologies have different strengths and weaknesses, and each technology may fare better in some respects than the others.

Bus technologies are also constantly evolving. New fuel technologies may become available in the ensuing years, costs are constantly decreasing in some and increasing in other cases driven by process optimization, economies of scale or commodity costs. For example, the initial purchase price of BEBs or hydrogen buses are expected to further decline significantly in the upcoming years. Batteries are also constantly getting better (higher energy density) and cheaper (cost per kWh). In case of diesel buses, local air pollutant emissions have been drastically reduced by the introduction of new emission standards. The economic and ecological measurements and values presented in this report should therefore be considered as indicative as they only present a snapshot of the current development.

Total cost of ownership (TCO)

It is difficult to compare various bus technologies on individual dimensions of financial aspects. While some technology like diesel buses may be cheaper to acquire, there operating costs per year may be higher. Fuel or energy prices vary a lot among regions and countries due to a variety of reasons such as local taxation and general volatility of the energy market. Conventional buses may be more expensive as compared to BEBs to maintain due to higher maintenance activity and inventory of parts that are required but surpass other technologies when it comes to availability and reliability. Total useful life of the bus and residual values can also alter the financial models. In some countries, useful life of the bus is dictated through legislative processes (like Australia, Hong Kong, India) while in others they are determined by the commercial viability of operation (when maintenance cost become higher than the renewal costs).

Having said this, individual financial dimensions are important considerations as they affect the cash-flow planning, financial framework, viability gap funding and operating strategies. A complete aggregated perspective is provided by TCO analysis which considers all the financial (and sometimes economic) aspects of the bus operation, agnostic to individual bus technology. This is an important decision-making tool for evaluation and procurement of a particular bus technology.

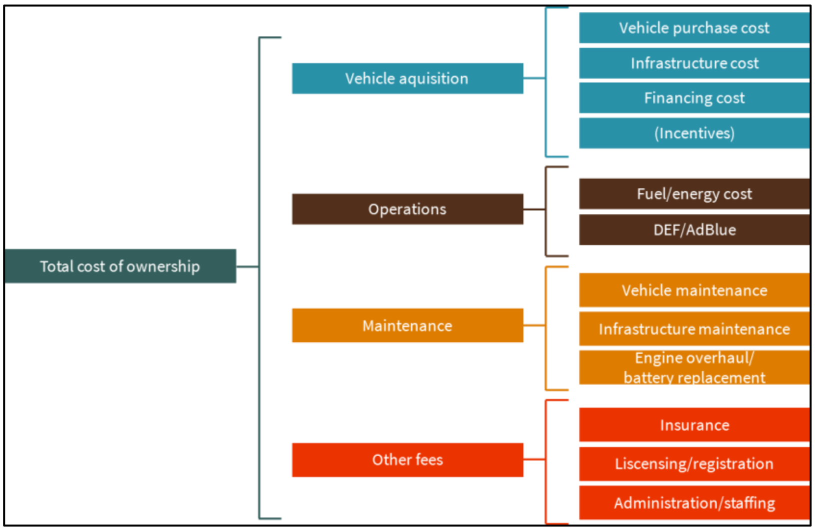

Figure 7 Total cost of ownership divided into subcategories

Data availability of various variables particular to a deployment is one of the key requirements for TCO analyses. There are several simulation models and tools available but if they cannot truly reflect the local operating conditions, the calculations may not yield sensible results.

- Some of the important questions to ask before undertaking a TCO analysis are -
- Are the data components available for electric buses?
- Are the data components available for legacy fuel (diesel / CNG) buses? Simulations/estimations may be needed to generate data in case of non-availability
- Are there any similar cities that can be benchmarked?
- Route-level or System-level analysis?
- What are the variances on utilization (duty cycle / load factor)?
- What are the variances due to amenities (Air-conditioning / Heating)?

TCO must carefully evaluate the costs as there are huge differences of TCO models in-between the different manufacturers. In recent years, European bus manufacturers have shown to be much more conservative in estimations than the Chinese manufacturers. The practicalities of navigating around these different views, which are completely different philosophies are very difficult and make a real assessment of the market complicated.

