South Africa flagship on green mobility: Johannesburg Metrobus

PART I: GREENING THE FUTURE FLEET

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ICCT CONSULTING REPORT

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LIST OF ACRONYMS

BC	black carbon
BEB	battery electric bus
CO_2e	carbon dioxide-equivalent
CH_4	methane
CNG	compressed natural gas
CTL	coal to liquids
DEF	diesel exhaust fluid
DDF	diesel dual-fuel (DDF) engines
DLE	diesel liter equivalent
DPF	diesel particulate filter
EPA	Environmental Protection Agency (United States)
EURO V	European emission standards for heavy-duty vehicles level V
FCV	Fuel cell vehicle
GDP	gross domestic product
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GHG	greenhouse gases (CO2, CH4, N2O)
GWP	global warming potential over a 20- or 100-year time horizon
HEV	Hybrid electric vehicle
HD, HDV	heavy duty, heavy-duty vehicle
ICCT	International Council on Clean Transportation
IPCC	Intergovernmental Panel on Climate Change
IRP	integrated resources plan
Mt	million metric tons, mega tones
NO_x	oxides of nitrogen
NO_2	nitrogen dioxides
OC	organic carbon
O3	ozone
PM_{10}, $PM_{2.5}$	coarse particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$)
TCO	total cost of ownership
TTW	tank-to-wheel
UJ	University of Johannesburg
SCR	selective catalytic reduction
ULSD	ultralow-sulfur diesel, with <15 ppm sulfur content
WTT	well-to-tank

EXECUTIVE SUMMARY

This report aims to identify the least-cost technology pathways to improving air quality and reducing carbon dioxide emissions from the Metrobus fleet operating in the City of Johannesburg, South Africa. Based on these pathways, this report provides a fleetwide emissions control strategy that sets ambitious climate and air quality goals. Through assessment of technology and fuel pathways, emissions modeling, and total cost of ownership analysis (TCO), this report makes recommendations to Metrobus as a flagship model for South Africa.

Metrobus has not endorsed any fleetwide target for vehicle conventional pollutant emissions or greenhouse gas (GHG) emissions. However, the Johannesburg Integrated Development Plan (IDP) for 2017/2018 endorses compliance with national air quality standards and reduction of GHG emissions of 45% to 65% compared with a 2007 baseline by 2040. The Johannesburg IDP and the National Green Transport Strategy (GTS), which aims for 5% reduction in emissions from transport by 2050, have endorsed deployment of diesel dual-fuel (DDF) engines as a key technology solution. The national GTS is South Africa's government plan for the sector in support of meeting its nationally determined contribution under the Paris Agreement.

This report finds that DDF technology is insufficient to meet stated climate goals. The adoption of DDF buses alone would not be enough to achieve government's climate goals. DDF buses provide a minor GHG emissions benefit relative to older diesel buses in the current fleet. However, this benefit is not sufficient to offset the increased activity projected for the fleet in the future. Moreover, we conclude that there is no attractive decarbonization pathway in which diesel engines can remain in the Metrobus fleet. Instead, alternative technology and fuel pathways are available to meet and even exceed existing goals.

We recommend that the city adopt the following fleetwide targets and recommend a set of actions to implement them:

Target 1: Reduce fleetwide particulate matter (PM) and nitrogen oxides (NOx) emissions to 80% below business-as-usual projected levels by 2030.

Target 2: Reduce fleetwide life-cycle GHG emissions from present levels by 25% within 12 months.

Target 3: Reduce fleetwide GHG emissions to 50% below projected levels by 2040.

Target 4: Establish a Green Bus Team at Metrobus to deliver on targets.

The ongoing procurement of DDF buses with no DDF optimization program and no change in the existing fuel mix would increase, not decrease, fleetwide GHG emissions. In contrast, the procurement of dedicated Euro VI gas engines in the near term accompanied by a transition from fossil gas to biomethane can deliver a 55% reduction in fleetwide GHG emissions by 2040. Alternatively, the procurement of Euro VI diesel engines in the near term, operated without coal-to-liquids fuel and followed within 10 years by the exclusive procurement of zero-emission engines would deliver a 73% reduction in fleetwide GHG emissions by 2040.

The relatively low average number of kilometers traveled per year by buses in the Metrobus system serves to limit the financial benefit of capital-intensive technologies like battery electric buses, which offer greater operational cost savings, public health benefits, and environmental benefits relative to the baseline Euro V DDF technology. Because of the relatively high capital expenses for these technologies, greater utilization rates are necessary to make them more financially competitive with conventional technologies on a TCO basis. In the base assessment, where annual activity was assumed to be 36,000 km/yr, the battery electric bus was estimated to have the highest TCO. However, as annual activity increases, the battery electric bus reaches TCO parity with hybrid engines at 45,000 km/yr, diesel engines at 58,000 km/yr, and CNG engines at 72,000 km/yr. Utilization can be increased through extended ownership periods or greater annual activity that serve to make better use of the capital investment. When the social costs of climate and health damages from emissions are considered in TCO assessments, all alternative bus technologies provide substantial economic benefits relative to Euro V DDF buses.

BACKGROUND AND OBJECTIVES

The Republic of South Africa is a signatory to the United Nations Framework Convention on Climate Change and is taking active steps to reduce its greenhouse gas (GHG) emissions as agreed to and envisioned in its nationally determined contribution (NDCs) under the Paris Agreement. Additionally, Germany's Federal Ministry of the Environment, Nature Conservation, and Nuclear Safety provides support to countries working to fulfill their climate goals through its International Climate Initiative (IKI).

The Climate Support Program (CSP), implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, supports the development of climate policy and governance, as well as their implementation in the areas of mitigation, adaptation, monitoring, and evaluation. CSP supports the Department of Environment, Forestry and Fisheries (DEFF) in achieving ambitious climate objectives through so-called flagship projects.[1] Transport is one focus for flagship programs, including support to the City of Johannesburg to promote green mobility, protect the environment, and increase safety for commuters.

ABOUT METROBUS AND EMISSION GOALS

Metrobus is an operator of public transit services in the greater metropolitan area of Johannesburg. Established in 1942, Metrobus operated until 1999 as a public transport agency. In 2000, the City of Johannesburg converted Metrobus into a municipally owned entity that is overseen by a board of directors appointed by the city. As of June 30, 2019, Metrobus owned 419 buses with an additional 10 buses on lease that operated along 229 routes carrying 10 million passengers per year in the greater metropolitan area.

In a June 2018 report, Metrobus was found to be technically insolvent.[2] Falling ridership over the previous five years combined with service delivery and fare collection challenges contributed to this decline. One consequence was the decision in recent years to reallocate funds for maintenance and re-fleeting to other areas. In the absence of funds to procure new vehicles, Metrobus invested in refurbishing existing vehicles.

The continued reliance on vehicles as many as 18 years old has contributed to poor air quality in Johannesburg. In 2017, the city issued an Air Quality Management Plan (AQMP), explaining that the city is not in compliance with national ambient air quality standards for nitrogen dioxides (NO_2), coarse particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$) and ozone (O_3).[3] The strategy identifies vehicles as a target for emission reductions to achieve compliance with the standards in alignment with the surrounding Gauteng province's AQMP, which also targets tailpipe emission controls. Projects listed in the AQMP include using Rea Vaya, the Johannesburg bus rapid transit system; conversion of dual-fuel buses to achieve a 10% reduction in GHG emissions from the current fleet; and deployment of efficient public transport vehicles powered by renewable energy.

The city has highlighted investments in its urban bus fleet as a priority to meet local climate change targets. In addition to the AQMP, the city has a Climate Adaptation Plan (2009) and a Climate Change Strategic Framework (2015).[4] Moreover, in its Energy and Climate Change Strategy and Action Plan, Johannesburg adopted a goal of cutting

1 https://www.giz.de/en/worldwide/17807.html

2 Metrobus 2018/2019 Fourth Quarter Performance Report https://www.mbus.co.za/index.php/publications-101

3 https://www.joburg.org.za/documents_/Documents/By-Laws/Draft%20CoJ%20AQMP%202017.pdf

4 For the Climate Adaptation Plan see https://www.preventionweb.net/files/38589_38507climatechangeadaptationplancit.pdf. For the Climate Change Strategic Framework see https://www.globalcovenantofmayors.org/wp-content/uploads/2015/06/CCSF-CoJ-Final.pdf

GHG emissions 43% by 2050, without stating a baseline. The Climate Change Strategic Framework proposes a reduction of 40%–65% below a 2007 baseline by 2040. The framework notes that the transport sector contributed to an increase in GHG emissions in the city of 26% from 2007 to 2014, attributable to road transport and reliance on private vehicles. In 2014, the transport sector contributed 6.8 mega tonnes (Mt) of CO_2 equivalent (CO_2e) per year. The framework emphasizes the conversion of the fleet of buses to diesel dual-fuel (DDF), and the deployment of the bus system through Rea Vaya.

These actions are further reflected in the Johannesburg Growth and Development Strategy – 2040, which aims for all city fleets to use green and renewable energy and fuel sources. Additionally, the city's 2017/2018 Integrated Development Plan (IDP) emphasizes the growth of low-carbon transport and modal shift in favor of public transport. The plan sets out to accelerate the shift to low-carbon transport through the re-fleeting of the public transport fleet with green technology and to achieve "clean air" through compliance with national ambient air quality standards by 2040.[5] The plan reinforces the aspirational target of a GHG reduction of 40%–65% by 2040 from a 2007 baseline and recommends the recapitalization of Metrobus with dual-fuel biogas and diesel buses, as well as a restructuring of the operator to a service delivery model, paying a fee per kilometer with penalties for poor performance. The plan sets a 2021 goal of a daily target of 51,000 passengers under Metrobus compared with 60,000 for Rea Vaya and an offset of 40,000 annual tonnes of CO_2 in the transport sector by 2020, capturing in part the benefits of a shift to DDF technology.

PROVINCIAL AND NATIONAL TRANSPORT GOALS

Gauteng province has also prioritized investments in urban bus fleets. Both Gauteng's 2009 AQMP and its 2011 Climate Change Response Strategy include actions aimed at the public transport sector. The Climate Change Response Strategy adopts the goal of switching public sector vehicles, including public transport, to compressed natural gas (CNG) to reduce GHG emissions and local air pollution. The aim is for government to lead by example through the construction of CNG filling stations, specification of CNG for all new acquisitions of public sector vehicles, and other measures. The strategy further sets a goal of generating liquid or gas biofuels for use in multiple sectors, including transport, particularly from bio-waste feedstocks including landfill gas, or purpose-grown crops. The introduction of minimum liquid fuel requirements from biofuels is one of several measures recommended.

Further support for investments in green urban bus fleets have come through the national government. The National Climate Change Response Policy mandates the Department of Transport to lead a Transport Flagship Programme that is to include promotion of lower-carbon mobility.[6]

The Green Transport Strategy (2018–2050) of the Department of Transport identifies the transport sector as the source of 10% of national GHG emissions, while road transport produces 91% of transport sector emissions. The strategy calls for specific actions toward cleaner fuels and alternative fuels in Section 8.7, and it names specific short-term, medium-term, and long-term objectives.

Over the short term, the strategy aims for modal shift of 20% of passenger transit to public transport; the conversion of 5% of the public and national fleet to cleaner alternative fuel and efficient technology vehicles, ideally powered through renewable energy, with annual increases of 2% after seven years; and environmentally sustainable low-carbon fuels by

5 For the 2017/2018 Johannesburg Integrated Development Plan see http://www.jicp.org.za/idp-2/

6 For the National Climate Change Response Strategy see https://www.environment.gov.za/sites/default/files/legislations/national_climatechange_response_whitepaper.pdf

2025. The strategy includes a short-term objective to promote hydrogen fuel cell public transport, which is under development through a joint project of the Department of Trade and Industry together with the Department of Science and Innovation.

Over the medium term, the strategy aims for government to set an example by instituting guidelines for publicly owned fleets that set appropriate targets for the procurement of alternative fuels and efficient vehicle technologies and fuels. Over the long term, the strategy names local government authorities led by DOT as the responsible parties for drafting regulations to enable conversion of 10% of public and quasi-public transport vehicles to dual-fuel vehicles within 10 years.

The strategy references the Clean Fuels II regulation led by the Department of Mineral Resources and Energy (DMRE) to transition national fuel quality standards to Euro V levels. Today Euro V fuels are produced in South Africa by Sasol using a coal-to-liquids (CTL) process, which makes such cleaner fuels (i.e., with much lower sulfur content) far more carbon-intensive than dirtier fuels. The DEA did not enforce a July 2017 deadline to require national availability of Euro V fuels and has not put forward a new timeline. A stalemate between national oil refineries and the government of South Africa on a finance mechanism for refinery upgrades has led to uncertainty about the timeline of availability of conventional Euro V diesel fuels, which are less carbon intensive than CTL-produced Euro V diesel.[7]

Meanwhile, the South Africa government has pledged to limit its economy-wide GHG emissions to 17%–78% above 1990 levels by 2030, excluding land use, land-use change, and forestry, and to 35% below to 25% above 1990 levels by 2050.[8] Current policy-based projections estimate an 82% increase in emissions above 1990 levels by 2030 on the same basis.[9] Currently 30% of gasoline and diesel fuels are generated from coal feedstocks. The government adopted a carbon tax that went into effect in June 2019 for all fossil fuel combustion emissions, although tax exemptions remain in place for 95% of emissions until 2022.

PROJECT OBJECTIVES

The project has the following objectives:

1. To produce a real-world performance assessment and cost-benefit analysis of fuel and engine technologies in the existing Metrobus fleet.
2. To assess alternative fuel and engine technology pathways.
3. To recommend a fleet technology roadmap, informed by (1) and (2) and in consultation with national and local stakeholders.
4. To develop policy and implementation guidance based on the findings.

This report, the first of two for this project, communicates the findings related to objectives 2, 3, and 4.

7 For further detail of the stalemate between public and private sector actors over implementation of the Clean Fuels II regulation see https://www.hydrocarbonprocessing.com/magazine/2017/april-2017/columns/refining-uncertainty-grips-south-africa-s-clean-fuels-program

8 https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/South%20Africa%20First/South%20Africa.pdf

9 https://climateactiontracker.org/countries/south-africa/current-policy-projections/

TECHNOLOGY POTENTIAL

Diesel engines are the most common powertrain technology in South Africa. But unlike other major vehicle markets that have implemented stringent emissions control measures, South Africa has been slow to advance to cleaner diesel emission standards. The largest vehicle markets today—Europe, the United States, Canada, Japan, Korea, China, India, Brazil, Mexico, and Colombia—mandate or are in the process of implementing Euro VI emission standards for buses and other heavy-duty vehicles. Compared with previous emission standards, including the Euro V standards currently available in Metrobus, Euro VI standards achieve a 90%–98% reduction in particulate mass, particulate number, and black carbon emissions from diesel vehicles. The Euro VI emissions level is the best available control technology to protect public health from combustion engine emissions.

Today the South African national government mandates Euro II emission standards, more than 20 years behind the European Union. With diesel fuel sulfur content limited to 50 parts per million (ppm), the national government can immediately implement Euro IV emission standards and bring the country within a 13-year lag behind Europe. Quick action can be taken to impose such standards on an interim basis, followed by more stringent standards later.

South Africa is a large-scale producer of domestic diesel fuel from coal-based feedstocks. While this fuel reduces reliance on imported energy, its combustion produces some of the highest rates of CO_2 emissions of any transport fuel available. The transition to a locally produced fuel source that is clean and low carbon is necessary in Johannesburg.

METROBUS FLEET

The current city-owned Metrobus fleet is composed of 419 vehicles. The buses have been powered by diesel fuel until the integration of DDF technology requiring a supply of gas within the last several years. Figure 1 presents a description of the Metrobus fleet composition, according to public records.

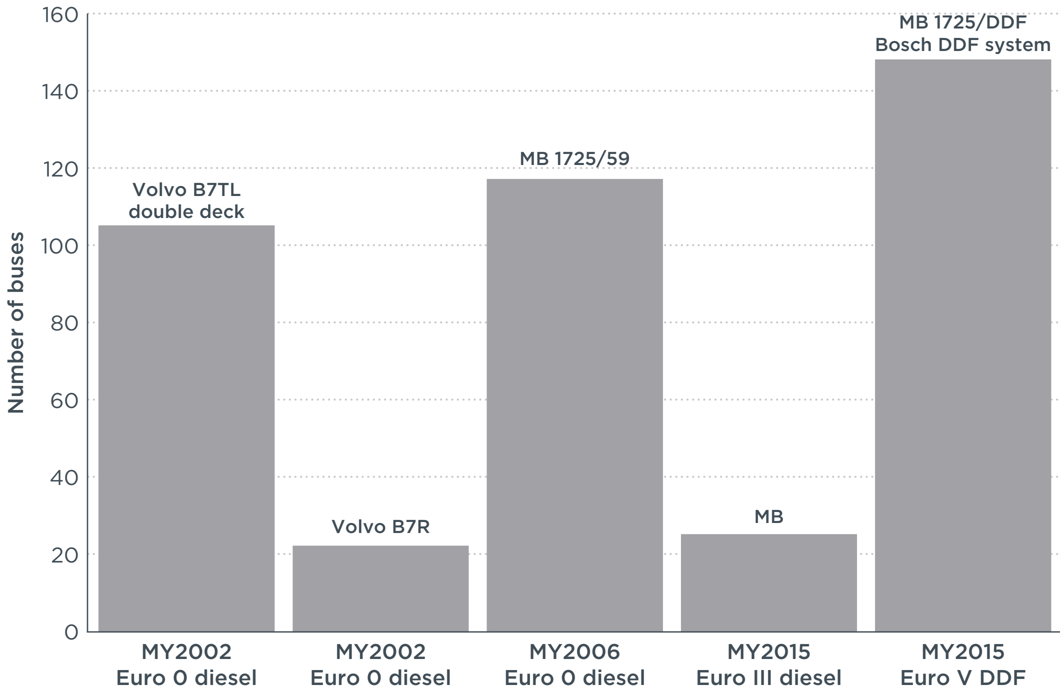

Figure 1. Metrobus fleet composition, June 2019. Data source: Metrobus Fourth Quarter Performance Assessment Report 2018/2019.

The most advanced emissions control technology in the present fleet uses a MY2015 Euro V Mercedes-Benz diesel engine retrofitted with a Bosch DDF system. The DDF system shifts the engine to CNG mode under specific operating conditions, especially high speed and low load. The emissions control system uses exhaust gas recirculation (EGR) and a selective catalytic reduction (SCR) system, typical of Euro V diesel emissions control technology.

DDF buses are refilled at a small compressor station with a supply via on-road (truck) deliveries at the Milpark depot. DDF buses stationed at other depots are driven to the Langlaagte filling station to refill, although this presents scheduling challenges and increases operating costs.

ENERGY CONSUMPTION OF ALTERNATIVE TECHNOLOGIES

We compared the performance of Euro V DDF technology against alternative soot-free and zero-emission technologies, such as Euro VI diesel, Euro VI diesel-electric hybrid, Euro VI CNG, and zero-emissions battery electric buses. To our knowledge, these technologies have not been used in Johannesburg. Due to this lack of Johannesburg-specific data, our approach here is to present information about the ways in which energy consumption and the relative performance of technologies can vary according to driving conditions and route type.

The ICCT previously reviewed the energy consumption of soot-free and zero-emissions bus technologies as part of an assessment of low-carbon technology pathways for urban bus fleets (Dallmann, Du, & Minjares, 2017). Key findings from this assessment are presented in Figure 2, which shows energy consumption for four soot-free and zero-emissions transit bus technology types across six different driving cycles. Energy consumption data is sourced from testing conducted by the Altoona Bus Research and Testing Center in the United States. Average energy consumption values are presented by bus technology and driving cycle, with driving cycles ordered from left to right in order of increasing kinetic intensity. Kinetic intensity is a metric that was developed to compare different driving cycles on an energy basis and specifically to identify those duty cycles where hybridization would offer the greatest fuel-saving benefits for heavy-duty vehicles. Driving cycles with low kinetic intensities typically have higher speeds and little stop-and-go driving, and the energy required to overcome aerodynamic resistance outweighs the energy required for vehicle acceleration. The reverse is true for high kinetic intensity cycles, which tend to have lower speeds and more frequent acceleration and deceleration events.

Figure 2 shows that energy consumption can vary considerably by driving cycle. For internal combustion engines, energy consumption tends to increase with increasing cycle kinetic intensity. This means that diesel, hybrid, and CNG buses will consume less fuel per kilometer when deployed on routes with higher average speeds and a lower number of stops than on routes with high levels of congestion or low-speed, stop-and-go driving conditions.

The relative performance among technologies also varies by driving cycle. Hybrids offer little to no energy consumption benefit compared with conventional diesels over low kinetic intensity driving cycles characterized by higher-speed cruise-type conditions. On the other hand, energy consumption values for hybrids are about 20% lower than those for diesels over medium- and low-speed cycles where the efficiency benefits of regenerative braking systems on hybrid buses are maximized. With respect to energy consumption, hybrid buses are less sensitive to driving conditions and route type than conventional diesel or CNG buses.

These data suggest that the energy consumption of CNG buses is most sensitive to driving cycle, with a factor of 2.4 difference in average performance between the highest and lowest kinetic intensity cycles. At low kinetic intensity cycles, average energy consumption for diesel and CNG buses is similar, although these data indicate that CNG buses tend to perform relatively worse over test cycles with higher kinetic intensities. The average energy consumption for CNG buses is about 10% greater than for diesel buses over medium kinetic intensity cycles and 20% more for high-intensity cycles.

Battery electric buses offer significant efficiency benefits relative to buses using internal combustion engines across all driving cycles. Battery electric buses use between 70% and 80% less energy per kilometer than conventional diesel buses. Reasons for this include the use of regenerative braking, significantly less waste heat generation, more-efficient motors, and more-efficient transmissions.

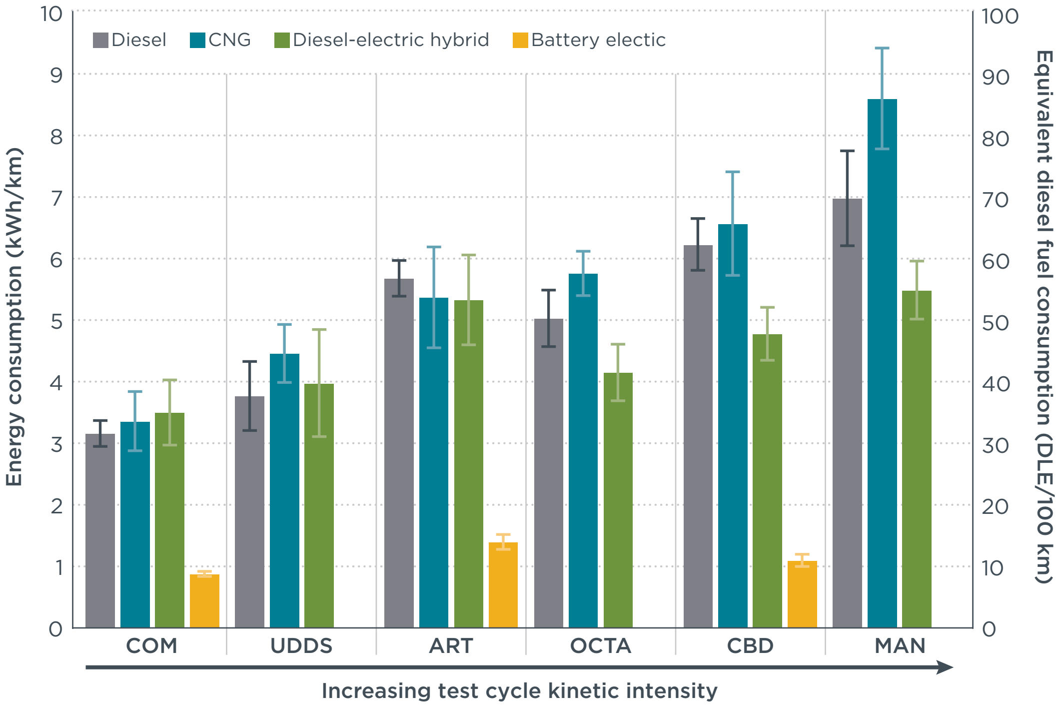

Figure 2. Average energy consumption by powertrain type and driving cycle for 2010 and newer model year buses tested at the Altoona Bus Research and Testing Center. The right axis shows fuel consumption in terms of energy equivalent of a liter of diesel fuel, referred to as diesel liter equivalent (DLE). Battery electric buses are not tested over the Urban Dynamometer Driving Schedule (UDDS), Orange Country Transport Authority (OCTA), and Manhattan (MAN) cycles in the Altoona test program. All buses were tested over commuter (COM), arterial (ART), and central business district (CBD) cycles. Uncertainty bars shows the standard deviation of average energy consumption values (Dallmann et al., 2017).

Energy consumption findings are summarized in Table 1. Results for individual driving cycles are grouped into three generalized route types: commuter suburban operations characterized by higher average speeds and few stops per kilometer; medium-speed urban operations, with average speeds of about 20 km/h; and low-speed urban operations characterized by low speeds and stop-and-go driving conditions. Comparisons among technologies presented here are consistent with findings of other recently published transit bus technology assessments (e.g., Lajunen, 2016; ADB, 2018).

Table 1. Energy consumption for alternative powertrain types relative to baseline diesel for different route types (Dallmann et al., 2017).

	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%

In general, these findings show that route characteristics such as road type, number of stops per kilometer, and average speed should be considered when evaluating potential alternative transit bus technologies. To the greatest extent possible, technologies should be matched to those route types where they can provide the greatest efficiency benefits, as this leads to reduced fuel consumption, operating costs, and GHG emissions.

The results in Table 1 give a general perspective of the energy consumption for alternative transit bus technologies. A more robust comparison could be performed through pilot testing of these technologies on Metrobus routes or through energy consumption modeling using detailed information about the operating conditions on selected routes. An example of how these strategies have been used in Santiago, Chile, to promote transitions to cleaner and more efficient bus technologies can be found in a recent study conducted by the International Energy Agency's Advanced Motor Fuels Technology Collaboration Programme (Castillo et al., 2018).

Similar modeling capabilities are currently being developed by the ICCT. While beyond the scope of this study, these methods could be used as part of a follow-up study to provide a more detailed analysis of the energy consumption of alternative bus technologies in Johannesburg. A first step that Metrobus could take to support this type of assessment would be to deploy GPS units throughout the fleet to collect detailed operating information such as vehicle speed, acceleration, and elevation.

WELL-TO-WHEEL (WTW) GHG EMISSIONS OF ALTERNATIVES

This section considers the fuel life cycle or WTW GHG emissions from alternative transit bus drive systems and fuels. Life-cycle GHG emissions can be calculated as the product of the energy consumption of a vehicle and the carbon intensity of the fuel that powers the vehicle. In this formulation, energy consumption is expressed in units of energy consumed per distance traveled, such as kWh/km, and fuel carbon intensity expressed in units of mass CO_2 equivalent emitted per unit energy of fuel consumed, such as gCO_2e/kWh. The product of these values yields GHG emissions estimates in units of mass CO_2e emitted per vehicle distance traveled (gCO_2e/km). For this analysis, we consider the difference in WTW GHG emissions for alternative technologies and fuels relative to the baseline Metrobus technology, Euro V DDF buses using commercial CNG and diesel fuels. Results are reported for three representative route types.

Energy consumption for alternative technologies is estimated using average fuel consumption values for the Metrobus fleet and the relative energy consumption performance levels reported in Table 1.

The carbon intensity of fuels used in transit bus applications includes both direct emissions of GHGs from the combustion of fuels in internal combustion engines and upstream emissions associated with the production of the fuel and feedstock. Emissions from the combustion of fuel in a bus engine are typically referred to as tank-to-wheel (TTW) emissions, whereas upstream emissions are referred to as well-to-tank (WTT) emissions. The sum of these two yields WTW emissions, which are the focus of this analysis. The carbon intensity metric includes emissions of the GHGs CO_2, methane

(CH_4), and nitrous oxide (N_2O). One-hundred-year global warming potential values are used to express non-CO_2 GHGs in units of CO_2e.

Figure 3 shows estimates of WTW carbon intensities for transit bus fuels produced completely or in part from fossil sources, including fossil diesel, fossil CNG, and grid electricity. For diesel fuels, estimates are shown for diesel derived from crude oil and coal feedstocks. Also shown is an estimate for the average South African diesel mix, assuming 30% of the diesel fuel consumed in the country is supplied by CTL fuels, with the remainder produced from crude oil feedstocks. Data for the carbon intensity values for diesel fuels and national diesel supply mix is taken from the Department of Environmental Affairs GHG Mitigation Potential Analysis Report (DEA, 2014).

The WTW carbon intensity of CTL diesel is more than twice the carbon intensity of crude oil-derived diesel. This means that any CTL-derived diesel in the fuel mix for the Metrobus fleet will considerably increase the WTW GHG emissions of diesel or DDF buses operating in the city. For our modeling of the baseline Euro V DDF technology buses, we assume diesel fuel consumed has a carbon intensity of 450 gCO_2e/kWh, equivalent to the value reported for the average South African diesel supply mix.

Fossil CNG carbon intensity values reported in Figure 3 are sourced from the Argonne National Laboratory (ANL) GREET model as reported in the ANL AFLEET tool (ANL, 2018). The carbon intensity of fossil CNG fuel is sensitive to assumptions made regarding the amount of methane leakage during the natural gas supply chain of production, processing, transmission, and compression as well as vehicle use. Here, we explore this sensitivity by calculating carbon intensity values for three levels of assumed methane leakage in the natural gas supply chain. The low CH_4 leakage estimate assumes a leakage rate of 1.3%, the default value employed in the AFLEET model. The medium CH_4 leakage estimate of 2.3% is in line with recent findings of an extensive experimental program to measure methane emissions from the natural gas supply chain in the United States (Alvarez et al., 2018). Finally, a high CH_4 leakage case is estimated by doubling the assumed supply chain leakage used in the medium case to 4.6%. The difference in fossil CNG carbon intensity estimated for the high and low supply chain leakage cases is approximately 15%, or 303 gCO_2e/kWh versus 265 gCO_2e/kWh. The carbon intensity value for the low CH_4 leakage case is 13% higher than the value reported in the DEA GHG Mitigation Potential Analysis report.

The carbon intensity estimates for fossil CNG are also sensitive to assumptions regarding methane leakage during vehicle use. For our base modeling of DDF and CNG vehicles, we apply default values reported in the AFLEET model to estimate such emissions. These estimates should be updated if further information becomes available through Metrobus emissions testing.

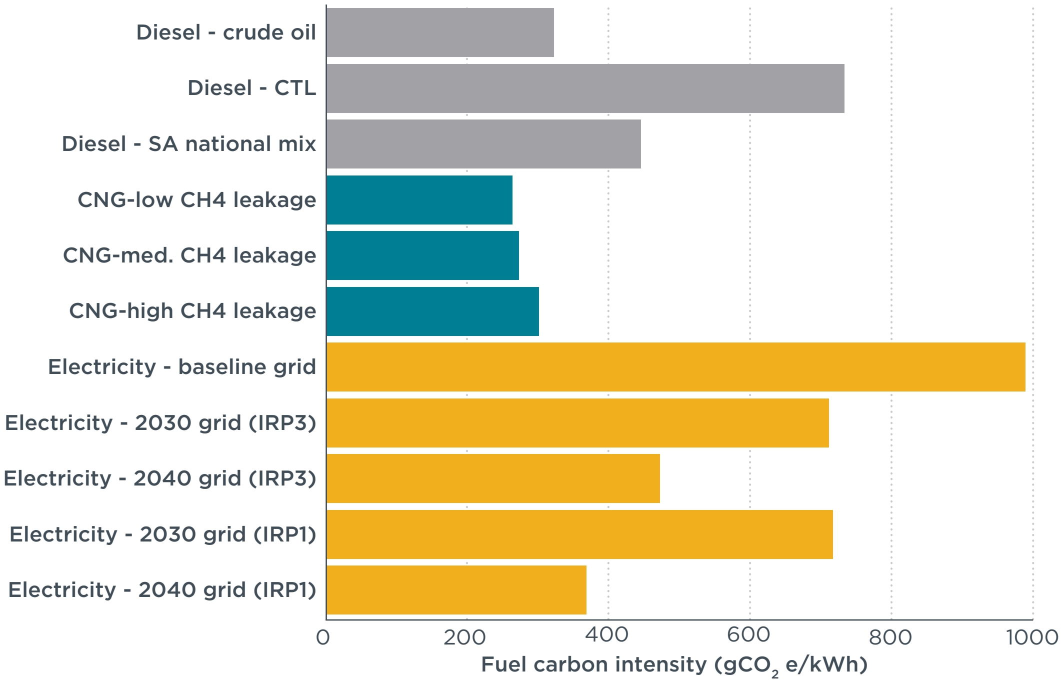

Figure 3. Fuel life cycle carbon intensities for fossil diesel, fossil CNG, and electricity.

The carbon intensity of the electricity used to power battery electric buses is estimated using the AFLEET model and data on national-level electricity production by generation source type for the baseline year, 2017, as well as projections for future years provided in the Department of Mineral Resources and Energy Integrated Resource Plan (2018). The assumed share of electricity generation by fuel type for each scenario is reported in Table 2. The year 2017 generation mix is dominated by coal, and this results in a relatively high grid carbon intensity. The estimated grid carbon intensity includes an adjustment for distribution losses, assumed to be 9% for the baseline year and assumed to decrease to 6% by 2040. We also consider two scenarios from the DMRE's Integrated Resource Plan (IRP). The IRP3 scenario is the reference scenario, and the IRP1 scenario reflects a situation in which there are no build limits on renewable generation sources. In each DMRE scenario, a significant level of grid decarbonization is achieved by 2040, resulting in considerably lower carbon intensities for grid electricity in 2040 relative to the baseline. The IRP3 trajectory results in a 52% reduction in grid carbon intensity, while the IRP1 trajectory, where renewables account for a larger share of total electricity production, results in a 63% reduction in grid carbon intensity relative to the 2017 baseline.

Table 2. Share of electricity generation by fuel in South Africa (IEA, 2018; DMRE, 2018)

Electricity source	2017	IRP3		IRP1	
		2030	2040	2030	2040
Coal	89.6%	63%	39%	64%	30%
Gas	0.0%	3%	8%	2%	7%
Diesel	0.1%	0%	0%	0%	0%
Nuclear	5.9%	4%	4%	4%	4%
Renewables	4.4%	30%	49%	30%	59%
Estimated grid carbon intensity (gCO$_2$e/kWh)	990	712	474	718	370

The carbon intensity of biomethane is heavily dependent on feedstock and production pathways. To illustrate the variability in biomethane carbon intensity, Figure 4 shows carbon intensities for biomethane fuels certified under the State of California's Low Carbon Fuel Standard. For each biomethane fuel, life-cycle assessment was conducted to assess WTW carbon intensity. The wide difference in carbon intensities for biomethane is readily apparent. Biomethane derived from animal waste has large negative values because of credits from avoided methane emissions. The certified pathways for biomethane produced from food and green waste also have negative or near-zero carbon intensities. Wastewater sludge and landfill gas pathways generally have been found to have higher life-cycle GHG emission intensities but still provide improvements compared with fossil CNG. These data reinforce the importance of identifying secure supplies of low-carbon biomethane feedstocks for any transition to CNG buses fueled with biomethane.

For the GHG emissions modeling presented in this study, we assume a carbon intensity of 167 gCO_2e/kWh for biomethane, which is equivalent to the value reported in the California Air Resources Board Temporary Pathways table for biomethane produced from landfill or digester gas. This value is used within the scope of the California Low Carbon Fuel Standard for fuel pathways that have not yet undergone full life-cycle assessment.

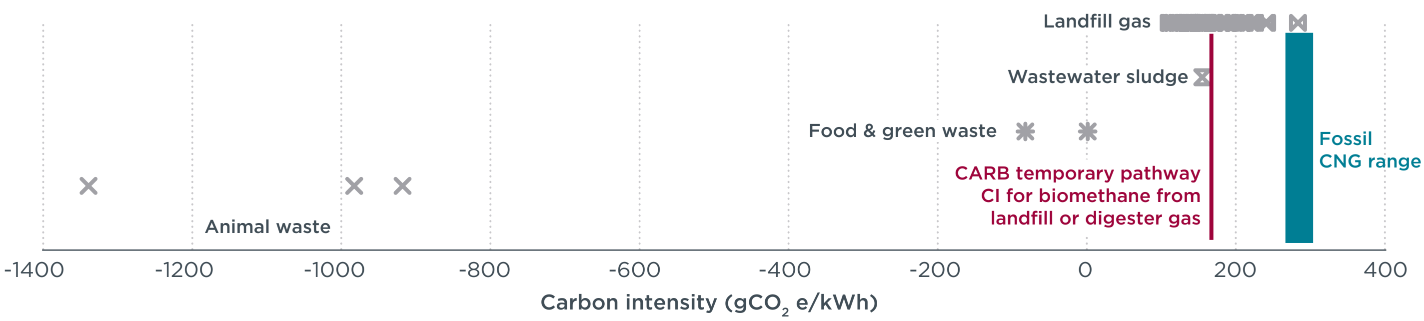

Figure 4. Carbon intensity for biomethane by feedstock (CARB, 2019)

Life-cycle fuel carbon intensities and energy consumption estimates were combined to estimate the relative WTW GHG emissions performance of alternative powertrain and fuel combinations as compared against the baseline Metrobus technology and fuel. That is, a Euro V DDF bus operating at a 15% diesel substitution rate and fueled with fossil CNG and commercial diesel fuel, 30% from CTL and 70% from crude oil. Figure 5 presents the WTW GHG comparison for suburban/commuter route types characterized by higher average speeds and few stops per kilometer.

Several conclusions can be drawn from this comparison:

» With the exception of diesel and hybrid buses fueled with CTL diesel, all technology and fuel options provide WTW GHG emission savings relative to the baseline DDF technology. If Euro VI diesel or hybrid buses fueled with low-sulfur CTL diesel fuel were to replace DDF buses on routes with these driving conditions, life-cycle GHG emissions could increase by 70%–80%.

» Optimizing the performance of the existing DDF fleet could yield GHG emission savings if tailpipe methane emissions are low. We estimate that Euro V DDF buses operating at a 50% diesel substitution rate, in line with the top performing buses in the current Metrobus fleet, reduce GHG emissions by approximately 15% relative to the case where a 15% substitution rate is assumed. If tailpipe methane emissions from DDF buses increase at higher gas substitution rates, GHG emission savings from displacing high carbon intensity diesel fuel will be lower than estimated here.

» Hybrid and diesel buses fueled with crude oil-derived diesel fuel and battery electric buses assuming the 2017 grid mix provide similar WTW GHG emissions performance. In each case, GHG emissions are about 20% lower than those for the baseline technology.

» Efficiency penalties for CNG engines are minimized under suburban/commuter operating conditions, leading to better GHG emissions performance than other alternative technologies in cases where low natural gas supply chain leakage is assumed. With higher leakage rates, performance is more similar to diesel, hybrid, and battery electric options.

» Low-carbon technology options—CNG buses fueled with biomethane and battery electric buses powered by decarbonized grid electricity—provide the greatest GHG emission benefits, with reductions of 60%–70% relative to the baseline.

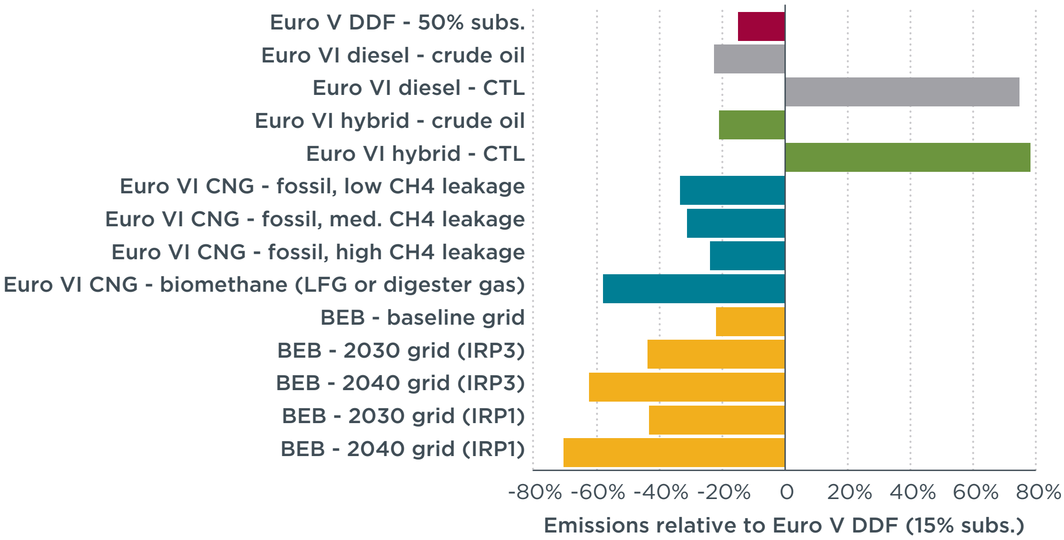

Figure 5. WTW GHG emissions relative to the Euro V DDF baseline for buses operating in commuter/suburban driving conditions. Battery electric buses are abbreviated as BEB.

Figure 6 presents the WTW GHG emissions comparison for medium-speed urban route types. Relative to suburban/commuter driving conditions, hybridization and electrification provide greater GHG emission benefits on medium-speed urban routes. In these conditions, battery electric and hybrid buses using crude oil-derived diesel have a distinct GHG emissions benefit relative to diesel and CNG buses using fossil fuels. CNG buses maintain an advantage relative to diesel buses using crude oil-derived diesel in the cases where low or medium natural gas supply methane leakage is assumed. The technologies have similar GHG emissions performance in the high supply chain leakage scenario. Buses fueled with CTL diesel fuels remain a poor option with respect to life-cycle GHG emissions.

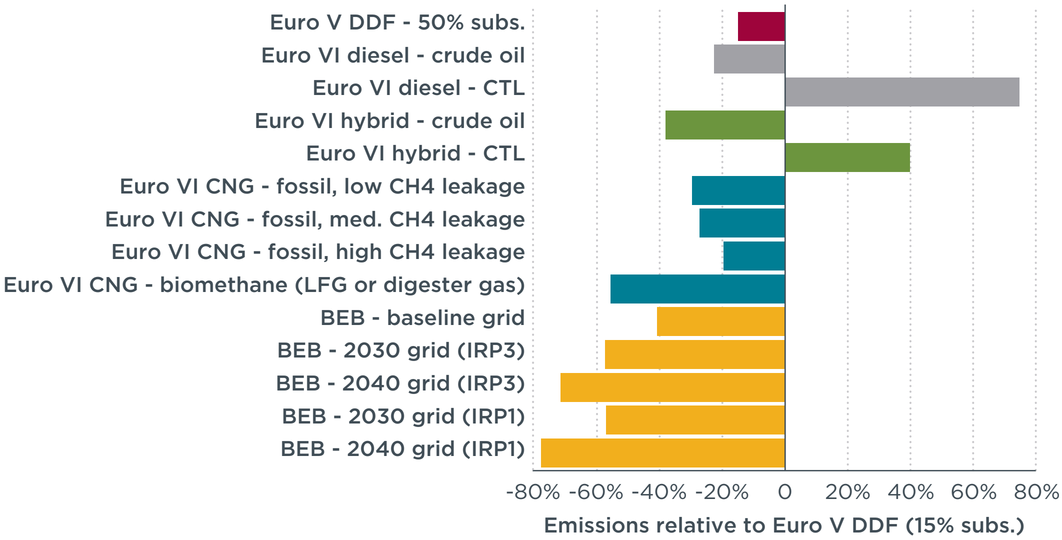

Figure 6. WTW GHG emissions relative to Euro V DDF baseline for buses operating in medium-speed urban driving conditions.