Capital cost: Buses

The capital costs of buses are often the main purchase criterion for transit agencies. It is therefore crucial to understand that the cost figures are very context-specific and often vary between countries or regions due to different circumstances such as e.g., taxation, fees, buying incentives or subsidies. Available financial support often is the most important factor in deciding upon a bus technology. Due to vast regional differences and forms, sometimes it is hard to truly reflect the full extent of financial incentives. The capital costs (CAPEX) for buses include purchase costs and planned replacement of bus parts, such as the batteries of electric buses. Depending on the operating model, they may also be separated into separate CAPEX items or converted into operating cost (OPEX).

There are significant price differences in the cost of a bus, irrespective of the technology, between low-price markets such as China or India and high-price markets like Europe or North America. Due to low cost of diesel buses, interestingly, the percentage difference for the alternative bus technologies becomes even higher in the low-price markets. Bus prices also differ due to differences in specifications, warranties, and indigenization.

Diesel buses are by far the lowest in terms of capital costs as compared to other bus technologies. This is mainly due to the market maturity, availability from many suppliers, and significant local know-how. Diesel engines are an established and well-researched technology.

CNG buses are also quite common around the world and can be considered a well-established bus technology. The purchase price of CNG buses, however, is still 10-15% or even higher than a diesel bus in 2020 but they can be offset by local CNG costs, which can be lower than the cost of diesel on a litre-equivalent basis.

The initial purchase price of regular hybrid buses can be up to +20-30% more than conventional diesels but can exceed +50% in the case of plug-in hybrids.[66]

Electric buses have a much higher purchase price (ca. 80-160%) than comparable diesel buses, although being dependent upon regional differences. This estimation includes the costs for the necessary replacement of batteries after half of the service life, as batteries have an average life expectancy of 6-10 years. BEB manufacturers have recently been giving warranty on battery life of 8 years. With batteries being the most expensive part of the BEB, this has a significant impact on the TCO. The capital costs of BEBs and batteries will constantly drop in the coming years. The price of batteries has already fallen by 79% since 2010 and is expected to further decline[67]. If more batteries are built in a BEB, the bus cost is even higher, and a longer time will be needed for a BEB to be able to economically compete with a diesel bus. The high CAPEX currently is one of the most important barriers to the mass adoption of BEBs as they are the most visible costs upfront. Due to the budgetary pressures, many transit agencies focus on immediate capital costs than on potential long-term savings resulting in not fully informed decisions.[68] To address the high capital costs of BEBs, some new and innovative models are emerging which are bringing BEBs at par with diesel buses, e.g., see E-Bus as-a-service or Pooled Procurement in the annex 1. It is also worthwhile to investigate applying financial instruments that can help level the high CAPEX costs.

Trolleybuses usually have much longer useful life (20 years+) and taking this into account in comparison to the shorter life expectancy of diesel buses (ca. 12 years), CAPEX impact can be balanced to a large degree.[69] Since Trolleybuses have smaller or less batteries compared to BEBs, the CAPEX for the vehicle is lower.

FCEBs are by far the most expensive among all the technologies which is mainly a result of the current low production numbers and the trial and demonstration phase of technology. In recent years, increasing economies of scale drastically reduced the CAPEX of FCEBs by 49% in North America in 2018 compared to 2010. The capital costs of FCEBs thus proportionately declined more than BEBs at the same time, although the battery price decreased significantly as well[70]. Further scaling effects of hydrogen buses can be expected especially once FCEBs have reached a sufficient bus market maturity.

Capital cost: Infrastructure

The procurement of new bus technologies is accompanied by investments in necessary charging or refuelling infrastructure. This may also include provision of new depots or opportunity charging facilities. Conventional technologies like diesel buses already have the associated infrastructure established and putting the burden of the marginal cost of new infrastructure on assessment of new technologies may not produce a like-to-like comparison, yet it is important to note what a technology transition will entail. In the final decision-making

[66] Asian Development Bank, "Sustainable Transport Solutions: Low-Carbon Buses in the People's Republic of China", 2018, https://www.adb.org/publications/sustainable-transport-solutions-peoples-republic-china
[67] Bloomberg NEF, "Electric Buses in Cities. Driving Towards Cleaner Air and Lower CO2", 2018, https://about.bnef.com/blog/electric-buses-cities-driving-towards-cleaner-air-lower-co2/
[68] Clean Fleets Project, "Clean Buses – Experiences with Fuel and Technology Options", 2014, https://www.ajsosteniblebcn.cat/clean-buses_31741.pdf
[69] C40 Cities Finance Facility (CFF), "Evaluation of Electric Buses for Eje 8 Sur", 2018, https://cff-prod.s3.amazonaws.com/storage/files/OUfjGtaTa9DvErsxOvtsRUqWyVhy8223rwzGhclQ.pdf
[70] National Academies of Sciences, Engineering, and Medicine, "Guidebook for Deploying Zero-Emission Transit Buses", 2021, https://nap.nationalacademies.org/catalog/25842/guidebook-for-deploying-zero-emission-transit-buses

process, scenarios can be presented that ring-fence the infrastructure cost out of the TCO or convert them into a pay-as-you-go service model.

The purchase of new diesel units is not accompanied by additional costs for infrastructure as the necessary fuelling stations usually already exist. Conventional buses are fuelled at fuel stations and cost of the construction of these stations, cost of the fuel distribution and cost or rent of the land is included in the cost of the fuel. From a bus operator perspective, the CAPEX for the fuelling infrastructure is accounted for into the OPEX.

Regular diesel-electric hybrid buses do not require any specialized infrastructure over and above what is already provided for diesel buses thus limiting the CAPEX of hybrid buses significantly. Plug-in hybrids, however, would require building a charging infrastructure. The batteries in hybrid buses would also need to be replaced on a regular basis but these batteries are much smaller in size as compared to BEBs.

For BEBs, FCEBs and CNG/LNG buses, where in most places a brand-new infrastructure is required from scratch, the initial cost of distribution and supply can be substantial barrier to the technology selection or transition. One option is to use a similar model as conventional diesel buses by factoring the amortized cost of the infrastructure into the price of electricity freeing the bus operation from these cost penalties.

In case of trolleybuses, the existence of modern catenary wires is a crucial cost factor, as costs for new catenary network is quite high. The CAPEX can, however, be significantly improved by using already existing catenary wires.

In strong contrast to BEBs, FCEBs and CNG/LNG buses have fuelling stations with procedures and fuelling times that are like regular petrol stations. They will also require a much different type of asset investments as, e.g., the upscaling of hydrogen will require investment into new fuelling stations and a hydrogen pipeline network. [71]

To address the high capital costs of the infrastructure of BEBs, some new and innovative models such as Charging-as-a-service are being introduced. See annex 1.

Operating cost

Operating costs like fuel prices or maintenance costs also influence total cost of ownership (TCO) and hence bus procurement. Furthermore, as the purchase power and economic strength of countries and regions varies, the costs for bus purchases are not comparable between regions. Type of buses (low-floor or super-low floor), order size, and localization of supply chains can also swing the prices widely.

Labour costs form an important component of operating costs for any bus operation but are a function of local economies and wage trends and comparing them across geographies may not be useful. When evaluating various technologies for decision making within a defined location, they are a useful metric that must be factored into consideration.

The operating costs of diesel buses are comparably high due to the volatile fuel economy in the last decades. Fuel prices strongly influence the total cost of ownership (TCO) of diesel buses. Fuel prices might well further

[71] Clean Hydrogen Partnership, "Hydrogen Refuelling Concepts", accessed March 2023, https://www.fuelcellbuses.eu/wiki/hydrogen-supply-and-storage-hydrogen-refuelling-stations/hydrogen-supply-and-storage-0

increase in the coming years due to less state subsidies and increasing taxes on fossil fuels. Consequently, operating costs of diesel buses may further increase.

The operating costs of CNG buses are, however, lower currently as the price for natural gas is moderately lower than diesel fuel. It cannot be said with confidence if that would continue for time to come as it is determined by the larger dynamics of the world energy market.