Finally, figure 7 shows the WTW GHG comparison for low-speed urban route types, characterized by low average speeds and congested driving conditions. Results are generally similar to those for medium-speed urban routes. Hybrid buses fueled with crude oil-derived diesel fuel and battery electric buses provide the greatest GHG emission savings. If battery electric buses are powered by electricity with a carbon intensity similar to that of the 2040 estimate for the IRP1 scenario, GHG emissions could be reduced by about 75% from the baseline. Efficiency penalties of CNG buses are estimated to be highest under low-speed operating conditions. As such, GHG savings of biomethane-fueled CNG buses are not as great here as compared with other route types. However, this technology pathway still provides significant GHG emission savings relative to the baseline.

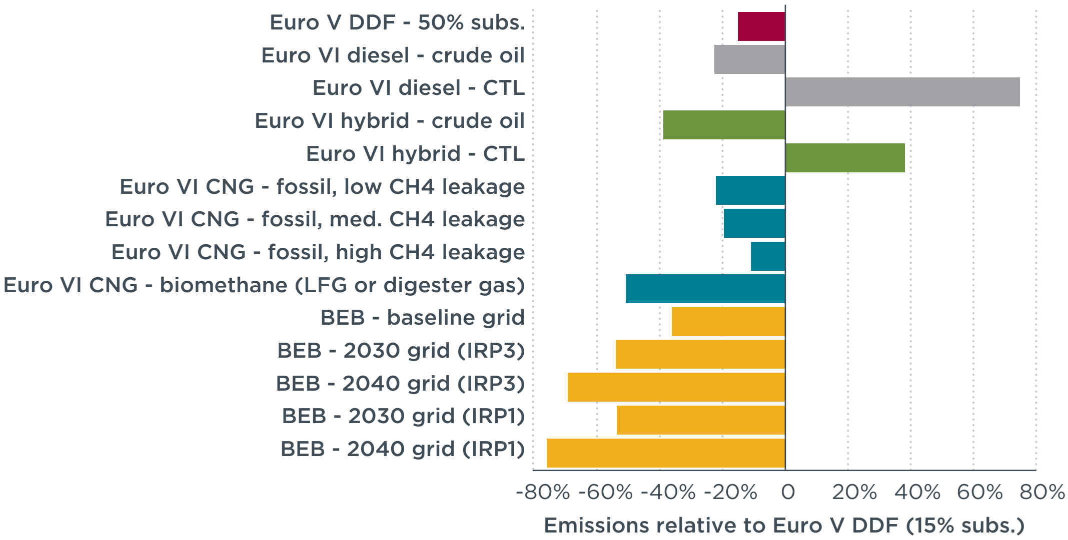

Figure 7. WTW GHG emissions relative to Euro V DDF baseline for buses operating in low-speed urban driving conditions.

Several important conclusions can be drawn from this assessment of GHG emissions performance. **From a GHG emissions perspective, diesel fuel derived from coal feedstocks should be avoided.** These fuels have a very high carbon intensity and, consequently, much greater GHG emissions relative to other technology and fuel options. If Metrobus were to consider Euro VI diesel technologies, a dedicated supply of low-sulfur diesel fuel would need to be procured. In this case, it is important that the fuel not be produced from high-carbon feedstocks like coal.

In general, Euro VI diesel buses using crude oil-derived diesel and CNG buses using fossil CNG have similar WTW GHG emission levels. CNG buses are estimated to have moderately better performance under suburban/commuter driving conditions, while diesel buses perform better under congested, low-speed urban conditions. Life-cycle GHG emission estimates for CNG buses are sensitive to assumptions regarding methane leakage in the natural gas supply chain. For the range of leakage rates considered here, the impact on WTW GHG emissions is similar in magnitude to the impact of varying driving conditions. Biomethane provides a low-carbon fuel pathway for CNG buses. The carbon intensity for biomethane fuels can vary considerably depending on the feedstock and production pathway. The carbon intensity applied in this analysis is representative of biomethane produced from landfill or digester gas. In this case, WTW GHG emission savings were estimated to be in the range of 50%–60% relative to the baseline. If biomethane were to be produced from lower-carbon feedstocks, such as animal or food waste, GHG emission savings could be much greater.

Battery electric buses provide GHG emission savings relative to the baseline technology, even when powered with today’s relatively high carbon intensity grid electricity. For the baseline grid case, WTW GHG emissions are similar to those estimated for hybrid buses fueled with crude oil-derived diesel and for low- and medium-speed urban route types, lower than those of Euro VI diesel and CNG buses fueled with fossil-derived fuels. The GHG emission benefits of battery electric buses are even clearer under the grid decarbonization scenarios, where the technology is estimated to reduce emissions by 60%–80% relative to a baseline Euro V DDF bus.

AIR QUALITY BENEFITS OF SOOT-FREE EURO VI AND ZERO-EMISSION TECHNOLOGIES

One of the most important reasons for transitioning to soot-free and zero-emission engine technologies and fuels is the improvement in emissions performance that they provide. Zero-emission technologies such as battery electric and fuel cell technologies have zero tailpipe emissions of harmful local air pollutants, such as nitrogen oxides (NO_x) and particulate matter (PM). Soot-free technologies, such as diesel or natural gas engines certified to world-class emission standards (Euro VI or EPA 2010), employ emissions control technologies that greatly reduce tailpipe emissions in real-world conditions. Transitioning to soot-free and zero-emission technologies thus reduces emissions and contributes to improved air quality and public health. This section considers the air pollutant emissions of these alternative powertrain and fuel options.

Figure 8 demonstrates the improvement in PM and NO_x emissions performance of diesel and CNG buses with the development of the European regulatory program for heavy-duty vehicles. Emission factors for each pollutant are presented by engine type and Euro standard, beginning with Euro I and ending with Euro VI, the current standard in force. National standards for heavy-duty vehicles in South Africa are currently equivalent to Euro II standards. Emission factor data is sourced from the Handbook Emission Factors for Road Transport (HBEFA), a European emission factor model used widely in emissions inventory development applications (HBEFA, 2019).

The air pollutant emission benefits of Euro VI technologies are readily apparent in Figure 8. The PM emission factor for Euro VI buses is estimated to be 99% lower than for Euro

I buses and 75% lower than for buses certified to Euro V emission standards. Similar reductions are reported for the Euro VI NO_x emission factor relative to previous emission control stages. Likewise, the emissions performance of CNG buses has improved with the introduction of more-stringent emission standards and associated technological development. The percentage change in emission reductions offered by Euro VI technologies is only slightly less than that offered by zero-emission technologies such as battery electric buses.

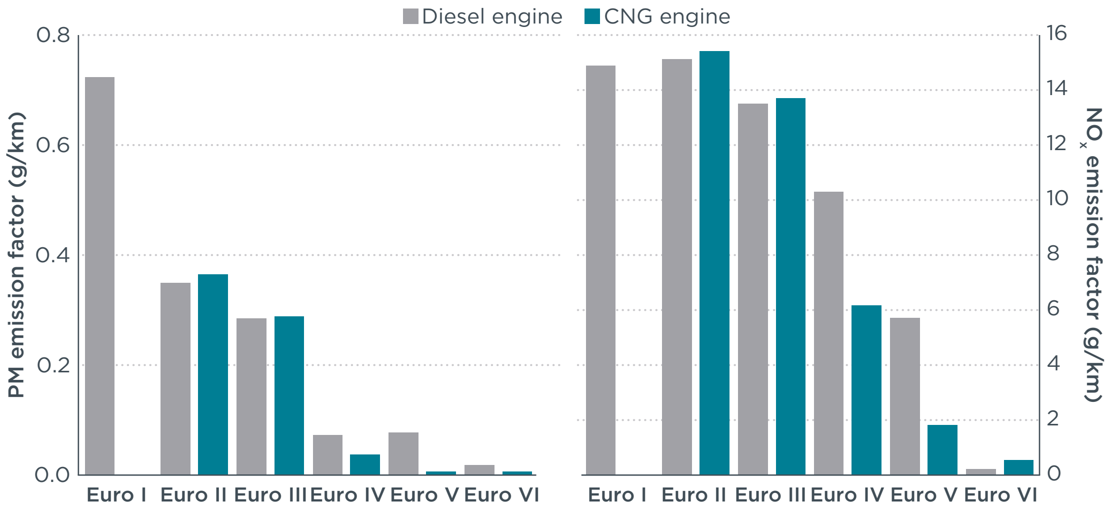

Figure 8. PM and NO_x emission factors for standard-sized diesel urban buses by emissions control level and engine technology. Data sourced from HBEFA (2019).

Euro VI engines are also effective at controlling particle number and black carbon emissions. Particle number is associated with the detrimental health impacts of vehicular PM emissions, while black carbon is a major component of diesel PM and an important short-lived climate pollutant. Up to 75% of diesel PM emitted from older-technology engines contains black carbon. However, Euro VI engines reduce diesel black carbon emissions by 99%, primarily through the application of a diesel particulate filter (DPF). The DPF also effectively controls particle number emissions, as demonstrated in Figure 9. The particle number emission factor for Euro VI diesel buses is two to three orders of magnitude lower than older-technology buses that lack particulate filters. For CNG engines, particle number emissions have been relatively well controlled since the implementation of Euro IV standards.

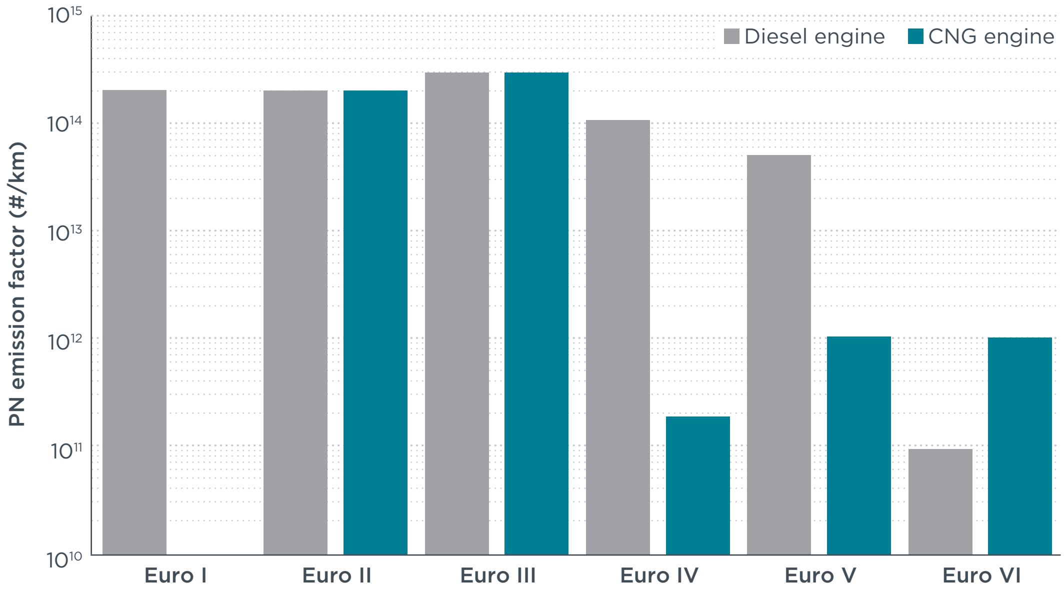

Figure 9. Particle number emission factors for standard-sized diesel urban buses by emissions control level and engine technology. Data sourced from HBEFA (2019).

In addition to more-stringent emission standards, the Euro VI regulation also strengthened or introduced a number of important provisions that have resulted in significantly improved real-world emissions performance for heavy-duty engines certified to these standards. These include the introduction of certification test cycles that better represent real-world driving conditions, including cold-start requirements, in-service conformity testing requirements, and extended durability periods. The improved real-world emissions performance of diesel buses certified to Euro VI or similar emission standards is demonstrated in Figure 10, which shows estimates of real-world NO_x emissions from buses by emissions control level for four major vehicle markets. In the European Union, there was little real-world improvement in NO_x emissions between Euro II and Euro V standards. It was only with the implementation of Euro VI standards that real-world NO_x emissions became effectively controlled. Similar trends are also apparent in emission estimates for other regions.

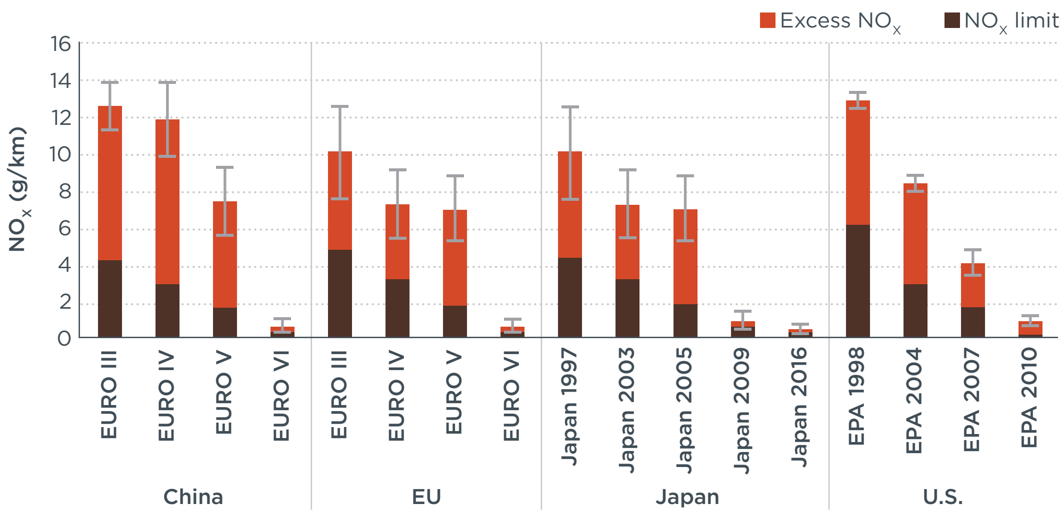

Figure 10. Real-world NO_x emission factors for buses by vehicle emissions standard (Anenberg et al., 2017).

The effectiveness of Euro VI diesel engine emission systems in controlling real-world NO_x emissions is further demonstrated in Figure 11, which shows results from a recent on-road vehicle testing campaign conducted in London. The third panel of the figure shows emission results for London transit buses by Euro standard. These data provide further evidence of the relatively poor performance of Euro V operating systems in urban conditions. In contrast, Euro VI buses appear to be performing well in real-world situations. The average NO_x emission factor for these buses was 74% lower than the Euro V emissions rate when presented on a fuel-specific basis.

Figure 11. Average emission factors for London buses measured using remote sensing technology. Emission factors are presented on a fuel-specific basis with units of grams NO_x emitted per kilogram of fuel burned (Dallmann et al., 2018).

TOTAL COST OF OWNERSHIP

In this section, we explore the costs of alternative transit bus technologies through a total cost of ownership (TCO) assessment of the capital and operating expenses incurred throughout the lifetime of a representative, standard-sized, 12-meter bus operating in the Metrobus fleet.

Existing procurement and contracting practices often favor or require the bus technology option with the lowest purchase price. This, however, is a poor measure of the total cost of owning and operating a vehicle. Over a 10- to 15-year service life, operating and maintenance costs can amount to several times the purchase price of a conventional diesel bus. Using purchase price as the metric for cost also biases comparisons against hybrid, battery electric, and other bus technologies. While these often have a higher purchase prices, they offer substantially reduced operating and maintenance costs, and in some cases lower net costs over the lifetime of the bus (Miller, Minjares, Dallmann, & Jin, 2017).

A better metric for comparing the costs of bus technologies is TCO, also known as life-cycle cost. TCO is defined as the sum of the costs to acquire, operate, and maintain the vehicle and its required fueling infrastructure over a given period. Figure 12 summarizes the components of TCO.

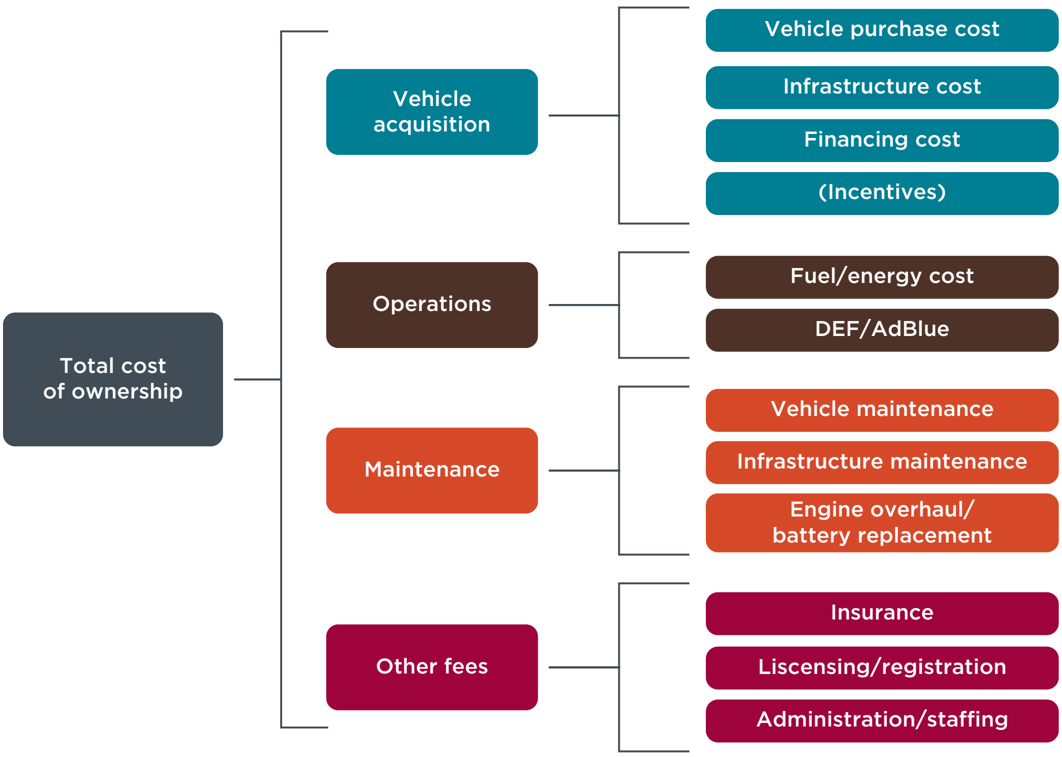

Figure 12. Total cost of ownership components. Resale value at end-of-life included.

Table 3 summarizes the components of TCO that are considered for this analysis. Because the objective is to evaluate those costs that depend on the selection of bus technology, some cost components, such as administration, staffing, license and registration, and insurance, are not evaluated. Including those costs would not be expected to change the outcome of the analysis.

Table 3. Components of total cost of ownership considered in this analysis.

Category	Component	Definition
Bus and infrastructure purchase	Down payment	Initial cash outlay for bus or infrastructure purchase. The remainder is assumed to be covered by a loan.
	Loan payments	Principal and interest payments over a specified loan period.
	Resale value	If the duration of planned operation is shorter than the bus service life, this positive cash flow considers the resale value of the depreciated vehicle.
Operation and maintenance	Fueling	Annual cost to fuel the vehicle, determined by vehicle efficiency, distance traveled, and fuel price.
	Other operational	Includes the cost of diesel exhaust fluid for diesel buses with selective catalytic reduction systems (typically Euro IV+).
	Bus maintenance	Cost of regular bus maintenance; includes tires, parts, lubricants, etc.
	Infrastructure maintenance	Where not already included in the retail fuel price, includes the cost of infrastructure maintenance and operations.
	Bus overhaul	For bus purchases that do not include a warranty for the service life of the vehicle, a major mid-life overhaul would include the cost of battery replacement for electric buses and engine overhaul for other buses. For this analysis, battery warranties are assumed to cover the bus operating life.

Our approach to evaluating the TCO for baseline and alternative transit bus engine technology and fuel options follows methodologies developed by the ICCT (Miller et al., 2017) for an analysis of the cost of soot-free transit bus fleets in 20 global megacities. These were further developed in a case study for São Paulo (Slowik et al., 2018). TCO results are presented for a base modeling scenario, reflective of our current best estimates for input values for cost components. Because most of the technologies considered here have not yet been deployed in Johannesburg or anywhere in South Africa, some uncertainty exists in the TCO modeling assumptions. To help address uncertainties and explore the influence of individual cost components on TCO estimates, a sensitivity analysis is conducted. Finally, monetized health and climate damages from pollutant emissions are evaluated to explore the impact of including social costs on TCO assessments.

The baseline Metrobus technology is a Euro V DDF engine with a 15% diesel substitution rate. Detailed financial information for the procurement of Euro V DDF buses was provided by Metrobus. Alternative technologies considered in the TCO assessment include Euro VI diesel, CNG, hybrid, and battery electric buses. The TCO is also estimated for the case where operations of the current DDF fleet are optimized and a 50% diesel substitution rate is achieved.

Purchase prices for alternative technologies are estimated assuming a set price difference relative to the baseline technology. This approach is followed due to the lack of robust cost information for alternative technologies in South Africa. Relative price differences among technologies are taken from cost data for alternative transit bus technologies compiled by the California Air Resources Board (CARB, 2017) and are equivalent to values used in previous TCO modeling assessments conducted by the ICCT.

Table 4. Bus purchase price

Bus technology	Assumption	Value used for TCO modeling (Rand)	Source
Euro V DDF (baseline)	Reported by Metrobus	R 3,174,539	Metrobus
Euro VI diesel	+2% relative to baseline technology	R 3,238,000	CARB, 2017
Euro VI hybrid	+50% relative to baseline technology	R 4,761,800	
Euro VI CNG	+12% relative to baseline technology	R 3,555,500	
Battery electric bus	+75% relative to baseline technology	R 5,555,400	

Other capital expenses for alternative technologies include fueling infrastructure costs. These costs are considered for DDF, CNG, and battery electric buses. Table 5 shows estimates of per-bus infrastructure acquisition costs used for the base TCO modeling assessment. Estimates for CNG fueling infrastructure come from discussions with Metrobus and an independent consultant contracted previously to conduct financial assessments of alternative transit bus technologies for the Rea Vaya fleet. For the purposes of this assessment, we assume that the battery electric bus will be charged overnight at a depot and that each bus will require one charging system. The cost for a single charger is estimated to be R 715,000 (USD$50,000). Grid connection costs are not included.

Table 5. Infrastructure costs

Bus technology	Assumption	Source
Euro V DDF	R 100,000/bus Calculated assuming daughter station servicing 60 buses costs R 6 million	Metrobus
Euro VI CNG	R 230,000/bus	Rob Short, personal communication[b]
Battery electric bus	R 715,000/bus Calculated assuming depot charger servicing 1 bus costs $50,000[a]	CARB, 2017

[a] The currency conversion rate is $1 = R 14.3.
[b] Owner, Sustainable Transactions, Johannesburg, South Africa

Fueling costs are calculated on a per-kilometer basis using estimates of energy consumption in diesel liter equivalents (DLE) and the price of fuels. These data are listed in Table 6. Energy consumption values for alternative technologies are calculated assuming medium-speed urban driving conditions. The effect of route type/driving conditions on TCO estimates is explored further in the sensitivity analysis. In addition to fueling expenses, the cost of AdBlue needed for NO_x control systems is calculated for DDF, Euro VI diesel, and Euro VI hybrid buses.

Table 6. Fueling costs.

Bus technology	Energy consumption (DLE/km)	Fuel price (R/DLE)	Fueling cost (R/km)
Euro V DDF (15% subs.)	0.54	12.1	6.53
Euro V DDF (50% subs.)	0.54	10.0	5.40
Euro VI diesel	0.52	13.0	6.76
Euro VI hybrid	0.41	13.0	5.33
Euro VI CNG	0.57	7.0	3.99
Battery electric bus	0.16	11.4	1.82

Note: Diesel price assumed to be R 13.0/DLE and CNG, R 7.0/DLE. Electricity price estimated from City Power tariff for industrial users, 114.610 c/kWh.

Maintenance cost estimates are presented in Table 7. For the baseline DDF technology, per-kilometer costs are estimated using the value of maintenance contracts and a 90,000 km contract period. An additional R 3.4/km ($0.24/km) is assumed for the cost of consumables, such as tires and lubricants. Per-kilometer maintenance costs for alternative technologies are calculated using information on the relative maintenance costs of these technologies reported by CARB (2017).

Table 7. Maintenance costs.

Bus technology	Assumption	Values used for TCO modeling (R/km)	Source
Euro V DDF (baseline)	Calculated form Metrobus service contract for chassis and body maintenance and assumed cost of R3.4/km for consumables	5.35	Metrobus; Dallmann, 2019
Euro VI diesel	-7% relative to baseline	4.95	CARB, 2017
Euro VI hybrid	-20% relative to baseline	4.26	
Euro VI CNG	Equivalent to baseline	5.35	
Battery electric bus	-30% relative to baseline	3.76	

Additional assumptions related to the estimates of TCO in the base assessment include:

» Costs in future years are discounted at a rate of 8.2% (DMRE, 2018).

» A bus service life of 12 years is assumed.

» Annual activity is assumed to be 36,000 km/yr.

» Financing terms for bus and infrastructure acquisition capital expenses are assumed to be a 50% down payment with the remainder of expenses covered by a loan with a five-year term and real interest rate of 10.25%.[10]

» Depreciation of 8% annually for all bus types. The value of the depreciated vehicle at the end of its ownership term is treated as a positive cash flow.

Figure 13 presents total cost of ownership estimates for the Metrobus baseline Euro V DDF technology, as well as the four alternative bus technologies considered in this assessment—Euro VI diesel, Euro VI diesel-electric hybrid, Euro VI CNG, and battery electric buses. Cost estimates represent the net present value of all modeled costs incurred throughout the assumed 12-year ownership period. Total cost of ownership estimates are broken down by the four primary cost categories: vehicle acquisition costs,

10 Interest rate reflects South African Reserve Bank prime lending rate (April 2019).

infrastructure acquisition costs, operating costs, and maintenance costs. TCO results are presented on a per-kilometer basis, assuming a total lifetime activity of 432,000 km.

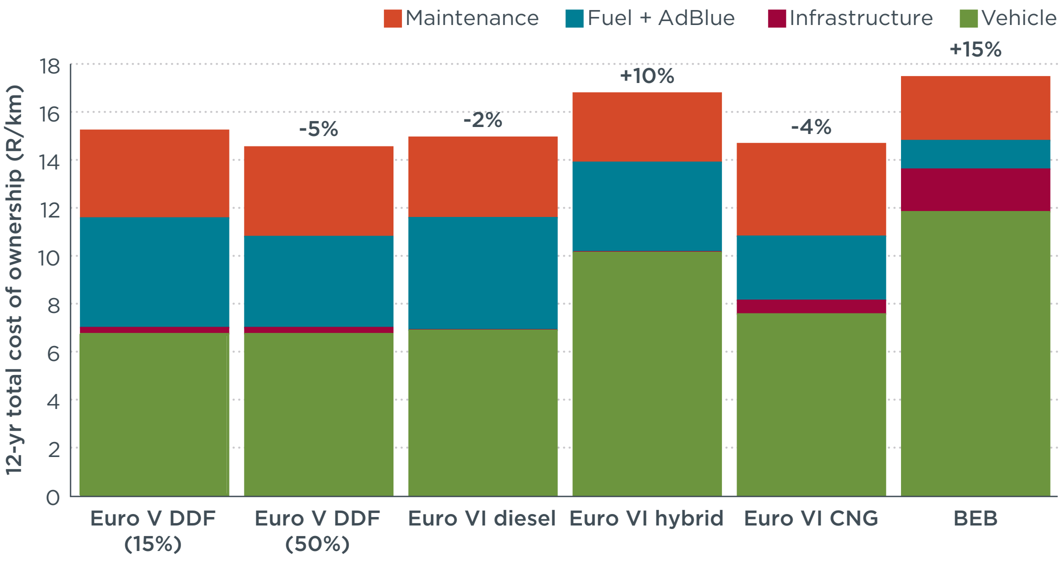

Figure 13. Total cost of ownership over 12 years for baseline and alternative technology standard (12 m) type buses in Johannesburg. Percentages show the change in TCO relative to the baseline Euro V DDF technology with a 15% diesel substitution rate. Acquisition costs include down payment and loan payments minus any bus resale value at the end of the ownership term.

In the base assessment, the total cost of ownership of a Euro V DDF bus with 15% diesel substitution rate is estimated to be R 15.24/km. Costs are split approximately equally between capital and operating expenses. In the case where the DDF bus is modeled with a 50% diesel substitution rate, fueling costs are reduced by about R 1/km, resulting in a 5% lower TCO than the baseline case. Because natural gas has a significant cost advantage relative to diesel, optimizing the performance of the current DDF fleet can lead to significant operational savings.

The TCO and cost breakdown for the Euro VI diesel bus is similar to that of the Euro V DDF bus. The slightly higher technology cost of the diesel bus is offset by the infrastructure costs associated with natural gas filling stations needed to support the DDF fleet. In the base case, the diesel fuel price for the Euro VI bus was assumed to be the same as for the 50 ppm sulfur diesel fuel currently used by the Metrobus DDF buses. Any cost premiums associated with the diesel fuel with no more than 10 ppm of sulfur (or 10 ppm sulfur diesel) needed for Euro VI diesel engines would result in a higher TCO estimate. In a similar fashion, any additional infrastructure needed to support the use of 10 ppm sulfur fuels, such as dedicated fuel storage tanks, would also increase the TCO estimate for the Euro VI diesel bus.

The CNG bus fueled with commercial fossil CNG fuel is estimated to have the lowest TCO of any of the alternative technologies considered in the baseline assessment. That vehicle's TCO is 4% lower than the TCO of the baseline Euro V DDF bus. While the capital expenses for the CNG bus are greater than for the DDF bus, the low price of natural gas results in considerable operational savings, R 1.7/km.

Both the Euro VI diesel-electric hybrid and the battery electric bus are estimated to have a higher TCO than the baseline Euro V DDF bus and other alternative-technology buses. In the base assessment, the TCO for the hybrid bus was 10% greater than for the Euro V DDF bus, and the battery electric bus's cost was 15% higher. This increase is driven by relatively high capital expenses associated with vehicles, and for the battery electric bus, infrastructure acquisition. Operational cost savings are realized for each technology; however, due in part to the relatively low number of kilometers Metrobus vehicles are driven each year, these are not enough to offset the higher capital expenses. The effect of vehicle useful life and annual activity on TCO estimates is explored further in the sensitivity assessment.

TCO estimates are compared in Figure 14 against similar estimates for buses operating in China and in Latin American cities. In general, the results for the base TCO assessment for Johannesburg are in line with findings from other regions. However, it should be noted that there is a considerable spread in estimates across cities. For example, the highest TCO estimates for a battery electric bus are more than twice as high as the lowest estimates. This spread reflects differences in technology and fuel costs across cities and regions, different operational characteristics, and different TCO modeling assumptions and approaches, among other factors.

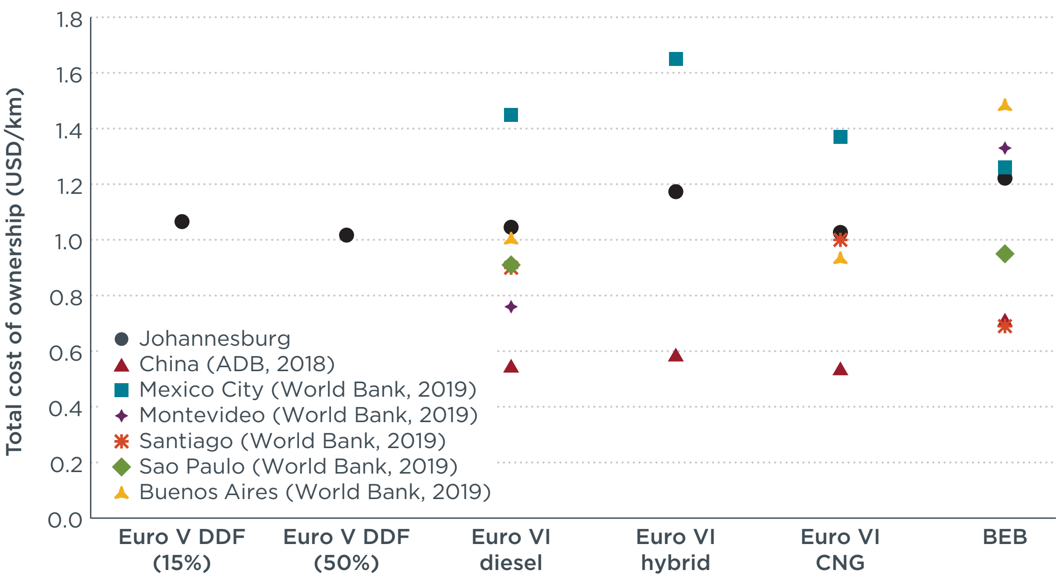

Figure 14. International TCO comparison. Note that estimates for China diesel, hybrid, and CNG buses are for pre-Euro VI technologies.

SENSITIVITY ANALYSIS

Given uncertainties in the base TCO assessment, it is useful to explore the effect of assumptions for individual cost components and the relative ranking of technology types. This type of analysis can better characterize the range in TCO that one might reasonably expect for each bus technology and helps to identify those components with the greatest influence on life-cycle costs. Here, we pursue these questions through a sensitivity analysis of six key TCO modeling input variables: battery electric bus purchase price, energy price, route type, ownership period, depreciation or resale value, and interest rate.

For each of these variables, this analysis defines multiple sensitivity cases in which the variable is changed from its baseline value. The single bus TCO is then calculated using the modified input variable, with all other cost modeling inputs set to their baseline levels. All sensitivity cases considered here are summarized in Table 8. The sensitivity analysis is limited to soot-free and zero-emission bus technologies.

Table 8. Overview of sensitivity analysis

TCO component	Sensitivity case	Description
Battery electric bus purchase price	Low battery electric bus price	Battery electric bus price 1.3 x price of baseline technology
	Baseline	Battery electric bus price 1.75 x price of baseline technology
	High battery electric bus price	Battery electric bus price 2 x price of baseline technology
Energy price	Baseline	Default diesel, CNG, and electricity prices
	Energy price +25%	Fuel prices 1.25 x default values
	Energy price +50%	Fuel prices 1.5 x default values
Route type	Low efficiency	Low speed urban routes (0.65 DLE/km)
	Baseline	Medium speed urban routes (0.54 DLE/km)
	High efficiency	Commuter/suburban route types (0.45 DLE/km)
Bus ownership period	10-yr	10-year ownership period
	Baseline	12-year ownership period
	15-yr	15-year ownership period
Bus depreciation/ resale value	Baseline	8% bus depreciation index
	Depreciation 15%	15% bus depreciation index
	No resale	Bus resale value set to zero
Interest rate	Low interest rate	Interest rate of 2.0% assumed
	Medium interest rate	Interest rate of 5% assumed
	Baseline	Interest rate of 10.25% assumed

Results of the sensitivity analysis for the total cost of ownership for a standard type bus are summarized in Figure 15. The battery electric purchase price case is shown in the leftmost panel. As battery electric buses have only recently been commercialized, there is a fair amount of uncertainty associated with the purchase price for this technology, in particular for regions where they have not yet been deployed. In our base assessment, we assume a purchase price equal to 1.75 times the price of the baseline Euro V DDF technology (R 5,555,400). Increasing this factor to two results in an increase in TCO of 10%. On the other hand, decreasing the cost premium relative to the DDF bus to 1.3 brings the TCO of the battery electric bus in line with Euro VI diesel and CNG options. The low battery electric bus price sensitivity case is reflective of the projected purchase price reductions over the next 10 years in response to declining battery prices (CARB, 2017). Thus, while this technology may have a higher TCO than conventional buses today, projected technological developments should serve to reduce capital expenses for electric bus technologies and make them more competitive on a TCO basis.

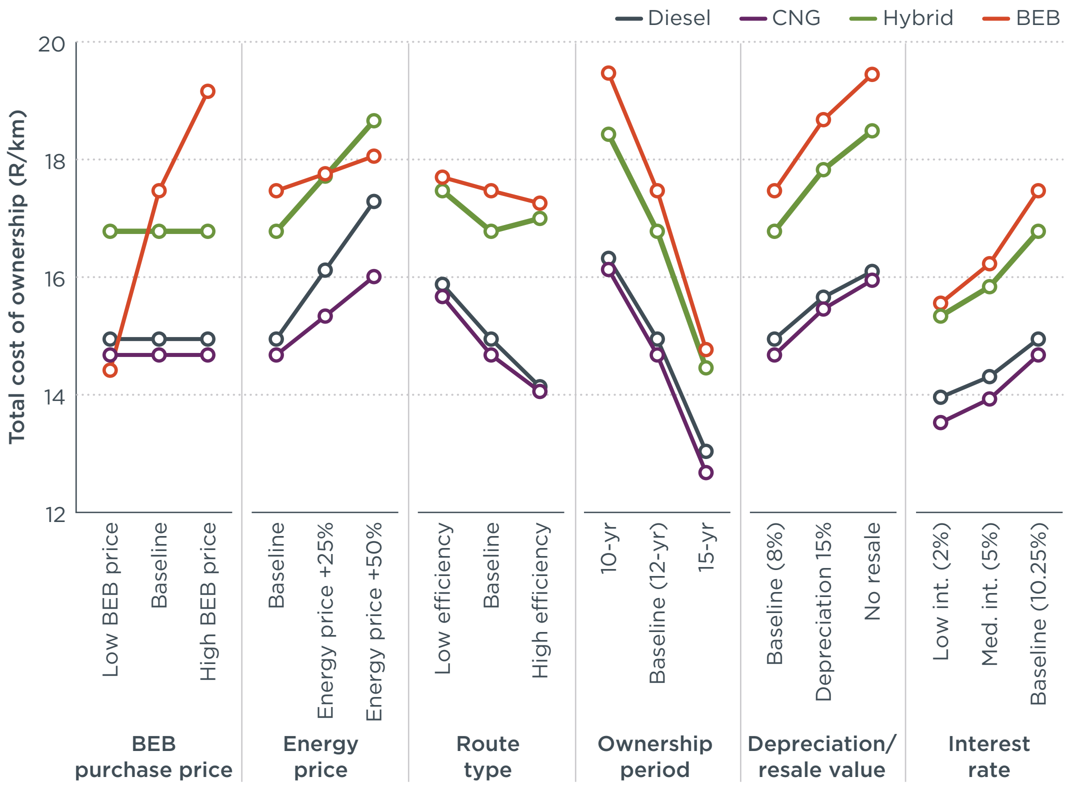

Figure 15. Sensitivity analysis for total cost of ownership of a standard (12 m) type bus.

Of the technologies considered here, fueling costs make up the largest portion of lifetime costs for the Euro VI diesel bus. As such, the TCO for this technology is most sensitive to changes in energy prices. Increasing the cost of diesel fuel by 25% raises the TCO estimate for the Euro VI diesel bus by 8%, and a 50% fuel-cost increase boosts TCO by 16%. The TCO of the battery electric bus is the least sensitive to changes in the energy price. Similarly, the TCO estimate for the battery electric bus is relatively insensitive to the assumptions made regarding route type or driving conditions. As with the energy price sensitivity case, this is due in part to the relatively low contribution of fueling costs to the TCO of the battery electric bus. Relative to electric and hybrid buses, the energy consumption of diesel and CNG buses is more sensitive to driving conditions. This contributes to the greater degree of sensitivity to route type shown in Figure 15 for the TCO estimates for these technologies.

Depreciation/resale value and interest rate assumptions both influence the capital expenses estimated for transit bus technologies. As such, TCO estimates for vehicle types like battery electric and hybrid buses, where bus and infrastructure acquisition costs account for relatively higher fractions of total lifetime expenses, are most sensitive to these variables. Under the financing terms assumed here, lowering the interest rate for battery electric bus capital expenses from the baseline of 10.25% to the low-rate scenario of 2% would lead to a 12% decrease in the TCO and would make this technology more financially competitive with other bus types.

As mentioned, the relatively low number of kilometers traveled per year on average by buses in the Metrobus system serves to limit the financial benefit of capital-intensive technologies like battery electric buses, which offer operational cost savings relative to the baseline Euro V DDF technology. Because of the relatively high capital expenses for these technologies, high utilization rates are needed to make them more financially competitive with conventional technologies on a TCO basis. Utilization can be increased through extended ownership periods or greater annual activity. Figure 15 considers the sensitivity of TCO estimates for each bus technology to assumed ownership period. For battery electric buses, extending the ownership period from 12 years to 15 years reduces the TCO by R 2.7/km, or 15%. The longer ownership period also serves to reduce the relative TCO differences between the battery electric bus and other technologies.

Utilization can also be increased through higher annual activity. Figure 16 shows the sensitivity of TCO estimates for diesel, CNG, hybrid, and battery electric buses to assumed annual activity. In all cases, the per-kilometer TCO decreases as annual utilization rises. This trend is most pronounced for the battery electric bus. In the base assessment, where annual activity was assumed to be 36,000 km/yr, the battery electric bus was estimated to have the highest TCO. However, as annual activity expands, the battery electricity bus reaches TCO parity with the other technology types. This occurs at about 45,000 km/yr for the hybrid bus, 58,000 km/yr for the diesel bus, and 72,000 km/yr for the CNG bus.

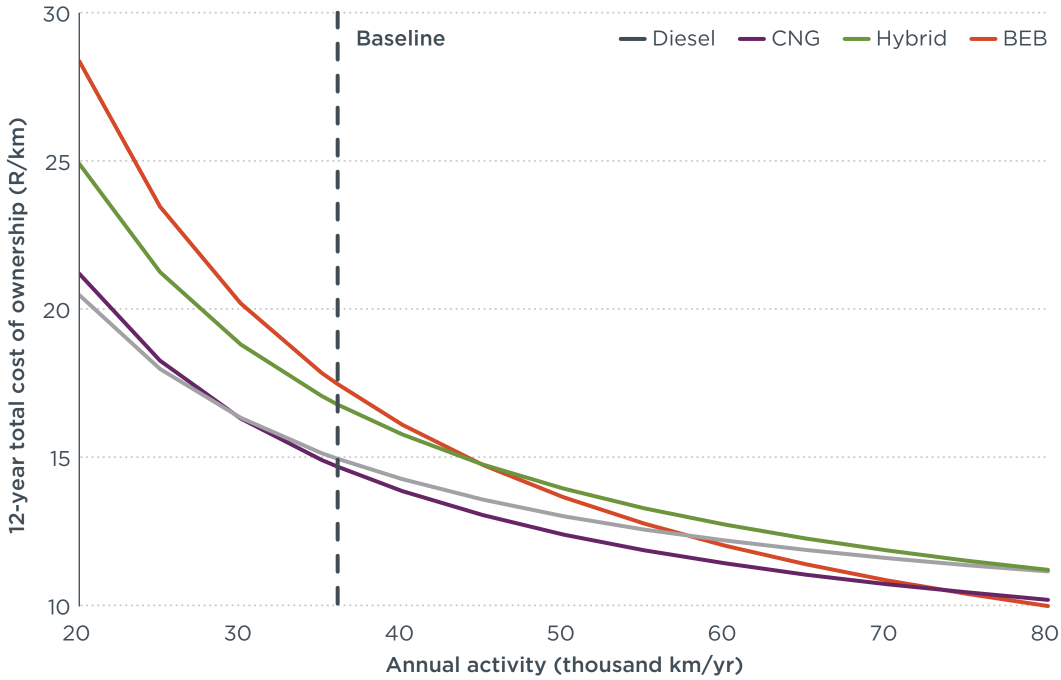

Figure 16. Sensitivity of TCO for a standard type bus to annual activity

The cost components described thus far consider only the financial outlays associated with bus procurement and operation. The climate and health costs of the emissions of GHGs and air pollutants from these buses are borne by society and are not directly paid by the operator. Because investments in clean fuels and technologies can generate broader social benefit, the analysis also undertook an estimate of the additional climate and health damages of lifetime emissions associated with each bus technology.

Lifetime emissions of GHGs and air pollutants—NO_x, black carbon (BC), and particulate organic carbon—were calculated for each bus technology considered in the base TCO assessment. The costs of climate and health damages from these emissions were calculated using global average estimates for the social cost of atmospheric release (Shindell, 2013). The median values from that study, which were based on 2010 emission levels and a 3% discount rate, are used here after adjusting for inflation. The precise value of climate and health damages varies according to time period and regional characteristics such as geographic location, population size and density, and meteorological conditions. And yet these values are useful as general indicators of the relative magnitude of climate and health benefits derived from investments in alternative bus technologies. The resulting cost estimates for climate and health damage were added to the TCO calculations for each bus technology. Results are shown in Figure 17.