The operating costs of electric buses, on the other hand, are significantly lower compared to diesel buses, especially since electricity costs are lower and less volatile than diesel fuel prices in most regions. They vary significantly depending on the operating cycle (generally longer the cycle, more cost effective), charging strategy (high availability of opportunity charging would mean lower battery weight on-board reducing the overall energy consumption), dead mileage (location of the depot / charging facilities) and local conditions (weather, topography, driving behaviour etc.).

The operating costs of trolleybuses are even lower than regular BEBs. The losses in battery charging cycles and battery weights are much less.

Hydrogen buses are most expensive to operate currently. Additional energy costs could be 200% more that the diesel buses due to conversion losses as well as additional costs for the distribution and fuelling of the hydrogen. However, the price of hydrogen as a fuel is declining fast but distribution of hydrogen is fundamentally challenging and hence more expensive.

In general, almost all alternative bus technologies have higher capital costs than conventional diesel buses due to higher vehicle and infrastructure costs. When comparing operating costs, however, many technologies can save expenses due to lower energy costs and fuel consumptions over the lifecycle of the bus – sometimes even resulting in lower total cost of ownership.

Maintenance cost

Most of the existing bus operators, their facilities and skillset of the manpower is adapted to diesel bus operation. Implementation of any new technology would require fundamental improvement to the infrastructure as well as skillsets.

Maintenance costs of the diesel buses is well-established and barring cost of manpower are quite comparable in different parts of the world, signifying maturity of technology. One source of cost variance comes from maintenance of subsystems such as passenger information systems, fare collection systems, passenger counting systems etc.

From a maintenance perspective one of the key differences from a fossil fuel-based transmission system to electrical traction is related to a big shift of focus from a mechanical engineering orientation to an electrical engineering orientation. Even though tires and interiors etc. remain pretty much the same, the presence of high voltage on the drivetrain, which is much more simplified as compared to a mechanical system. The number of parts involved in an electric bus is at factor of 1 to 10 as compared to a conventional bus. This means a significant reduction in part inventory as well as lower obsolescence costs.

Electric buses are technologically more advanced as their operation hinges on continuous close monitoring of the key operational parameters such as SOC (state-of-charge), BMS (battery management system), and/or CMS (charging management system). Many of the sub-systems referred earlier may require a separate communication infrastructure on diesel buses but can operate on the communication backbone in-built on electric buses. This allows for better integration and lower maintenance costs.

Compared to conventional buses, maintenance costs of diesel hybrid buses are higher, simply because dual engines must be maintained.

Residual value

When conventional buses reach their end of life, their residual value is minimal and literally their worth is the price of metal weight in them. Mostly these buses are scrapped. Some developing countries, because of affordability reason, utilize these buses after reconditioning. They are then poorly maintained and are prone to frequent breakdowns and safety issues. Before the buses reach the end of life and are being disposed for any reason, there could be a secondary market which may buy the buses at some discount to the book value. It varies country to country and such second-hand buses are usually deployed for rural applications.

BEBs are still an evolving technology and there aren't many buses which are reaching their end-of-life. The second-hand market is also not mature enough, especially because the cost of creating charging infrastructure is quite high. Batteries, however, are a different ball game. Usually, when a battery reaches around 80% of its original usable capacity due to cycle-based attenuation, the weight to energy ratio is not economical for deployment on buses. However, a 300kWh battery even after 20% attenuation has a power capacity of 240kWh, it could very well be used for static energy storage. Some bus operators use them as static power storage and deploy them for power balancing to bring the overall cost of electricity consumption down. They can also be used for many other uses, such as back-up power for housing, offices, or data centres.

Fuel-cell buses are more novel even as compared to BEBs. There are hardly any examples of their end-of life usage and hence, it is hard to assign a residual value to FCEBs.

In cases where there is no end-of-life market, and there are strict regulations governing disposal of assets, there could even be a cost associated with scrapping or decommissioning of the buses. Buses could be sent to recycling facilities, where anything worth recycling can be taken out and rest of the bus can be disposed of responsibly.

Revenue

Revenue impacts are in fact agnostic to bus technologies and should be explored in the framework of sustainability. In simple terms, there are two ways to increase revenue.

Increase fares and prices such that the users are forced or enticed to pay more for consumption of services. In captive or monopolistic markets, price increases are forced without customer having a choice but in highly contested markets, price increases can only be achieved by service differentiation and better quality of service, such as by introducing premium services.

Increase ridership by influencing mode share. One of the biggest influencers for the mode choice of public transport is travel speed. When travel speeds of buses are comparable to bus journeys, people become more amenable to make the switch from their private cars. Higher travel speeds can be achieved through dedicated bus lanes, junction priorities and other traffic measures.

Fossil fuel buses are omnipresent and often making hardcore changes to their operation is fraught with politicization and irrational public reaction. However, many cities around the world have taken an opportunity to overhaul their public bus systems while introducing new technologies such as BEBs. Many cities have also used this opportunity to restructure the routes into an efficient hub-and-spoke system. If new technology buses can be implemented as part of the agenda for traffic congestion management, there could be significant revenue impacts.

Subsidies / Grants

Subsidy or grants are also theoretically agnostic to bus technology deployed. They are often driven by politics and become part of policies to promote a particular agenda. Some subsidies such as fare concessions for senior citizens or students or children are given to all type of bus users. However, in the quest to drive the transition to zero emission buses, many countries or cities have launched special subsidies / grants or tax breaks for clean buses. There are several examples of this in Asia. The entire electric bus uptake in China was driven by heavy subsides provided by the central and local government (nearly 50% of the capital cost of buses). India has recently launched FAME II scheme under which central government is providing subsidies for 9,000 buses across the country. Tax breaks such as exemption of import duties, first registration tax or road tax are also quite common in case of zero-emission buses.

There could be multiple sources through which a bus project can be financed. The project can be broken down into three activities.

- Pre-operations - Upfront Capital costs
- During operations – Operating deficits and maintenance deficits
- Post operations – Replacement costs

The figure below shows the typical sources of funds for each of the activity in a public bus project.

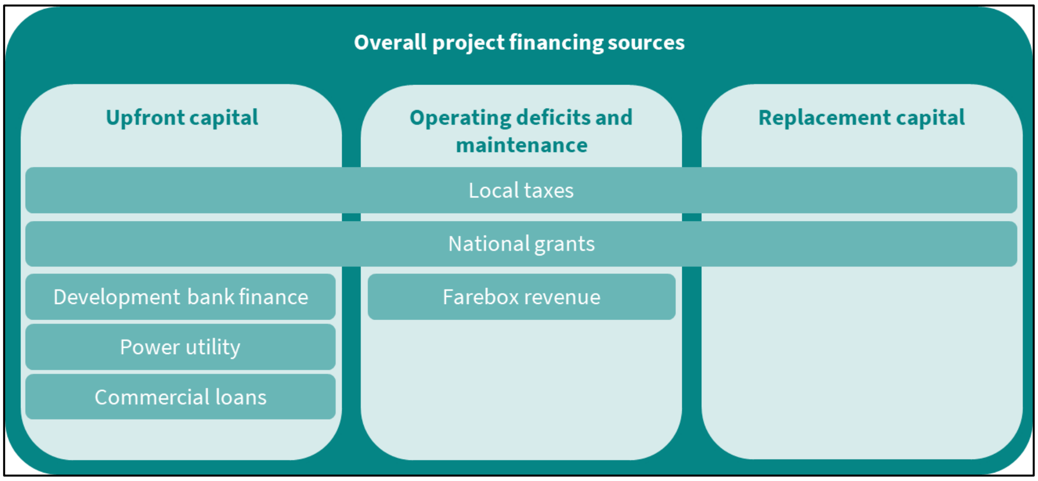

Figure 8 Sources for funding of different project costs

All these subcategories of the TCO vary strongly depending on local conditions, so the TCOs of different technologies must be evaluated case by case.

Conclusion

The decision for or against the deployment of a specific bus technology is always depending on the main objectives and preferences of a transit agency. Every examined technology does have its advantages and disadvantages, but it is the decision of the transit agency to decide which criteria matter the most: If the only concern of a bus operator is the financial result, the decision for a bus technology can be made only by comparing the bus costs. However, if environmental impacts are important as well and if environmental regulations are in place, there are more criteria to consider and can change the cost-based decision.