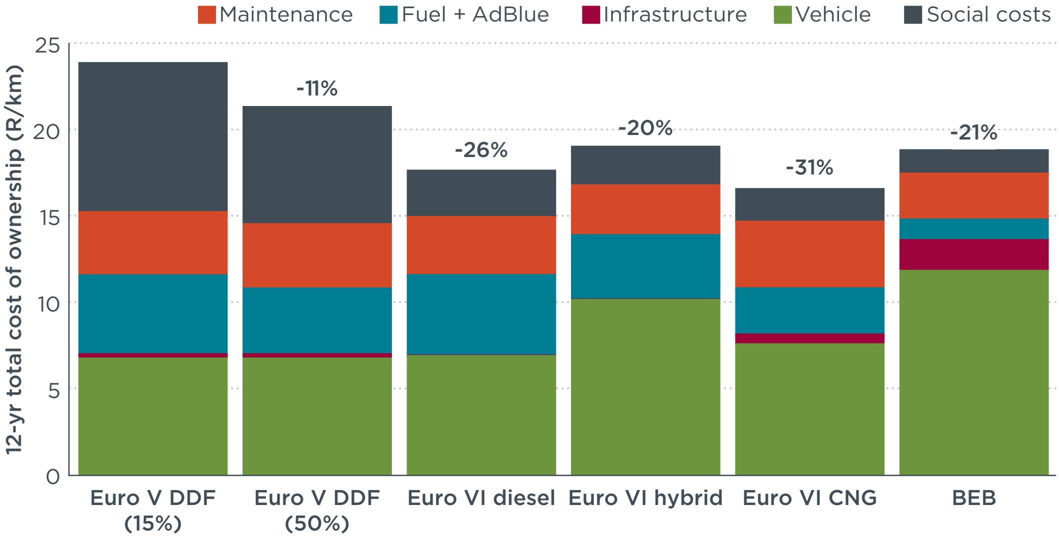

Figure 17. TCO including social costs of pollution emissions.

Investments in all alternative bus technologies result in substantial economic benefits relative to the Euro V DDF engine. Cost savings range from 20% for the hybrid bus to 31% for the CNG bus. In all cases, reductions in air pollutant emissions are largely responsible for decreased social costs for Euro VI and zero-emission technologies relative to Euro V DDF buses. These findings highlight the importance of considering social costs in comparative assessments of transit bus technology options. When social costs are included, any TCO advantages of Euro V DDF buses are offset by their relatively high emissions. If future tenders include consideration of the public health and environmental costs of these emissions, alternative technology options, such as Euro VI CNG and battery electric buses would be among the lowest cost options available for the Metrobus fleet.

FLEET RENEWAL TECHNOLOGY ROADMAP

Comparing the various technology and fuel pathways reveals their relative contributions to long-term economic, environmental, and energy objectives. This section aims to define the long-term technology pathways and the investments that will optimize the performance of the future Metrobus fleet. We first consider the current state of technology being used in the Metrobus fleet and projections regarding how the fleet composition is expected to change in coming years. Recommended technology procurement strategies are informed by the joint long-term vision for fleet transformation developed by project implementing partners and the project's steering committee.

Several fleet renewal roadmaps are considered to evaluate alternative options for the transition to a soot-free and low-carbon Metrobus fleet. For each procurement pathway, air pollutant and GHG emissions are modeled and compared against a business-as-usual procurement scenario in which no changes are made to existing technology procurement practices. Finally, for the recommended procurement pathways, we consider financing strategies, capacity building, implementation timelines, and areas for future research.

EXISTING FLEET MANAGEMENT PLAN

The establishment of a fleet renewal roadmap for the Metrobus fleet requires detailed understanding of the engine technologies and fuels currently in use, as well as the projected changes in the composition and size of the fleet. As of June 2019, the Metrobus fleet was composed of 419 buses. Euro V DDF buses accounted for 35% of the fleet while the remainder consisted of Euro 0 to Euro III diesel buses. Close to 60% of the buses in the fleet were 12 years old or older, and the oldest buses in the fleet, 111 Volvo B7L buses and 19 Volvo B7R buses, were 18 years old.

The most recent publicly available Metrobus Performance Assessment Report indicates that on average 116 buses in the fleet were out of commission (Metrobus, 2018a). This left 303 buses available for operations, falling well short of the peak operational requirement of 386 buses. The lack of operational buses, along with other factors such as a shortage of drivers, has led to shortcomings in service reliability. As shown in Figure 18, the lack of reliable service was a contributing factor in the decline of Metrobus ridership in recent years. Annual ridership estimates are presented for the years 2013–2017, as calculated from mid-year passenger trends reported by Metrobus (2018a). Over this period, annual ridership dropped by 33% from approximately 16.5 million to 11 million passengers per year.

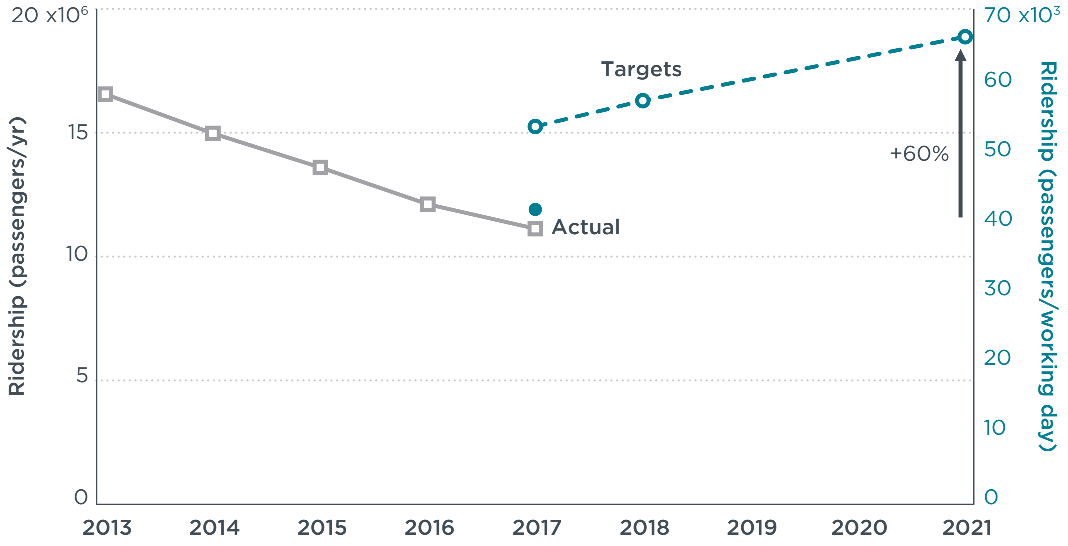

Figure 18. Historic and projected Metrobus ridership. Annual ridership estimates are calculated from mid-year passenger trends reported by Metrobus (2018a).

Also shown in Figure 18 are service targets in numbers of passengers transported per weekday. In 2017, performance fell short of the established target by about 12,000 passengers/day. Metrobus has a stated goal of increasing ridership to 66,000 passengers daily by 2021 (Metrobus, 2018b). This would be a 60% increase in ridership relative to 2017 levels. To meet this goal, the size of the fleet will need to increase. In discussions with Metrobus, we were informed that the projected fleet size to meet 2021 service targets is 460 buses, which will require the addition of 40 vehicles. At the same time, the oldest buses in the fleet will need to be retired and replaced under normal fleet renewal procedures. During a May 2019 project steering committee meeting, Metrobus stated that the current re-fleeting strategy is to procure 40 buses a year over five years for a total of 200 buses.

We used this information about ridership targets and re-fleeting strategy to develop a preliminary long-term procurement schedule for the Metrobus fleet. This schedule in Figure 19 provides the basis for the fleet renewal roadmaps discussed in later sections. We extend the Metrobus estimate of adding 40 new buses a year over five years to produce a procurement schedule through 2040, providing a sufficient period for long-term technology planning. In the first year of the procurement schedule, 40 new buses would be added to the fleet to expand the total fleet size to 460 buses. In following years, the oldest diesel buses would be replaced, followed by the Euro V DDF bus fleet between 2027 and 2030. For the fleet renewal roadmap, we assume a service lifetime of 12 years for new buses. Thus, buses purchased in 2020 would be retired and replaced in 2032 and similarly for buses purchased in the 2021–2030 timeframe. This schedule would allow for two procurement cycles in the 2020–2040 time period, including a single year, 2031, when no buses must be procured. In the absence of more detail from Metrobus about long-term planning from 2020 onward, the size of the fleet is assumed to stay constant at 460 buses. Nonetheless, future population and economic growth would suggest the need to further expand the fleet.

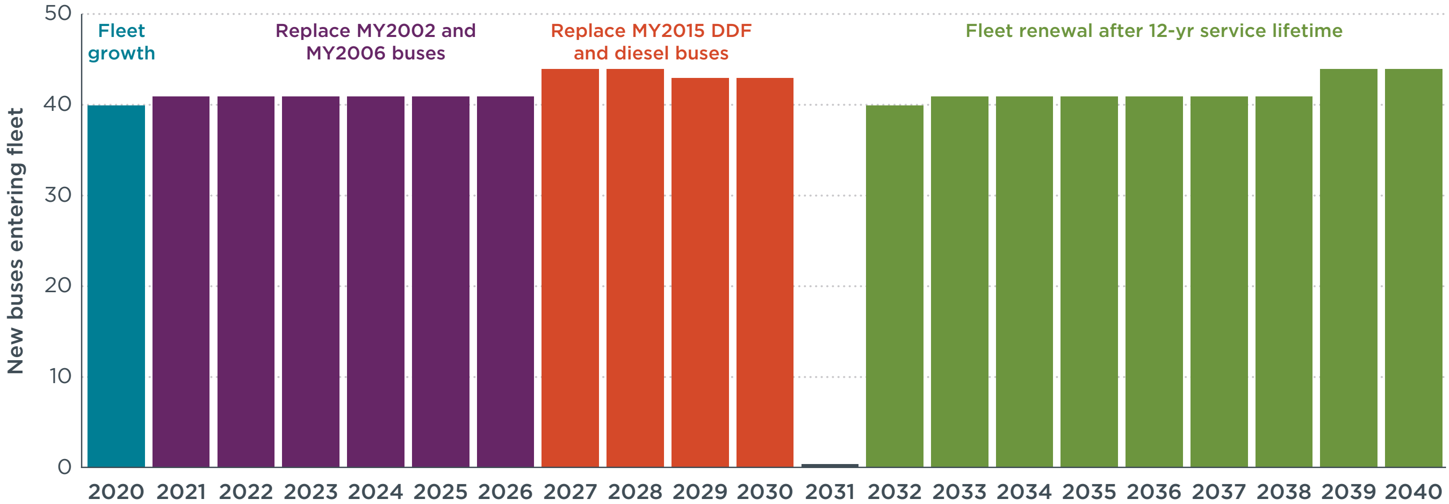

Figure 19. Long-term procurement schedule for Metrobus fleet.

POTENTIAL TECHNOLOGY PROCUREMENT PATHWAYS

In this section we consider two technology procurement pathways for the Metrobus fleet and compare them against a business-as-usual (BAU) scenario in which no changes are made to existing technology procurement practices. In each case, modeled procurement follows the schedule presented in Figure 19. The fleet technology evolution for the BAU scenario is shown in Figure 20. In it, we assume that all new buses entering the fleet are Euro V DDFs, the most advanced technology present in the current fleet. The diesel fleet is phased out between 2021 and 2027, resulting in a 100% Euro V DDF fleet from 2027 onward.

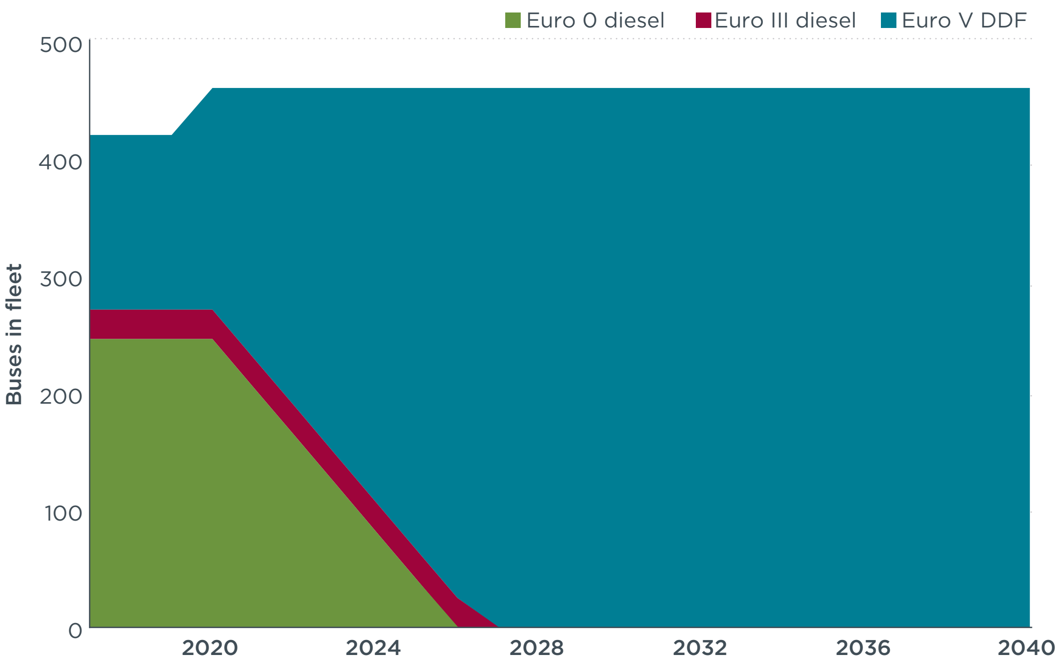

Figure 20. Fleet technology evolution under business-as-usual procurement pathway, where all new bus purchases are Euro V DDFs.

Compared against the BAU scenario are two alternative technology pathways that deliver soot-free emissions performance and the potential for long-term transitions to low-carbon fuels. The first alternative technology pathway expands on the existing incorporation of CNG fuel to satisfy DDF technology in the Metrobus fleet by adopting a full transition to dedicated Euro VI CNG buses. In the Euro VI CNG scenario, all new buses entering the fleet are assumed to be powered by CNG engines certified to Euro VI emission standards. Figure 21 shows the Metrobus technology evolution under the Euro VI CNG procurement scenario. As is the case with the BAU scenario, diesel buses would be phased out between 2021 and 2027. Here, Euro V DDF buses would remain in the fleet through 2029 and the entire fleet would be made up of Euro VI CNG buses from 2030 onward. CNG engines can be fueled with fossil CNG or biomethane. In our emissions modeling for the Euro VI CNG procurement scenario, we consider two fuel pathways. The first assumes biomethane production is not realized and fossil CNG is used throughout the modeled period. The second considers the gradual incorporation of biomethane into the fuel mix with 5% of CNG fuel demand supplied by biomethane in 2021, growing by 5% yearly through 2040.

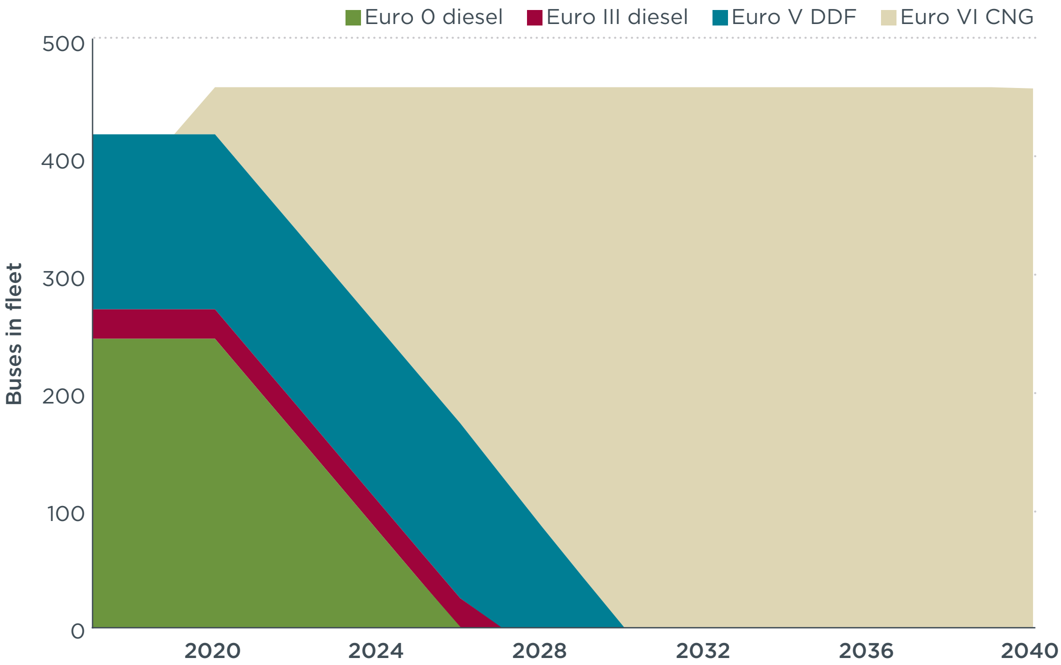

Figure 21. Fleet technology evolution under Euro VI CNG procurement pathway.

The second alternative technology procurement scenario considers a near-term transition to soot-free Euro VI diesel buses accompanied by a gradual long-term transition to a zero-emission battery electric bus fleet. In this scenario, battery electric buses would account for 10% of new buses purchased from 2020–2022, 25% from 2023–2025, 50% from 2026–2028, and 100% from 2029 onward; all other new buses would be Euro VI diesels. The introduction schedule for zero-emission technologies follows zero-emission bus purchase requirements established in the California Innovative Clean Transit legislation. As can be seen in Figure 22, the Euro VI diesel/zero-emissions procurement scenario results in a 100% zero-emission Metrobus fleet in 2040. Like the CNG scenario, we consider two fuel pathways for a Euro VI diesel/zero-emission scenario. The first assumes that the diesel fuel feedstock mix follows the current South African national average—30% CTL and 70% crude oil—and that the electricity generation pathway follows the DMRE IRP3 scenario. The second, low-carbon fuel pathway assumes all diesel fuel is sourced from crude oil feedstocks and the electricity generation pathway follows the DMRE IRP1 scenario.

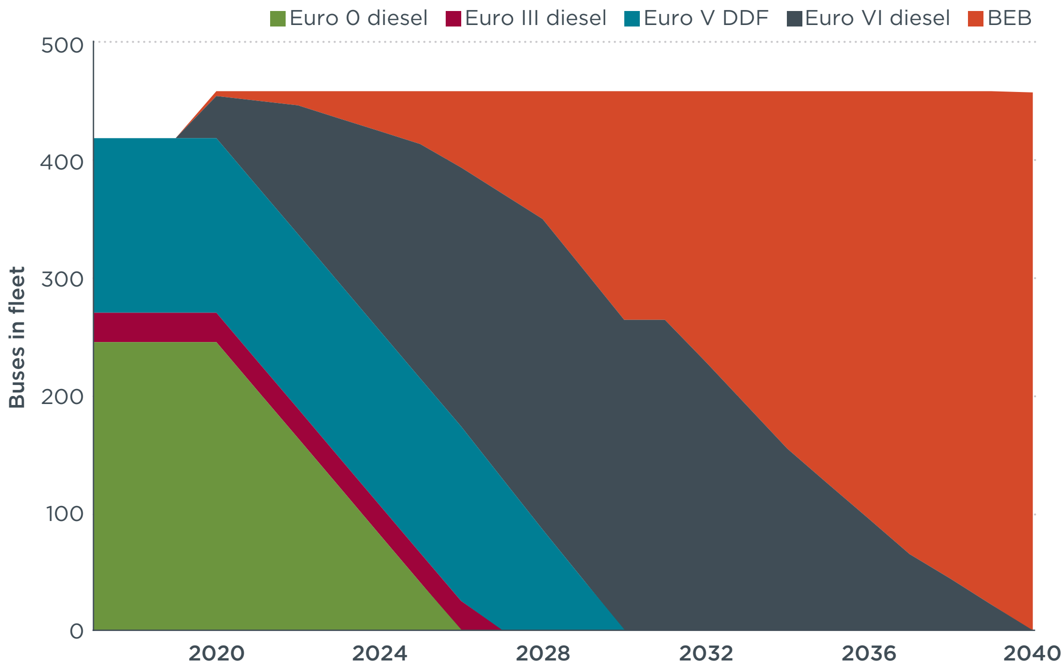

Figure 22. Fleet technology evolution under Euro VI diesel/zero-emission procurement pathway. Assumes battery electric buses account for 10% of new bus purchases from 2020–2022, 25% from 2023–2025, 50% from 2026–2028, and 100% from 2029 onward.

The technology procurement scenarios and fuel pathways considered in our assessment are summarized in Table 9.

Table 9. Summary of modeled procurement pathways

Pathway	Description
Business-as-usual (BAU)	All new buses are Euro V DDFs. Assumed 15% diesel substitution. Diesel fuel feedstock mix follows South Africa national average – 30% CTL and 70% crude oil. Gas usage is 100% fossil CNG.
Euro VI CNG	All new buses are Euro VI CNG. Gas usage is 100% fossil CNG.
Euro VI CNG – low carbon	All new buses are Euro VI CNG. It is assumed 5% of CNG fuel demand for the Metrobus fleet is supplied by biomethane in 2021, growing by 5% per year through 2040.
Euro VI diesel/zero-emission	Battery electric buses account for 10% of new buses purchased from 2020–2022, 25% from 2023–2025, 50% from 2026–2028, 100% from 2029 onwards; all other new buses are Euro VI diesels. Diesel fuel feedstock mix follows South Africa national average – 30% CTL and 70% crude oil. Electricity generation pathway follows SA DMRE IRP3 reference scenario.
Euro VI diesel/zero-emission – low carbon	Battery electric buses account for 10% of new buses purchased from 2020–2022, 25% from 2023–2025, 50% from 2026–2028, 100% from 2029 onwards; all other new buses are Euro VI diesels. Diesel fuel produced from crude oil feedstock. Electricity generation pathway follows DMRE IRP1 scenario.