There is no "one size fits all" solution for bus deployment as the decision is always highly dependent on local circumstances: For example, different policy regulations, financial incentives or taxes, city characteristics, existing fuelling or charging infrastructure or citizens demand for public transport will strongly influence the decision-making process and will thus lead to different outcomes. Furthermore, choosing the best technology is also dependent upon daily mileage, bus size or frequency. Therefore, the report is not advocating that one technology is better than all the others. It rather aims at providing a first overview to examine in which context a certain bus technology might be most appropriate, and which conditions favours the deployment of another technology.

Table 3 Comparison of technologies

Fuel Type	Environmental Impact		Economical Aspects		Infrastructure*	
	GHG Emission (Tailpipe)	Air Pollutant Emission (Tailpipe)	Total Cost of Ownership	Upfront Cost	Capital Cost	Physical Space
Diesel	High	Medium	Low (Trend →)	Low (Trend →)	Low	Low
Biodiesel	High	Medium	Low (Trend →)	Low (Trend →)	Low	Low
CNG	Medium	Low	Low (Trend →)	Low (Trend →)	Medium	High
Hydrogen Fuel Cell	Medium to High	None	High (Trend ↓)	Very High (Trend ↓)	High	High
Battery Electric	Low to Medium	None	Medium (Trend ↓)	High (Trend ↓)	High	Medium
Hybrid	Medium	Low	Medium (Trend ↓)	Medium (Trend ↓)	Low	Low

Conventional diesel buses may have the least entry costs. Diesel buses have a very high driving range and high reliability levels which increase the flexibility of route assignments. Diesel buses thus are of advantage on long distance routes. On the downside, however, no other technology is responsible for the production of that much GHG emissions and local air pollutants as diesel buses. Further, the fuel costs are high and are expected to increase in the coming years due to additional taxes. Most countries rely on the import of fossil fuels and the current energy crisis caused by Russia's attack on Ukraine that a dependency on import will lead to an extreme spike in prices when international relations are not stable.

Buses running on natural gas can almost economically compete with diesel buses, especially CNG buses. However, they do not significantly reduce GHG emissions or air pollutants and might even produce more emissions. If transit agencies want to actively contribute to the reduction of GHG emissions, natural gas buses are not viable options as the energy is still produced by fossil fuels. Only biogas can contribute to the mitigation of CO2 emissions. The deployment of natural gas buses can be useful in countries with domestic natural gas resources (e.g., Sweden or the Philippines) as these countries do not have to import fuels but can strategically use their own resources which lowers operating costs.

The financial advantage of diesel buses is expected to gradually change in the next few years as BEBs are becoming less and less expensive due to decreasing battery prices. TCO for electric buses are already quite competitive on high mileage routes because of the lower price of electricity and operating costs. The charging capacity of batteries will increase over time, which would allow for a longer driving range too.

One of the biggest critiques for BEBs relates to the sources of power and the "dirty" grid. However, the composition of the electricity grid is becoming more reliant on renewable energy sources and less on coal and petroleum-based fuels. This will further mitigate CO2 emissions and increase the already strong ecological advantage of BEBs. Electric buses are quieter and produce significantly less GHG emissions and local air pollutants.

Like electric buses, hydrogen buses have the potential to heavily contribute to the decarbonization of the public bus transit sector in the future as both technologies do not exhaust tailpipe emissions. The fuelling approach and the driving range of FCEB are quite like those of diesel buses which is why FCEB are a promising alternative to diesel buses in the future. Nowadays, however, hydrogen buses are still only used in pilot projects and are far away from mass deployment. Currently, only a negligible part of the hydrogen is produced by renewable energy sources. Furthermore, the purchase of hydrogen buses is associated with the highest initial costs of all presented technologies and are twice as expensive as BEBs. Therefore, hydrogen buses are not able to compete with BEBs financially or ecologically in the foreseeable future. They do remain a very promising alternative to diesel buses, for long distances due to their greater range and for extreme temperatures where BEBs do not fare well.

It is vital to point out that the reduction of GHG emissions is and will continue playing a critical role for decision makers in the transport sector for coming decades, low-emission technologies, especially BEBs, are the most future proof technologies that can minimize the risk of stranded assets for bus owners. A transition to BEBs may have consequences in the design of the network and the routing, incl. charging. Decision makers therefore should consider a full transformation strategy instead of just changing a few buses and keeping the system as it is. This transition is already ongoing and further growth is predicted as shown below are the forecasts from UITP on the future propulsion systems for European markets, where a strongly increasing trend towards electric buses and a corresponding decline in diesel buses is observed.

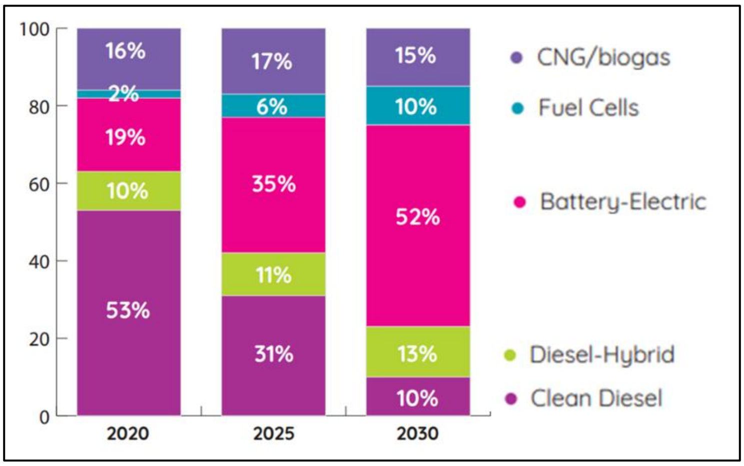

Figure 9: Future development of market share of bus technologies (by ZeEUS and UITP VEI Committee)

In conclusion, transit agencies have many options to renew or augment their bus fleets with alternative technologies. However, as there is no “one size fits all” solution, the best option might differ between regions and transit agencies as it depends on the overall objectives of the bus fleet renewal and changes due to local contexts. Each city has its own local character in terms of operation, regulation, stakeholders, and environmental conditions, making each of them unique. Depending on the operational requirement, geography and topography, weather, the existing infrastructure and planning objectives, operators may prefer one technology over the other. What is important is to identify all the variables and localize them for comparison and analysis purposes.

Annex 1: New business and financing models for buses

Bus as-a-service

The Bus-as-a-service model addresses those looking for an expert partner in mobility, electrification, and energy services, with an integrated approach compared to the traditional purchasing processes of administrations and public transport operators. It includes all the support necessary to deliver a turnkey project: from support in the preliminary analyses and in the design phase to the provision of the fleet, design, installation, and maintenance of the charging infrastructure. It also includes the supply of renewable energy, smart charging, and smart city services (connectivity services, security cameras, smart shelters).

Enel X in collaboration with BYD Chile and the PT company Metbus, has provided 436 e-buses, 13 electro-terminals, 40 integrated smart shelters fitted with digital systems and around 268 charging stations, in the framework of an 'E-Bus as a service' solution.[72] Enel X covers all the initial investment and the technological, construction and operational performance risks of the project, against a single integrated fee paid throughout the duration of the project (between 10 and 20 years). 70% reduction in operating costs and a significant contribution in making the streets cleaner.