EMISSIONS MODELING

A transit bus emissions model developed by the ICCT was applied to estimate the annual emissions of air pollutants and GHGs under the BAU and alternative procurement scenarios. Details of the model development and prior application in São Paulo can be found in Dallmann (2019). Input variables for emissions modeling, including vehicle energy consumption, fuel carbon intensity, and air pollutant emission factors are given in the discussion of Technology Potential in this report. Following our approach for the TCO assessment, we assume annual activity of 36,000 km/yr for each bus in the Metrobus fleet. Emissions are modeled for the 2017–2040 period, with 2017 as the baseline year for the assessment.

Air pollutant and GHG emission projections under the BAU scenario are presented in Figure 23. GHG emissions reflect fuel life-cycle emissions and include both upstream and tailpipe emissions of CO_2, CH_4, and N_2O. For the air pollutants NO_x and PM, results are for tailpipe emissions only. A NO_x emission rate of 2.8 g/km is assumed for Euro V DDF buses based on the results of the on-road emissions testing component of this project. Baseline GHG emissions for the Metrobus fleet are estimated to be approximately 37,000 tonnes CO_2e/yr. Under the BAU scenario, GHG emissions grow with the introduction of an additional 40 buses to the fleet in 2020. In our modeling, Euro V DDF buses provide a minor GHG emissions benefit relative to older diesel buses in the current fleet. However, this benefit is not sufficient to offset the increased activity projected for the fleet in 2021 and onward.

In contrast, we estimate that replacing Euro 0, I, and III diesel buses with Euro V DDF buses would lead to a significant reduction in PM and NO_x emissions from the Metrobus fleet. In the BAU scenario, fleet PM emissions would be reduced by about 85%, from 8.0 tonnes/ yr to 1.2 tonne/yr. Estimated NO_x emission reductions are more modest, approximately 65%.

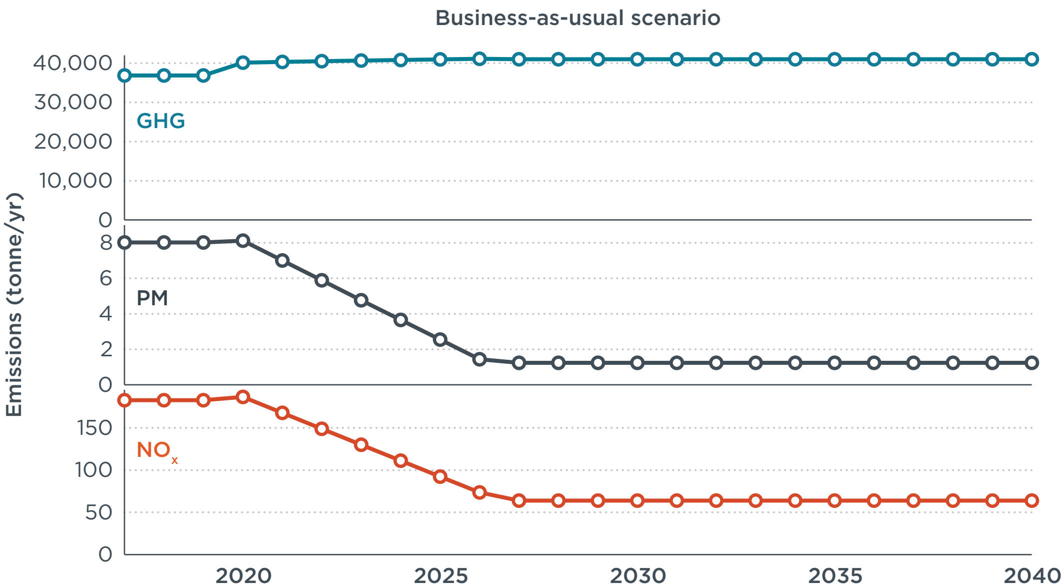

Figure 23. Air pollutant and GHG emission projections for the BAU procurement scenario.

These findings indicate that a fleetwide transition to Euro V DDF buses would considerably reduce PM and NO_x emissions from the Metrobus fleet. However, such a transition would not deliver the >90% reduction in tailpipe pollutant emissions offered by Euro VI and zero-emission technologies. Furthermore, GHG emissions in the BAU scenario are estimated to slightly increase relative to today's fleet. To achieve the environmental objectives set forth in the vision for fleet transformation, alternative powertrain technologies and low-carbon fuels must be considered.

Figure 24 presents emission results for the first alternative technology procurement pathway considered here, the Euro VI CNG scenario, where gas usage of 100% fossil CNG is assumed throughout the entire modeling period. Annual emission results for GHGs, NO_x, and PM are presented as percentage changes relative to baseline year 2017 emissions. The air pollutant emission benefits of transitioning to soot-free, Euro VI CNG engines are clear, with reductions in fleetwide PM and NO_x emissions estimated to be greater than 95% relative to the baseline. This is a significant improvement over the BAU scenario. Relative to air pollutant emission reductions, GHG emission improvements in the Euro VI CNG procurement scenario are modest. We estimate that the transition to Euro VI CNG buses fueled with fossil CNG would reduce GHG emissions from the Metrobus fleet by approximately 25% relative to today's levels. These reductions largely result from displacing high carbon-intensity CTL diesel from the Metrobus fuel mix and replacing it with the relatively lower carbon-intensity fossil CNG. It should be noted, however, that Euro VI CNG engines fueled with fossil CNG would provide relatively modest, if any, GHG emission savings relative to diesel buses fueled with crude oil-derived diesel, depending on the bus operating conditions.

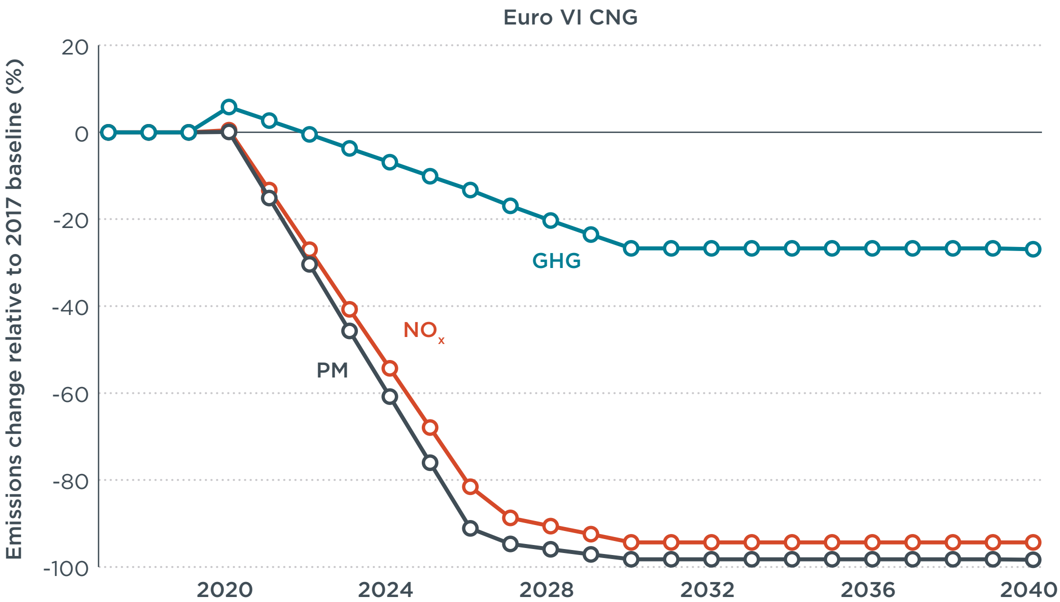

Figure 24. Projected changes in emissions for the Euro VI CNG procurement scenario. It is assumed fossil CNG is used to fuel CNG buses throughout the modeling period.

To achieve greater GHG emission reductions under the Euro VI CNG procurement pathway, lower-carbon fuels are needed. Figure 25 shows the emissions modeling results for the Euro VI CNG scenario under the assumption that biomethane is incorporated into the Metrobus fuel mix beginning in 2021 and displaces larger and larger amounts of fossil CNG through 2040, when it is assumed that the CNG bus fleet would be fueled entirely with biomethane. For this modeling, we assume a biomethane carbon intensity of 167 gCO_2e/kWh, which is representative of fuel produced from landfill or digester gas feedstocks. Because this value is lower than the carbon intensity of fossil CNG, GHG emission reductions would be greater than the case where fossil CNG is used throughout the modeling period. Under the biomethane fuel pathway, year 2040 GHG emissions would be reduced by approximately 55% relative to 2017 baseline levels. Cumulative emission savings in the 2020–2040 timeframe relative to the Euro VI CNG and fossil

CNG pathway are estimated to be 98,000 tonnes of CO_2e. Even greater savings could be achieved through a faster transition to biomethane fuels than what is considered here. Similarly, biomethane produced from lower-carbon feedstocks, such as animal or food waste, would also lead to greater GHG emission reductions than are shown in Figure 25.

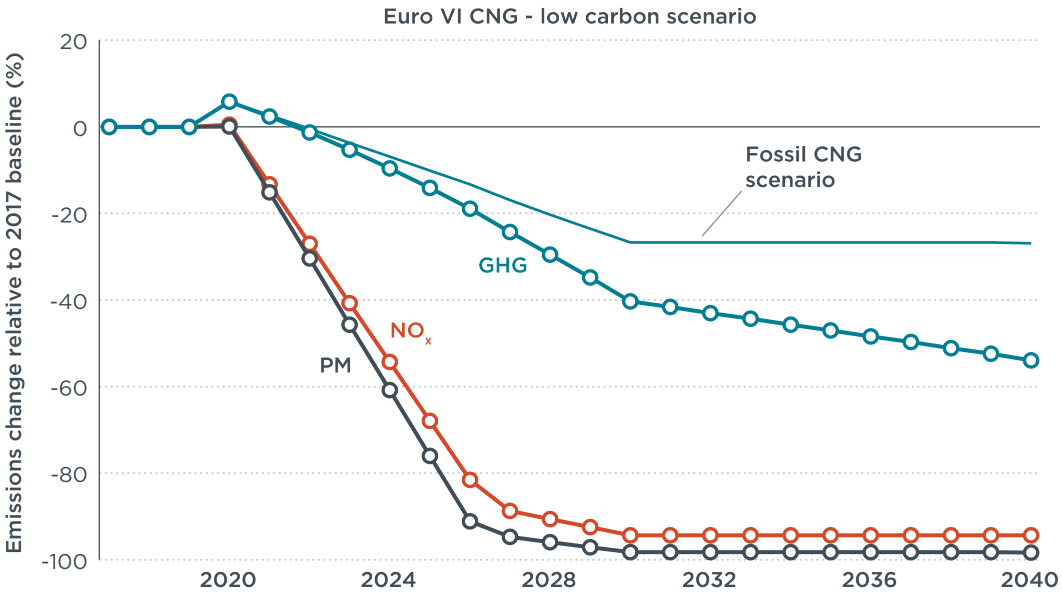

Figure 25. Projected changes in emissions for the Euro VI CNG scenario with phased introduction of biomethane. It is assumed that 5% of CNG fuel demand for the Metrobus fleet would be supplied by biomethane in 2021, growing by 5% per year through 2040.

The second alternative technology procurement pathway we consider is a near-term transition to Euro VI diesel buses accompanied by a long-term zero-emission bus procurement strategy. In the base case, we assume a diesel fuel feedstock mix of 30% CTL and 70% crude oil for Euro VI buses and an electricity generation pathway following the DMRE IRP3 scenario. Emission results for this technology and fuel pathway are presented in Figure 26. As was shown for the Euro VI CNG scenario, near-term transitions to soot-free technologies—in this case Euro VI diesel and a smaller number of battery electric buses—greatly reduce emissions of PM and NO_x. These tailpipe emissions would be entirely eliminated in 2040 when a 100% zero-emission fleet is achieved. With regard to GHG emissions, levels initially increase relative to the baseline as the fleet is expanded and when Euro VI diesel buses make up a larger share of new buses. This technology and fuel combination provides little GHG emissions improvement relative to technologies currently in use. It is not until battery electric buses make up a greater percentage of the fleet and higher levels of grid decarbonization are realized that GHG emissions from the Metrobus fleet start to come down. We estimate that the transition to a 100% battery electric bus fleet, accompanied by the level of grid decarbonization laid out in the DMRE IRP3 scenario, would result in annual GHG emission reductions of approximately 65% in 2040 relative to the 2017 baseline.

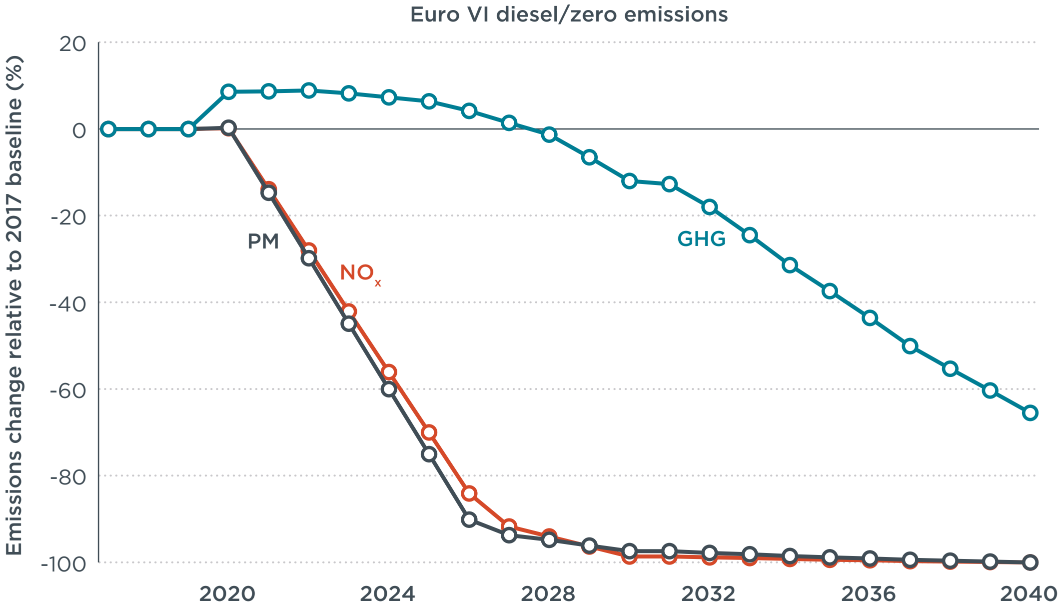

Figure 26. Projected changes in emissions for the Euro VI diesel/zero-emission procurement scenario. Assumed 30%/70% CTL/crude oil diesel feedstock mix and IRP3 electricity generation scenario.

Results for the second fuel pathway assessed for the Euro VI diesel/zero-emission procurement scenario are presented in Figure 27. In this case, we assume that diesel fuel would be sourced entirely from crude oil feedstocks and that the electric generation pathway follows the DMRE IRP1 scenario, where a greater degree of grid decarbonization is achieved by 2040 relative to the IRP3 scenario. This fuel pathway delivers greater near-term GHG emission savings through the displacement of CTL diesel in the fuel mix and long-term improvements due to the lower carbon-intensity grid electricity estimated for the IRP1 generation scenario. For this fuel pathway, cumulative GHG emissions between 2020 and 2040 would be reduced by about 100,000 tonnes of CO_2e relative to the base Euro VI/zero-emission fuel pathway. Annual GHG emissions would be reduced by 73% in 2040 compared with the 2017 baseline in this scenario.

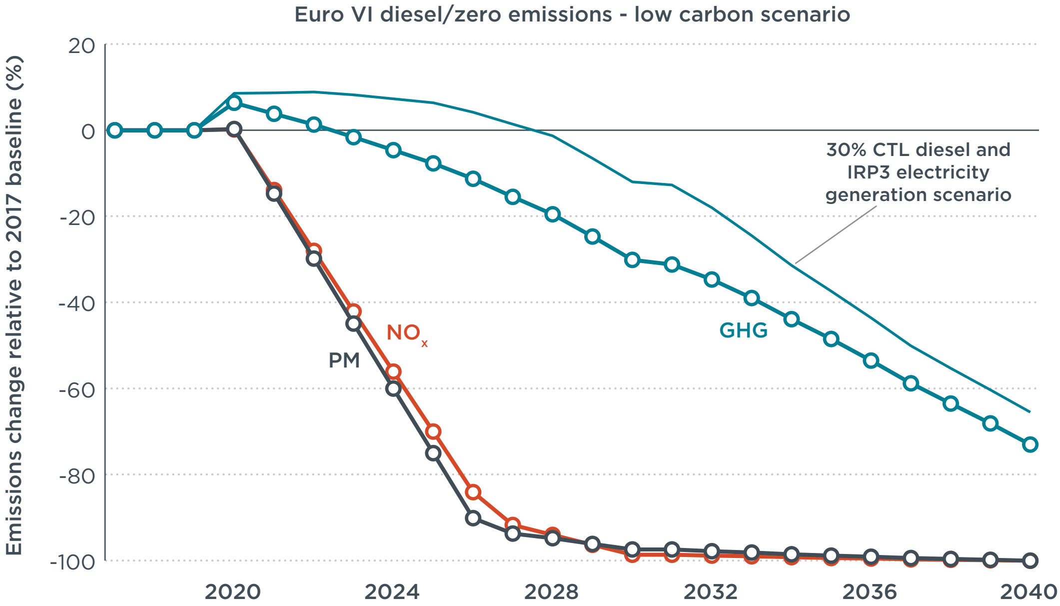

Figure 27. Projected changes in emissions for the Euro VI diesel/zero-emission procurement scenario. Assumed 100% diesel produced from crude oil and IRP1 electricity generation scenario.

Figure 28 compares cumulative GHG emissions between 2020 and 2040 estimated for the BAU scenario and the two alternative technology procurement pathways. For each technology pathway, results for baseline and low-carbon fuel pathways are shown. In each case, the low-carbon alternative technology scenarios deliver similar and significant GHG emission savings relative to the BAU scenario, approximately 320,000 tonnes of CO_2e through 2040.

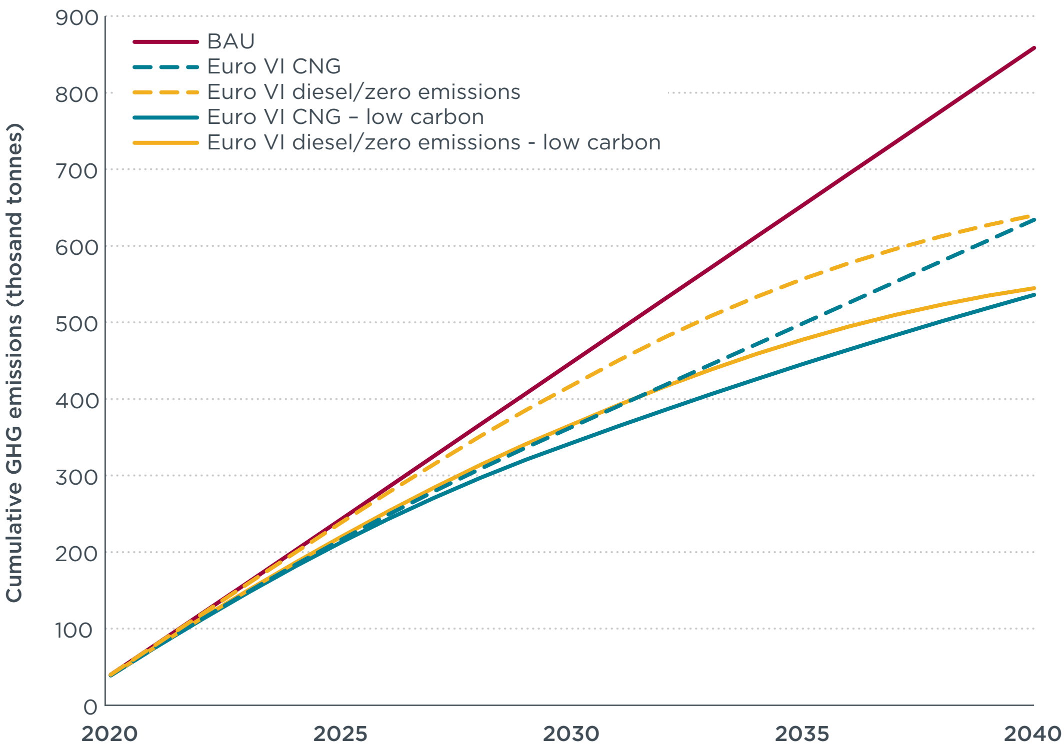

Figure 28. Cumulative GHG emissions 2020–2040 under BAU, Euro VI CNG, and Euro VI diesel/zero-emission procurement scenarios and low carbon fuel pathways.

This analysis has shown the comparative reductions in life-cycle GHG and local air pollutant emissions of alternative technology pathways, but several steps could be taken to further strengthen the analysis. For example, analysis of energy consumption and technology deployment specific to individual routes would allow for optimization of technology cost and environmental performance. Further assessment of methane leakage rates in the South African natural gas supply chain would resolve uncertainties in the existing WTW GHG emission estimates presented here for CNG buses. A detailed life-cycle assessment of GHG emissions for biomethane fuel pathways specific to Johannesburg would provide estimates that reflect local conditions. The refinement of input data for TCO modeling such as technology costs for Euro VI vehicles, local cost of biomethane fuel, and local electricity costs for electric buses would more accurately reflect local conditions. And finally, grid-side analysis of infrastructure needed to support electrification of the Metrobus fleet would provide more-tailored cost estimates. These are examples of the additional ways in which the present analysis could provide detailed estimates more reflective of local conditions.

THE WAY FORWARD

The present analysis leads to a set of recommendations on the way forward for Metrobus. These recommendations take into account goals stated in the most recent Johannesburg Integrated Development Plan that calls for compliance with national air quality standards and a reduction of GHG emissions of between 45% and 65% below a year 2007 baseline by 2040. These goals, supported by the National Green Transport Strategy, provide the basis for recommending a reduction in fleetwide air pollutant and greenhouse gas emissions from the future Metrobus fleet.

We propose the following fleetwide emissions reduction targets and accompanying actions to achieve them:

Target 1: **Reduce fleetwide PM and NOx emissions to 80% below projected levels by 2030.**

Action 1.1 Require minimum Euro VI emissions certification in all future vehicle procurements.