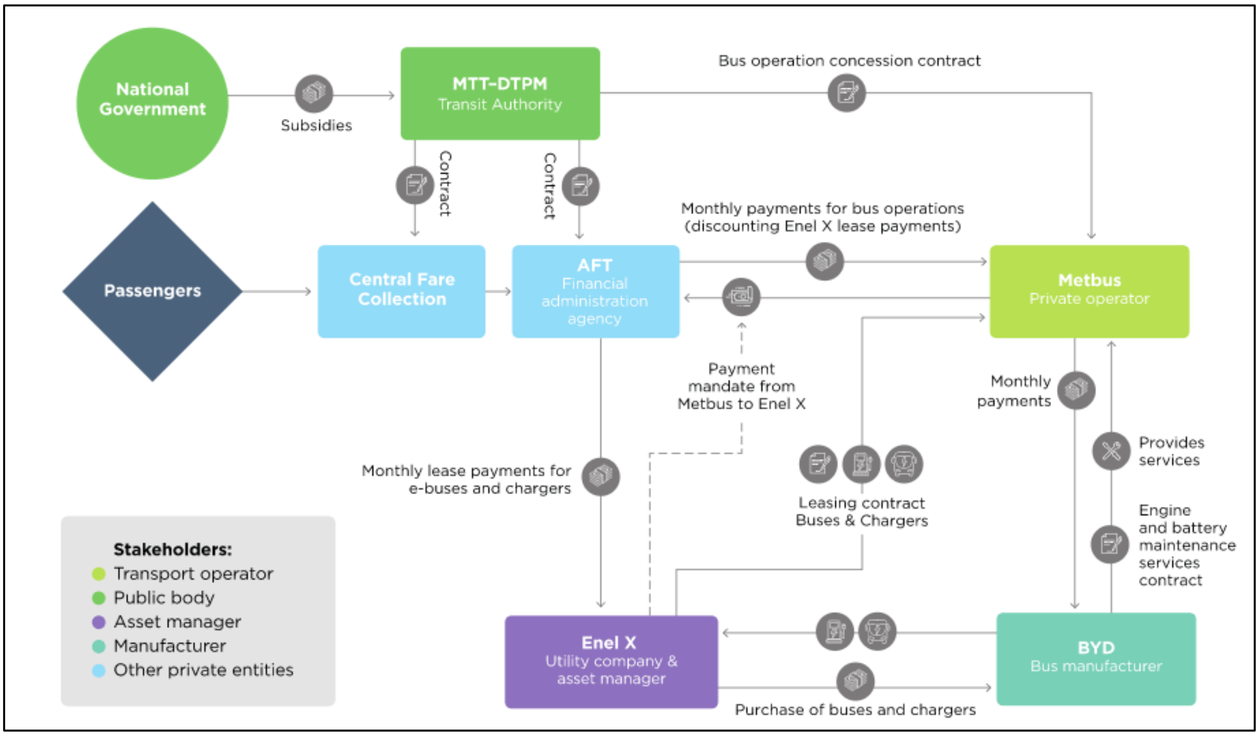

Figure 10 Bus as a service model[73]

[72] Sustainable Bus, "Enel X strategies for public transport: electrification carries the need for innovative solutions", 2021, https://www.sustainable-bus.com/news/enel-x-public-transport-electric-bus/

[73] ZEBRA partnership, "Case study: Metbus pioneering e-bus deployments in Santiago", 2020, https://www.c40knowledgehub.org/s/article/Metbus-pioneering-e-bus-deployments-in-Santiago?language=en_US

Pooled Procurement of E-Buses in India

The Convergence Energy Services Limited (CESL) tender for 5,450 e-buses that closed in April 2022, is by far the largest tender for e-buses in India. Through a process called Grand Challenge – I (GC-I), CESL was able to homogenise the contract conditions and aggregate the requirements of five out of nine cities eligible to access the government incentives.

The GC-1 tender resulted in prices reducing 15% to 48%, compared to prices paid in the past. In fact, the prices through this tender were lower than even those of the diesel/CNG buses.

However, almost every city preferred buses of a different specification, somewhat reducing the benefit of demand aggregation to achieve economies of scale. Reducing the number of bus categories could have increased the benefits even further, although easier said than done.[74]

Charging-as-a-service

The supplier deals with the planning, construction, installation, management, and maintenance of charging services for fleets of electric buses, in addition to energy supply, whereas the electric bus is supplied by third parties. The capital costs could be borne entirely by service provider and amortised over each kWh of electricity supplied for recharging.

Shenzhen, China has adopted this model. Charging piles are provided by a separate service provider which charges a small premium over the prevailing power charges to supply energy on a per unit basis. This approach makes the financials very similar to conventional diesel buses.

[74] ITDP, "An analysis of e-bus procurement in India", accessed in March 2023, https://www.itdp.in/an-analysis-of-e-bus-procurement-in-india/

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