Action 1.2 Require maximum 10 parts per million sulfur content in new diesel fuel supply contracts.

Action 1.3 Prioritize the replacement of the oldest buses in the fleet to maximize fleetwide emission reductions.

Target 2: **Reduce fleetwide life-cycle GHG emissions by 25% within 12 months.**

Action 2.1. Ban coal-based feedstock from existing and future diesel fuel supply contracts.

Target 3: **Reduce fleetwide GHG emissions to 50% below projected levels by 2040.**

Action 3.1.a Establish a long-term purchasing agreement to expand biomethane share of gas supply by at least 5% annually and in combination with immediate procurement of Euro VI CNG buses, or

Action 3.1.b Procure Euro VI diesel buses immediately and transition to 100% zero-emission bus purchases by 2029.

Target 4: **Establish a Green Bus Team at Metrobus to deliver on targets.**

Action 4.1 Establish an interdisciplinary team consisting of professionals from engineering, planning, public relations, and finance.

Action 4.2 Grant responsibility to deploy and monitor a fleetwide strategy necessary to achieve operational and environmental targets.

Action 4.3 Tender for new vehicles in combination with new fuels by encouraging bids from consortia of fuel and vehicle providers.

Action 4.4 Restrict eligible bids to those that demonstrate technology and fuel pathway alignment with fleetwide GHG, PM, and NOx targets.

Action 4.5 Grant longer fuel-supply contracts and award greater points in the bidding process to consortia that offer the lowest life-cycle GHG emissions at the least cost.

Action 4.6 Launch a zero-emission bus pilot program designed to test small-scale fleets of dedicated electric buses.

IMPLEMENTATION TIMELINE

This study presented an example procurement schedule and two alternative soot-free, low-carbon technology and fuel pathways that can deliver long-term improvements in the environmental performance of the Metrobus fleet. The results of the technology potential assessment, emissions modeling, and TCO analysis can be used to inform future procurement decisions by Metrobus. However, it is up to Metrobus, the City of Johannesburg, and other stakeholders to determine the desired technology pathway and take meaningful steps toward its implementation. While there will be differences in the specific implementation steps for the two fleet renewal roadmaps presented in this report, here we provide a general framework guiding long-term technology transitions that is applicable to each pathway.

Figure 29 shows the example framework. The first step is a political commitment to define the objectives of the technology transition and set the high-level vision for fleet transformation. This commitment can take different forms. In Los Angeles, a target of a zero-emission fleet for LA Metro was established through the mayor's office and by the board of directors of LA Metro. These commitments are now guiding long-term technology planning and procurement. Similarly, California has established a goal of achieving a full statewide transition to zero-emission buses by 2040. In this case, the political commitment of the state has taken the form of the Innovative Clean Transit regulation which mandates 100% zero-emission bus purchases by 2029 for all transit agencies in the state. Santiago, Chile, has supported the transition to soot-free and zero-emission buses in its fleet through the introduction of Euro VI/EPA 2010 emission standards for new buses via an air quality management plan for the metropolitan region. Government officials have also publicly endorsed a 25% zero-emission fleet by 2025 and a 100% zero-emission fleet by 2040, although these are not included in the AQMP. A final example of a political commitment to support transitions to soot-free and low-carbon buses is the Climate Change Law of São Paulo, Brazil. As amended in 2018, this law sets 10- and 20-year targets for fleetwide reductions in tailpipe emissions of fossil CO_2, PM, and NO_x. The ultimate aim is to eliminate emissions of fossil fuel-derived CO_2 and reduce emissions of PM and NO_x by 95% from 2016 levels by 2038. In this case, the political commitment takes the form of technology-neutral performance targets for the fleet.

For Metrobus and the City of Johannesburg, an example of a first step would be to follow the São Paulo model and set emissions reduction targets for the Metrobus fleets. Suitable targets are a 90% reduction in PM and NO_x emissions from 2017 levels by 2030 and a 50% reduction in WTW GHG emissions from 2017 levels by 2040. The latter would be in line with citywide targets established in the Climate Change Strategic Framework.

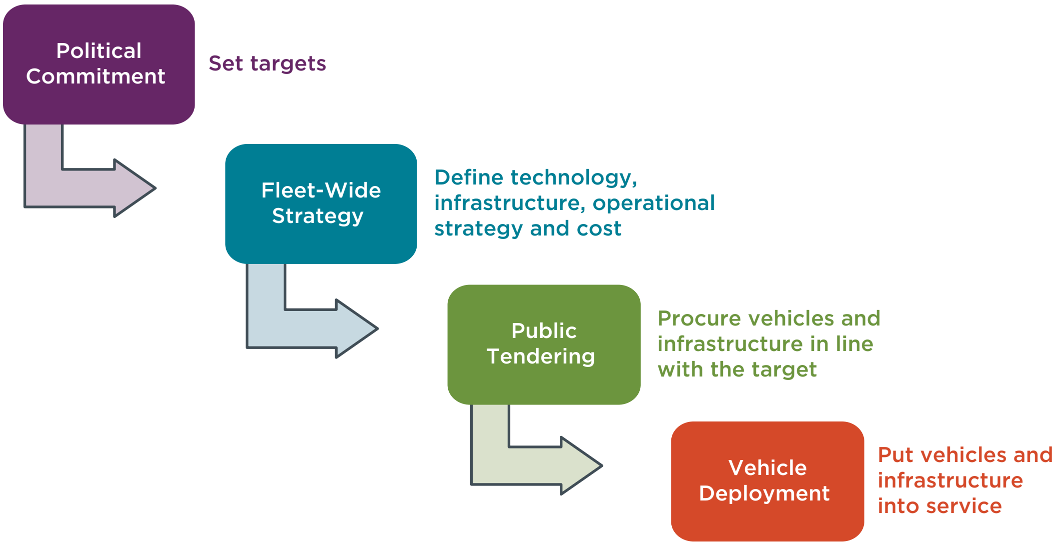

Figure 29. Framework for technology transition in urban bus fleets.

The second step in the technology transition framework is the development of a fleetwide strategy to implement the desired fleet-renewal pathway. This step covers the detailed planning needed to support the transition and includes technical analyses, operational planning, financial assessment, and training schedules, among other things. An example of the structure of a fleetwide strategy is included below:

1. A goal of a full transition to soot-free buses and low-carbon fuels including target year for both.
2. Identification of the types of soot-free bus technologies and low-carbon fuels the transit agency plans to deploy.
3. A schedule for the construction of facilities and infrastructure modifications or upgrades, including for charging, fueling, and maintenance facilities, needed to deploy and maintain soot-free buses. The schedule should specify the general location of each facility, type of infrastructure, service capacity of infrastructure, and timeline of construction. Adoption of electric buses would require the early involvement of electric distribution companies to address any power demand gaps and challenges.
4. A schedule for bus purchases and lease options. The schedule for bus purchases must identify bus types, fuel types, emissions standard, and number of buses.
5. A schedule for retirement and end-of-life management of buses, including the number of buses, bus types, emissions standard, and plans for disposal of vehicles and batteries.
6. A schedule for deployment of soot-free buses by route and depot, as well as retirement of buses by route and depot.
7. A training plan and schedule for bus operators and maintenance staff.
8. Identification of potential funding sources and their application.

A number of these components have been addressed in this report. In the implementation of the Metrobus fleet-renewal roadmap, these steps should be considered within the scope of the desired technology pathway.

The final two steps of the implementation framework are the tendering and deployment of soot-free and low-carbon buses and supporting infrastructure. Tendering should be carried out following the renewal pathway defined in the fleetwide strategy and should be informed by international best practices for procuring alternative-technology buses and fuels, such as those developed by the International Association of Public Transport.[11]

With respect to the implementation timelines for the two fleet renewal roadmaps presented here, the CNG-to-biogas pathway can most likely be implemented in the near term with less difficulty. Through its Euro V DDF program, Metrobus has experience with gas as a fuel, and refueling infrastructure is in place. Euro VI CNG buses are already operating in South Africa and should be available to Metrobus if a tender is issued. Experience with DDF buses indicates that additional driver training would be needed to overcome perceived concerns with gas buses. Additionally, the CNG pathway would require the build-out of refueling infrastructure to provide enough capacity for a CNG fleet. In the long term, to achieve GHG emission reductions for this pathway, low-carbon biomethane will need to be incorporated into the fuel mix. Further efforts would be needed to identify a source of biomethane and ensure that adequate feedstocks are available to provide enough gas for projected use under the CNG fleet renewal pathway.

11 https://www.uitp.org/report-bus-tender-structure-including-tendering-e-bus-third-edition

While an evaluation of the total availability of and access to additional biogas sources is beyond the scope of this study, it is worth additional evaluation.

Near-term actions to implement the Euro VI diesel/zero-emission fleet renewal pathway would include identifying and securing a dedicated supply of diesel fuel with no more than 10 ppm of sulfur and subsequently procuring Euro VI diesel buses. To our knowledge, Euro VI diesel buses have not yet been introduced to South Africa, and discussions with technology suppliers should take place before issuing a tender to ensure a competitive bidding process. From an operational perspective, Euro VI diesel buses should present little significant change relative to the diesel buses currently in the Metrobus fleet, though additional training of maintenance staff would most likely be needed to ensure adequate performance of aftertreatment control technologies like DPFs. In the near term, more-extensive study and planning are needed to support the introduction of zero-emission buses in the Metrobus fleet. Some of these planning steps are outlined in the fleetwide technology transition strategy presented above. A key near-term step to support a zero-emission bus transition would be to carry out a pilot project. A trial equal to 1% of the Metrobus Fleet—approximately four buses—would be necessary to evaluate the performance of more than one electric bus supplier and more than one charging strategy. For example, both depot charging and on-route charging could be demonstrated from more than one supplier, supported by an evaluation of these technologies along low-speed and high-speed routes. This would give Metrobus staff valuable new experience and capacity regarding the operation, maintenance, cost, and performance of such systems in Johannesburg. Results from the pilot study could then be used to refine modeling and support the development of more-detailed implementation planning for zero-emission bus technologies and charging infrastructure. In the long term, changes to financing and business models may be needed to achieve the widespread adoption of the zero-emission buses presented in the Euro VI diesel/zero-emission procurement scenario.

FINANCING STRATEGIES

Financing strategies are an important component of the implementation of the two proposed fleet renewal roadmaps. In each case, the strategies should take into account current Metrobus finances and bus procurement practices as well as potential changes needed to support the transition to alternative bus technologies and fuels. The TCO assessment provides some insight into how financing and business models can support the technology transitions proposed in the fleet renewal roadmap.

Figure 30 shows the relative contributions of individual cost components to the TCO estimated for the three technologies considered in the fleet renewal roadmaps—Euro VI diesel and CNG buses, and battery electric buses. Due to the relatively low annual utilization rates of Metrobus vehicles (~36,000 km/yr), capital expenditures account for a significant portion of the TCO for all three technologies. However, in the case of the battery electric bus, costs for buses and supporting infrastructure account for nearly 80% of total lifetime costs, as compared with 46% for the Euro VI diesel option and 56% for the CNG option. The relative capital expenditures for these two technologies are similar to the 46% estimated for Euro V DDF buses, so existing mechanisms for financing and buying buses should be adequate. In contrast, new financing and business models may need to be developed to overcome the higher vehicle technology and charging infrastructure costs associated with battery electric buses.

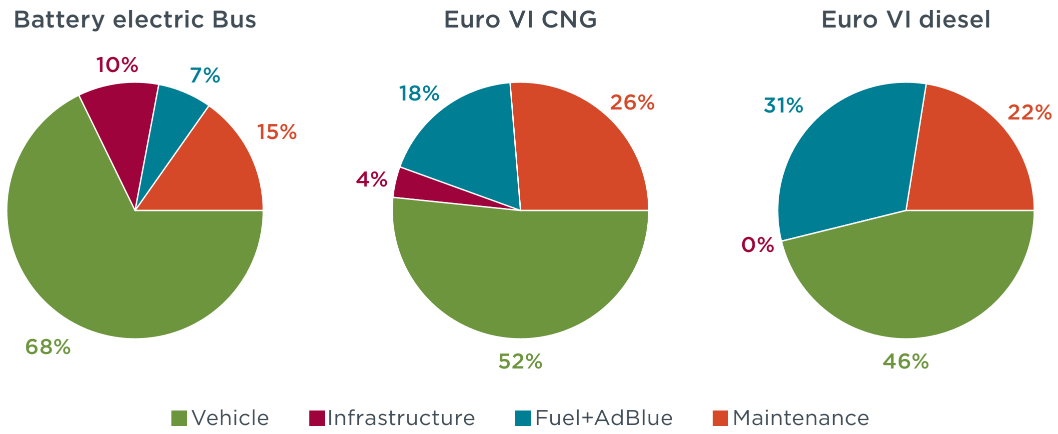

Figure 30. Relative contributions of individual cost components to TCO of Euro VI and zero-emission bus technologies.

Other municipalities have developed and implemented new business models for procuring and deploying zero-emission buses. In Shenzhen, China, new business models were developed to support the city's goal of a 100% electric bus fleet, which was achieved in 2018. Key components of the business model framework include vehicle leasing, separation of vehicle and battery costs, and separate provision of charging infrastructure and maintenance (Zhang, 2019). While government subsidies have also played an important role, this business model has been integral to the introduction of more than 16,000 electric buses in Shenzhen.

The government of India, through the Department of Heavy Industry, introduced a funding scheme to promote the manufacturing and deployment of electric and hybrid vehicle technologies. The second phase of this plan, the Faster Adoption and Manufacturing of Electric Vehicles, allocates $500 million to support the introduction of 7,000 electric buses in Indian cities. To receive funding for this, transit authorities are required to conduct bidding for transit bus service under a gross costs contracting (GCC) model. In this model, the authority requests bids for running electric buses in $/km for a minimum assured number of kilometers per year over a specified contract period. The bidder is then responsible for all expenses—purchase of vehicles, cost of operation, electricity, drivers, management of fleet, charging infrastructure, replacement of batteries, maintenance of vehicles, etc.—related to running the buses over the specified contract period. An additional profit margin is included on top of expenses incurred by the successful bidder. In the GCC model, the risks associated with the introduction of new vehicle technologies are transferred from the transit authority to the contracted operator.

Other lessons are available to optimize the cost of new technologies. For example, fleet operational management practices can capture efficiencies of vehicle scheduling and deployment. In the case of fleet electrification, the residual value of batteries can be captured through battery performance management systems during the first life and through stationary backup power during the second life. Additional joint strategies to procure renewable energy alongside electric-drive vehicles can enable efficiencies. Moreover, investments in domestic supply chains can ensure local job growth. These examples capture the strategies available to public officials as they consider policies and practices necessary to realize the full benefits of technology transition in urban bus fleets.

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APPENDIX: TECHNOLOGY COMPARISON

The following presents an analysis of the available alternative technologies to reduce the effects on public health and climate of urban bus emissions in Johannesburg. The ambition for Metrobus and other fleets throughout South Africa should be to deliver soot-free emissions performance using low-carbon, domestically produced energy sources, in line with domestic climate goals.

EURO VI DIESEL BUSES

While previous emission standards have generally required gradual reductions in emissions, the Euro VI standards achieve substantial reductions in emissions of particulate matter (PM) and nitrogen oxides (NO_x) in the real world while improving fuel economy and reducing carbon dioxide (CO_2) emissions. The Euro VI standards achieve these comprehensive benefits through a full set of regulatory changes, which include lower emission limits, a more representative test cycle, limits to off-cycle emissions, substantially higher durability requirements, and a variety of measures to ensure that emissions are being controlled in the real world.

Diesel vehicles have been known for high PM and NO_x emissions. NO_x is a precursor to the formation of secondary particles and ozone in the atmosphere. Diesel PM is composed mainly of black carbon (BC), the second-largest contributor to human-induced warming, according to one study.[12] But even in its cleanest state, fossil diesel fuel releases unacceptable levels of CO_2 when burned.

Diesel vehicles can achieve very low levels of emissions with several key emissions control technologies:

» **Diesel particulate filters (DPFs)** effectively control PM emissions, including mass and particle number, ultrafine particles, and BC, in a wide range of operating conditions.

» **Selective catalytic reduction (SCR)** systems can reduce NO_x emissions so effectively that the engines can be calibrated to generate higher NO_x emissions to improve thermal efficiency and reduce fuel consumption. Unfortunately, manufacturers sometimes can also calibrate SCR systems in such a way that reliable NO_x reductions are achieved only during laboratory tests and not in real-world operation. For this reason, it is necessary to have real-world certification using portable emissions measurement systems (PEMS) testing and to enforce emission standards with recalls and penalties.

» **Exhaust gas recirculation (EGR)** technology incorporates additional controls on NO_x and particles before the SCR and DPF. EGR introduces more-reliable reductions of NO_x at low engine loads but less so at medium and high loads.

Euro VI diesel technology requires ultra-low sulfur diesel—10 parts per million (ppm) sulfur or less—which is not currently used by Metrobus.

Table A1 provides some of the regulatory components of the European standards. The real-world NO_x emissions of Euro III, IV, and V vehicles tend not to reach the established limits demonstrated in the test laboratory. In contrast, the Euro VI standard delivers far more reliable real-world NO_x emissions, resulting in much larger real-world emission reductions from Euro VI engines than the certification limits imply.

12 https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/jgrd.50171

Table A1. Regulatory requirements of European heavy-duty vehicle emission standards

	Euro III	Euro IV	Euro V	Euro VI
Test cycle	**ESC (ETC)**	**ESC (ETC)**	**ESC (ETC)**	**WHSC (WHTC)**
Comment: The World Harmonized Test Cycle, transient (WHTC) and stationary (WHSC), is much more representative of real-world operation, especially for urban uses, than the European Cycles—stationary (ESC) and transient (ETC). The change of test cycle is one of the most important factors in the reduction of NO_x emissions in the real world, along with in-service conformity tests.				
PM (g/kWh)	**0.16 (0.1)**	**0.03 (0.02)**	**0.03 (0.02)**	**0.01**
Comment: Although the Euro VI limit requires a reduction of 67%, the reduction in the real world is 90% for the mass of emissions, 98% for black carbon, and 99% for number of particles due to the widespread use of the wall-flow diesel particulate filter.				
Particle number (#/kWh)	—	—	—	$6x10^{11}$
Comment: The limit in the number of particles ensures the use of a wall-flow particle filter. Although there were no particle number limits in the previous standards, the Euro VI standard nevertheless reduces the number of particles by more than 99% compared with previous engine technology.				
NO_x (g/kWh)	5.0	3.5	2.0	0.46 (.4)
Comment: Although the Euro VI limit requires a reduction of 77% compared with Euro V, due to the lack of control in the real world of Euro IV and Euro V, the real-world Euro VI NO_x reduction is 93% – 95%.				
Useful life	500,000 km/ 7 years	500,000 km/ 7 years	500,000 km/ 7 years	700,000 km/ 7 years
Comment: Euro VI requires greater durability of emissions control systems than previous standards, increasing the cumulative air quality benefit of the technology.				
Diesel sulfur content (ppm)	350	50	10	10
Comment: Diesel fuel containing no greater than 10 ppm sulfur is necessary for Euro VI vehicles, The occasional use of diesel with 50 ppm will not harm the emissions control system, but it will reduce its performance. Fuel with 50 ppm sulfur is sufficient for Euro V, as Euro V buses do not have DPF systems.				

Note: emission limit values in parenthesis correspond to the limits under the test cycle shown in paranthesis in the test cycle row.

Practically no difference exists in the real-world emissions performance of Euro IV and Euro V vehicles, as shown in Figures 9 and 10. Both offer the same reduction in the mass of PM and BC, but since a DPF is not used, they do not capture the smallest particles, and they do not control the number of particles emitted. Also, both offer similar control of NO_x emissions. The improved vehicle for the environment, the Enhanced Environmentally friendly Vehicle (EEV), was a voluntary certification adopted in 2005 with hydrocarbon emissions slightly less stringent than Euro V, but otherwise with the same emission limits. The EEV certification does not reliably predict better performance on emissions or fuel consumption in any way.

While SCR systems allow optimization for greater engine efficiency, in practice there seems to have been little or no improvement in fuel economy for the Euro IV and V standards. However, significant reductions have been achieved in fuel consumption with the Euro VI engine. According to actual bus tests in a typical bus handling cycle conducted by the VTT Technical Research Center of Finland, Euro VI buses reduce CO_2 emissions by 5% – 7% (Nyland, 2016).

In summary, buses subject to Euro IV or V standards will not be equipped with DPF, and the focus for NO_x control is SCR or EGR. In Europe, most Euro IV and V models use SCR to control NO_x. Unfortunately, unlike with Euro VI compliance, the SCR used in Euro IV and V vehicles has had little real-world benefit. Especially in urban areas, NO_x emissions from Euro IV and Euro V vehicles can be similar to those of Euro III vehicles (Muncrief, 2015). The data collected by Muncrief (2015) shows that Euro IV vehicles that use EGR to control NO_x perform better in the real world than the more expensive SCR system. This poor real-world performance reflects a certification protocol that is based on a nonrepresentative engine emissions test cycle, and zero real-world in-use verification.

By contrast, it is well documented that the emissions control systems deployed in Euro VI diesel vehicles respond well under real-world conditions. This is for several reasons: (1) The systems are calibrated to operate over a wide range of conditions because they need to meet emission limits in the widest range of situations imposed by improved engine cycles, WHTC, and WHSC; (2) Euro VI compliance requires in-use testing, with PEMS testing that ensures laboratory improvements translate well to real-world operation; and (3) to integrate the SCR with the DPF, a different and slightly more expensive catalyst is used, and the new catalyst can operate over a wider range of exhaust temperatures, including the low temperatures characteristic of low-speed urban driving.

EURO VI GAS BUSES

For many years, compressed natural gas (CNG) has been a substantially cleaner option than diesel, especially when ultra-low sulfur diesel fuel was not available. CNG naturally has lower PM emissions, and they are similar to but in general not as low as what can be achieved with a DPF. Since NO_x emissions can be controlled using a three-way catalytic converter in modern Euro VI CNG engines, $NO_{x,}$ hydrocarbon (HC) and carbon monoxide (CO) can be well controlled. Nevertheless, the level of tailpipe emissions control depends on the emissions standard. Fortunately, there are few barriers to the adoption of Euro VI for vehicles fueled by CNG because no changes in fuel quality are required. The larger barrier for CNG tends to be the availability of infrastructure, given the overwhelming dominance of diesel across most vehicle markets.

CNG, which consists mainly of methane, contains approximately 25% less carbon per unit of energy than diesel, so burning it emits less CO_2 for the same amount of energy. However, when taking into account the fuel efficiency of CNG engines, CNG seems to have a small energy consumption penalty compared with diesel. Furthermore, methane is a potent greenhouse gas (GHG) and can leak from poorly sealed gas engines and valves. Even a small amount of supply chain leakage and vehicle emissions can overcome that advantage. Figures 5-7 of this report illustrate the potential climate impact of low, medium, and high methane leakage from CNG engines and show the extent to which methane leakage can result in climate performance worse than petroleum diesel and Euro V DDF engine technologies.

Although the initial price of a CNG bus is substantially higher than for a diesel, local fuel costs can be much lower than the cost of diesel on a liter-equivalent basis. The estimates of maintenance costs vary significantly; however, newer-generation CNG engines seem to be much more reliable than legacy versions. In cases where Euro VI diesel vehicles and ultra-low sulfur diesel fuel are not available, CNG makes sense as a cleaner, low-cost diesel alternative.

Euro VI engines—both CNG and diesel—will effectively reduce air pollution, including BC emissions. However, even the most efficient fossil fuel engine cannot deliver the substantial GHG reductions needed to meet global and South African national climate targets. To achieve substantial GHG benefits, buses need to abandon the use of fossil diesel in favor of low-carbon, nonfossil fuels

HYBRID BUSES

Hybrid buses can be understood as a technology midpoint between a conventional bus with an internal combustion engine and a dedicated electric-drive bus. Hybrid powertrains for buses are composed of a traditional diesel engine, an electric motor to assist or directly power the wheels, and a battery to store energy during braking, known as regenerative braking. If the battery can be charged via an external electricity supply, the vehicle is considered a plug-in hybrid. Hybrid drives are also used in combination with battery electric and fuel cell electric motors. Hybrid buses have been sold commercially for almost two decades (Grutter Consultancy, 2014).

Diesel hybrids offer substantial reductions in CO_2 emissions and modest reductions in pollutant emissions without significant changes in operations or maintenance. Optimal fuel savings are obtained under driving conditions that favor energy regeneration during braking. Hybrid vehicles also require advanced aftertreatment technologies, including DPF and SCR, and the necessary low-sulfur fuels to achieve soot-free emissions equivalent to nonhybrid counterparts. A Euro IV or Euro V hybrid vehicle will not provide substantial air pollution reduction benefits.

While traditional hybrid vehicles do not require infrastructure or, strictly speaking, specific operational change, optimizing fuel saving nevertheless requires driver training and strategic deployment along routes that have a high share of stop-and-go driving. Despite the higher initial costs, some hybrids offer fuel savings that can make them cost-competitive with diesel or CNG vehicles over their lifetime.

The cost of a hybrid will necessarily include the diesel propulsion system and the aftertreatment system, and it will not necessarily decrease substantially with the drop in battery costs. In the not-too-distant future, it is expected that battery electric buses will be cost-equivalent to or lower cost than hybrids (ARB, 2018).

BATTERY ELECTRIC BUSES

Battery electric buses are powered by electric motors that receive electricity from rechargeable batteries. In contrast to hybrid buses, battery electric buses require no internal combustion engine to operate. They produce zero tailpipe emissions, are highly efficient, and have the potential to achieve lower WTW CO_2 emissions than a fossil petroleum diesel engine. The carbon intensity of the electricity is a major contributor to the relative CO_2 benefit. Electric buses are silent and smooth, and they improve the quality of life for passengers and urban residents.

Battery electric buses can have significantly lower operating costs than diesel and CNG, which offsets the higher cost of buses over the life of the vehicle. The electric motor powered by a battery is much simpler and requires much less maintenance than a conventional diesel or CNG engine. The electric motor is also much more efficient and reduces the amount of energy needed to run the bus by 70% to 80% compared with hydrocarbon fuels.

While electric buses are being added to fleets around the world, many barriers to adoption exist in cities. These include but are not limited to higher up-front costs, product availability, operational planning, staff capacity, finance, business models, and the complexity of choosing a charging strategy unique to the operational conditions of individual routes. Cities can approach fleet electrification in stages and begin with a pilot fleet equal to 1% of the total fleet size to gain experience. Charging infrastructure plans should be designed to be scalable to fit a growing fleet of electric vehicles.

Route planning requires modeling fleet operations by route. It is important to take into account changes in elevation and route length as well as demand for heating and air conditioning, which can significantly reduce the range of the vehicle. With these details, a simulation model can determine the expected range of buses under consideration and can help bus providers determine the size of batteries needed. If new electric buses do not have enough range to cover the full daily route of existing buses under all operating conditions, a replacement rate greater than one unit will be needed, increasing acquisition costs.

Fully electric buses can use a wide range of charging strategies. These include overnight charging at the depot when the vehicle is not in use, charging during the day along the service route using strategically placed charging points, overhead catenary systems that provide instantaneous power while the vehicle is in operation, and inductive charging that provides wireless power to the vehicle from an underground charge point. Charging speeds can be increased. To determine the best strategy, it is important to consider infrastructure needs, investment costs, and the structure of the electricity tariff.

Investment costs: Depot charging buses designed for long range will require a large battery and the associated costs. On-route charging allows for smaller battery size but incurs additional infrastructure cost, and fast-charging infrastructure reduces operational flexibility. Cost can be further impacted by space limitations.

Electricity rates: Rates generally include both usage charges and demand charges, which are affected by the time of day. Demand charges reflect the additional expense to the utility provider to satisfy demand for power above a certain predetermined threshold and period of the day. Fast-charging infrastructure can incur demand charges and should be adopted in tandem with negotiated demand charge rates to avoid excessive cost. Depot charging can avoid demand charges; however, large demand can result from the interconnection of several small chargers simultaneously drawing electric load. Depot charging usually shifts usage to the night, which can reduce usage and demand charges.

Technology selection and charging strategy are influenced by the rate structure for electricity. Procurement of electric vehicles and design of charging strategy should therefore be informed by an agreed-upon rate structure for the fleet. For this reason, fleet operators will benefit from early discussions with power-generating and electricity distribution companies to develop a reasonable rate and infrastructure development plan for the system (Silver, 2017). Electric utility companies are generally eager to obtain new sources of revenue that draw power from sunk costs in existing infrastructure and are open to adjusting the fee structure to work with these new fleets.

FUEL CELL BUSES

Fuel cell (FC) technology is a special type of battery electric powertrain. The FC vehicle is powered by an electric motor that receives electricity from a fuel cell. The fuel cell generates electricity from an electrochemical reaction. This requires hydrogen and air to react and produce electricity and water as a byproduct. A fuel cell vehicle relies on a supply of hydrogen that is stored on board to generate electricity. This is somewhat similar to the CNG vehicle. Besides on-board hydrogen storage, the fuel cell vehicle requires a battery to store electricity generated during the electrochemical reaction and electricity recovered during vehicle braking. No internal combustion engine is required to convert the hydrogen into heat or to convert heat into work to move a crankshaft. Instead, the hydrogen is exclusively used to generate electricity during the electrochemical reaction. A bus that is powered by fuel cell technology is known as fuel cell electric bus (FCEB).

The fuel economy of an FCEB is substantially better than that of a conventional bus, diesel and CNG. A performance report by Delliali (2018) used data from several transit agencies in the United States to compare diesel and FCEB, and results show the fuel cell bus has a real-world operational average of 6.3 miles per gallon of diesel equivalent (MPGe), compared with 4.0 mpg for similar conventional diesel buses. Using data from bus fleets with CNG and FCEB vehicles, National Renewable Energy Lab (NREL) fuel cell bus status reports (Eudy et al., 2018) show that FCEB fuel economy is 1.2–1.8 times better than the fuel economy of similar CNG buses.

FUEL AND INFRASTRUCTURE CONSIDERATIONS

Each of the bus powertrain technologies presented requires detailed consideration of fuel quality and infrastructure needs. This section presents challenges and cost information when planning a technology transition in an urban bus fleet.

TRANSITION TO EURO VI DIESEL INFRASTRUCTURE

The most important change with Euro VI diesel is the procurement of ultra-low sulfur fuel, with less than 10 ppm of sulfur. National regulations require diesel fuel with no more than 50 ppm of sulfur to be available. The ultra-low, 10 ppm of sulfur diesel is available in limited quantities from Sasol using a CTL process. A change in fuel quality, from S < 50 ppm to S < 10 ppm, does not require changing diesel fuel storage tanks. Diesel S < 10 ppm can be used by the current fleet and will reduce PM emissions in Euro V and older vehicles.

Euro VI diesel vehicles are manufactured with diesel particulate filters (DPFs) to comply with particulate emission standards. The particle filter retains the particles emitted during the process of diesel combustion, capturing them to be burned later. The DPF traps two types of particles. Some are of organic origin such as carbon and can be eliminated by high-temperature burning during normal vehicle operation. Other particles, known collectively as ash, are composed of partially burned lubricants. This ash is deposited in the pores of the DPF and reduces the available area for filtering. Euro VI diesel vehicles therefore require regular cleaning to purge this ash content. The cleaning of the filters is required every 150,000 to 300,000 km.

TRANSITION TO BIODIESEL EURO VI

Biodiesel has the potential to reduce the carbon footprint of the transport sector when its feedstock is a low-carbon, nonfood, renewable biomass source. Biofuels can be produced from seed oils or animal fats. In the United States, the majority of biodiesel is produced from soybeans, and in Europe, the main source is rapeseed. In Indonesia, the main feedstock is palm oil, a carbon-intensive material whose environmental performance is worse than that of fossil diesel fuel.[13] The main process for transforming these oils into engine fuel is transesterification, and it requires steam and electricity.

Biodiesel blends produce changes in tailpipe emissions. Soy and rapeseed biodiesel increase NO_x emissions compared with fossil diesel, but palm biodiesel reduces NO_x emissions because of its high level of saturated compounds, according to Searle and Bitnere (2018). All types of biodiesel reduce PM, CO, and unburned HC emissions when compared with older, pre-Euro VI diesel engines. Additionally, food-based biofuels, including palm oil and other plant-based oils, can increase life-cycle GHG emissions, while nonfood based biofuels from waste products such as animal fats can produce lower life-cycle GHG emissions when compared with fossil diesel fuel.[14]

13 https://theicct.org/publications/low-carbon-technology-pathways-soot-free-urban-bus-fleets-20-megacities
14 https://theicct.org/publications/low-carbon-technology-pathways-soot-free-urban-bus-fleets-20-megacities

Biodiesel affects materials used in vehicle components differently than fossil diesel. Most diesel engine manufacturers allow up to 7% by volume biodiesel blends in conventional diesel engines without risking long-term maintenance issues. At blend rates higher than 7%, biodiesel causes corrosion in several types of metals used in vehicle components. The negative impacts of corrosion are partially offset by improved lubricity with biodiesel blends, which can reduce wear in moving parts. Biodiesel also degrades some types of elastomers and leads to greater deposit formation and clogging of some vehicle components compared with fossil diesel. Overall, studies on whole fuel/engine and vehicle systems find that more frequent replacement of various components such as fuel filters, fuel injector nozzles, and seals, as well as potentially more costly components central to diesel engines, is required when operating vehicles on biodiesel blends. Thus it appears likely that adopting biodiesel blends could result in increased maintenance costs.

A transition to biodiesel would require first defining the blend level allowed in current buses and the potential blend levels in future bus purchases. In addition, adopting biodiesel would require securing a supplier, preferably one using a low-carbon feedstock such as used cooking oil. A system of fuel quality testing is recommended as a way to ensure that the blend supplier is providing a product within the technical requirements of the legacy fleet and the new fleet of buses.

TRANSITION TO EURO VI NATURAL GAS INFRASTRUCTURE

The transition to dedicated gas engines requires a supply of gas and the ability to store it for any of the different forms of natural gas distribution: CNG, liquefied natural gas (LNG), or biomethane.

As Metrobus has already invested in CNG infrastructure, the only changes expected are an increase in storage and supply capacity. Four main elements define the complexity and cost of adoption: access to gas supply, physical space, storage of gas, and supply to the vehicle (Smith & Gonzales, 2014). Gas filling stations receive supply through local distribution lines or via mobile gas distribution vehicles. The fill station uses a compressor to compress the gas at a higher pressure necessary to store it on the vehicle. The pressure of the local supply line affects the costs of compression equipment. Sufficient physical space is needed for storage tanks, compressors, and supply stations. The physical space required depends on the type and number of vehicles to be served and the frequency of filling.

Two types of CNG filling stations exist. Rapid filling stations use high pressure and flow, while time filling stations use low pressure and flow (Johnson, 2010). The main differences are the storage capacity, capacity of the compressor, and the rate of supply. The compressor takes the gas supplied from the local line (typically at 30 psig) and compresses it to 3,600 psig. Horsepower and inlet pressure determine the flow of supply and therefore the price of the equipment. The tank stores the gas once compressed. The capacity of the tank and the compressor flow are balanced, so the equipment is acquired as a system. Compression and storage systems may require additional gas drying systems to remove moisture to a value required by the vehicle manufacturer. Some operators of gas fleets add an electronic filing management system to track consumption per vehicle (Smith & Gonzales, 2014).

An alternative for natural gas storage is liquid natural gas (LNG). LNG is natural gas that has been condensed to liquid form by cooling cryogenically to -260°F (-162°C). At atmospheric pressure, it occupies only 1/600 the volume of compressed natural gas. Due to its high density and low storage pressure needs, LNG fuel tanks are smaller and lighter than CNG tanks. However, they are still larger, heavier, and more expensive than diesel fuel tanks (NREL, 2000). Because LNG has a higher energy density per unit volume than CNG, it can be more readily used in long-distance service. LNG is stored on board in insulated tanks as a cryogenic liquid. If the fuel warms up (resulting in more evaporation) and pressure builds beyond a certain limit, natural gas is vented through a pressure relief valve.

The use of LNG for bus transit fleets requires identifying a supply of LNG and construction of storage and refueling systems. LNG is typically supplied via specialized tanker trucks with insulated double walls to keep the gas at the proper temperature.

Biogas, also known as renewable natural gas, landfill gas, digester gas, or biomethane is primarily a mixture of methane (CH_4) and CO_2 produced by the bacterial decomposition of organic materials in the absence of oxygen. The specific composition of biogas depends on the source of organic matter; biogas typically contains 50%–70% of CH_4, 30%–40% of CO_2, and other constituents such as hydrogen sulfide, hydrogen, and nitrogen (Arrhenius & Johansson, 2012). Biogas can be produced from a variety of sources within the forestry, agricultural, and municipal and industrial waste streams.

Raw biogas cannot be used as vehicle fuel, and it requires a number of gas separation processes to reach the right quality of methane-rich biogas needed for vehicular applications. Gas separation processes include the separation of CO_2, which increases the final gas heating value, removal of water and other vapors, and the removal of trace substances like oxygen, nitrogen, hydrogen sulfide, ammonia, and siloxanes (Vienna University of Technology, 2012). Production, upgrading, and distribution of biogas for vehicular application requires fixed investments along the supply chain.

TRANSITION TO ELECTRIC BUS INFRASTRUCTURE

The transition to electric buses requires infrastructure changes defined by the type of technology used to recharge the bus. Two main types exist: recharging in bus depots and opportunity or on-route charging. Buses with high-capacity batteries are designed for recharging in depots. Depot charging can be divided into three types (Eudy et al., 2016): 15 kW–22 kW up to 10 hours; 22 kW–50 kW up to 4–6 hours; and 50 kW–120 kW up to 2–4 hours. Faster charging systems up to 450 kW are being deployed in Europe.

Opportunity charging systems are marketed under two main types of technologies: overhead conductive charging and underfloor inductive charging. Overhead conductive charging implies the use of a pantograph structure to physically connect the bus battery ports with the power lines above the bus. Inductive charging technology does not require a physical contact between the source of electricity and the bus; it uses a base fitted with an induction coil to create an electromagnetic field that can drive a secondary coil in the bus that uses the field to generate electricity for the batteries. Conductive charging systems can be designed for up to 500 kW of power, while the inductive systems are limited to 200 kW. The opportunity charge can serve as a range extender or, if enough power is available, it can recharge the batteries in about 10 minutes. Opportunity-charge buses can use smaller batteries than depot-charge, or they can serve as top-up to extend the range of depot-charge buses. Opportunity charging requires 300 kW–500 kW chargers on bus routes.

In general, battery electric bus infrastructure requires substations for the management of the electric charge, charging stations, and an emergency generator (Eudy et al., 2016). The complexity and installation costs depend on the current connection conditions to the network, the state of the yards/stations, and the location. Some electric vehicle manufacturers provide charging stations as part of the cost of buses (Ambrose et al., 2017).

Bus compatibility with different charging systems would mean that different brands of buses could share the same charging system so long as charging standards are pre-defined. The European Automobile Manufacturers Association (ACEA), which includes Daimler, Iveco, MAN, Scania, and Volvo, issued several recommendations in May 2017 to support the interoperability of charging technologies. For depot charging, ACEA recommends the use of CCS Combo 2 devices. For opportunity charging—for example, at the end stops—ACEA recommends "contact rails on the roof of the vehicle or on the front axle; pantograph lowering from a load mast above the head; and Wi-Fi protocol for communication between vehicle and freight mast" (ACEA, 2017).

Depot and opportunity charging buses have different benefits and challenges that make them suitable for specific routes and driving conditions. Battery buses designed for depot charging have heavier batteries; while they take longer to recharge, they can also run for longer distances between charges (Eudy et al., 2016). On the other hand, while opportunity charging buses are lighter and require less time for recharging, they require more frequent charging stops. Depot charging can be less capital-intensive and allow more flexibility in coordinating route with bus type; opportunity charging requires better planning for the development of infrastructure, in addition to coordination with electricity companies and landowners. The table below presents a summary of the general characteristics of these types of systems.

Table A3. Comparison of infrastructure for electric buses using depot or opportunity charging (Eudy et al., (2016)

Characteristic	Depot Charging	Opportunity charging
Battery size in bus	230–340 kWh	70–80 kWh
Charger type	40–120 kW	Pantograph 350–500 kW
Recharge time	3–6 hr	5–10 min
Operation range	150–320 km	80–90 km
Benefits	• Charge in yard • Low-cost electricity benefits during the night • Route flexibility	• More time of operation • Lower size of battery • Distribute the load in the network
Cons	• Hours out of service during recharging • Battery weight • Space on patio	• High infrastructure cost • Requires change in route schedule • Special recharge system

TRANSITION TO FUEL CELL TECHNOLOGY

Fuel cell electric buses require hydrogen infrastructure. Hydrogen can be produced on site or can be transported by truck. On-site production of hydrogen is traditionally accomplished via steam gas reforming. Steam gas reforming uses natural gas and water vapor at high temperature and pressure and a catalyst to yield hydrogen. Other pathways for hydrogen production exist, and they include electrolysis, but these pathways can be carbon intensive when renewable electricity is not used.

All transit authorities in the United States with FCEBs have built new facilities or expanded existing facilities to accommodate hydrogen storage, fueling, and bus maintenance (Delliali, 2018). Delliali found a few examples of the cost of hydrogen infrastructure: $10 million for a 600 kg/day fueling station, and $1.8 million for the construction of a hydrogen production facility with an output of 300 kg of hydrogen per day. Additional data points are available from European consortia that have been deploying fuel cell buses and infrastructure through the Joint Initiative for hydrogen Vehicles across Europe (JIVE).

NREL (2018) suggests a tendency among some transit agencies in California to build their own hydrogen production using natural gas steam reforming. The cost of hydrogen produced on site was at least 50% lower than the cost of hydrogen purchased from commercial suppliers. Either hydrogen supply option, transported or produced, presents inherent challenges and cost impacts. Delliali (2018) reports a large variability of the cost of hydrogen among U.S. transit agencies using trucked or produced hydrogen, from $4.50 per kg to $23.50 per kg.

TRANSITION TO SYNTHETIC FUELS

Several noncommercial fuels that are in pilot testing or early commercialization stages can be used in diesel engines. These include synthetic natural gas, gas to liquids (GTL), biomass-to-liquids (BTL), and electrofuels.

Synthetic natural gas is produced via thermochemical reactions using coal as the feedstock. Coal undergoes gasification via combustion under limited supply of oxygen and water vapor. A process of cleaning and purification removes ammonia and sulfur from the coal. The resulting CO and H_2-rich gas is then methanized over a catalyst.

The most commercially available synthetic fuel is GTL, a process that converts natural gas to liquid fuels such as gasoline, diesel, and jet fuel. Sasol has been producing GTL for more than 60 years in South Africa, and about 30% of the diesel consumed in the country comes from this process. GTL is a carbon-intensive fuel with GHG emissions higher than petroleum-based diesel (Elgowany et al., 2016).

Biomass-to-liquids (BTL) includes synthetic fuels produced from biomass through a thermochemical route. Note that this is not the same transesterification process required to produce biodiesel from mixing an oil and an alcohol over a catalyst. BTL can use any biomass, which is gasified to obtain hydrogen and carbon monoxide. The resulting syngas is used in a second catalytic stage, typically Fischer-Tropsch, to produce the desired liquid fuel (Golušin et al., 2013). According to ETIP (2019), commercial-scale production of BTL in Europe has stalled due to regulatory uncertainty around advanced biofuels.

Electrofuels utilize low-carbon electricity to produce gas or liquid fuels that can deliver GHG savings in a combustion engine. These alternative fuels are increasingly cited as a promising solution for achieving decarbonization of the transport sector—particularly in aviation and marine applications—because they can be used in internal combustion engines and, unlike most types of biofuels, have low land-use impacts. Electrofuels are produced by reacting hydrogen from electrolysis with CO_2 in a synthesis reactor to form liquid or gaseous hydrocarbons or alcohols. As with hydrogen, the CO_2 benefits of electrofuels will be defined by the carbon intensity of the electricity. The high carbon intensity of electricity in South Africa today suggests there will be little benefit from electrofuels unless the existing electricity can be decarbonized via renewable energy sources.

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