South Africa’s green mobility flagship project: Leeto la Polokwane

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ICCT CONSULTING REPORT

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LIST OF ACRONYMS

BC	black carbon
BAU	business as usual
BEB	battery electric bus
CO_2e	carbon dioxide-equivalent
CH_4	methane
CNG	compressed natural gas
CTL	coal to liquids
DEA	Department of Environmental Affairs, Republic of South Africa
DFFE	Department of Forestry, Fisheries, and the Environment, Republic of South Africa
DLE	diesel liter equivalent
DMRE	Department of Mineral Resources and Energy, Republic of South Africa
DPF	diesel particulate filter
EURO V	European emission standards for heavy-duty vehicles level V
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GHG	greenhouse gas (CO_2, CH_4, N_2O)
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
LLP	Leeto la Polokwane
Mt	million metric tons, mega tonnes
NOx	oxides of nitrogen
PM	particulate matter
$PM_{2.5}$	fine particulate matter ($PM_{2.5}$)
TCO	total cost of ownership
TTW	tank-to-wheel
UJ	University of Johannesburg
SCR	selective catalytic reduction
WTT	well-to-tank
WTW	well-to-wheel

EXECUTIVE SUMMARY

This report identifies the least-cost technology pathways for improving air quality and reducing carbon dioxide emissions from the Leeto la Polokwane (LLP) bus fleet operating in the City of Polokwane, South Africa. Based on these pathways, the 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), the report makes recommendations to LLP as a flagship model for South Africa.

The municipality of Polokwane is one of 10 cities selected to implement the Integrated Rapid Public Transport Network (IRPTN). LLP is a brand new bus rapid transit system designed to address the city's public transportation needs. Increasing the modal share of public transportation is one of the greenhouse gas mitigation actions identified in South Africa's National Green Transport Strategy (GTS). The GTS aims for a 5% reduction in emissions from transport by 2050 as part of the South African government's nationally determined contribution under the Paris Agreement.

Transit operators in Polokwane are using the best diesel technology available to them now, but continuing to rely on these technologies for their service expansion goals will not ensure reductions in greenhouse gas emissions and local pollution over time. However, alternative bus technologies and fuel pathways are consistent with the goal of decarbonization.

We explored four technology options for adoption in Polokwane: diesel Euro VI, diesel hybrid Euro VI, compressed natural gas (CNG) Euro VI, and battery electric buses (BEB). The report compared costs across technologies and were adapted to local conditions through a total cost of ownership (TCO) analysis, which considers the upfront purchase costs of buses and infrastructure as well as the operational costs of fuel/energy use and maintenance.

The results of the TCO analysis show that:

- The marginal TCO of diesel Euro VI buses is lower than the baseline cost for Euro V diesel buses.
- CNG Euro VI can provide the lowest TCO only if the price of natural gas is half the price of diesel on a liter-equivalent basis. Because no natural gas supply exists in Polokwane today, this conclusion must be revised with input from a future local supplier, and the TCO must be recalculated.
- The TCO of BEBs can be lower than the TCO of baseline Euro V buses depending on the rate of bus utilization or annual kilometers traveled. In Polokwane specifically, the projected TCO of BEB is lower, and that will remain true as long as utilization remains above 54,000 km per year.
- The cost of hybrid buses is similar to BEBs at the bus utilization levels that LLP plans to reach, but hybrids become more costly than BEBs at lower utilization levels.

We also evaluated the environmental benefits of a transition to soot-free alternatives and assessed, for all technologies under the four technology adoption scenarios, the greenhouse gas (GHG) emissions and local pollutant emissions of particulate matter (PM). We built the scenarios around an assumed near-tripling in the number of buses operated by LLP (from 36 to 101). Highlights of the environmental analysis are:

- Baseline GHG emissions for the LLP fleet are estimated to be approximately 5,000 t of carbon dioxide-equivalent (CO_2e) per year in 2020. Under the business as usual (BAU) scenario, GHG emissions grow with the introduction of an additional 65 buses to the fleet in 2025 to 13,500 t CO_2e per year.

- Only a transition to 100% BEB technology starting in the next bus procurement cycle would offer GHG emissions reductions for the larger number (3x) of buses. Early acquisition of BEBs would result in the lowest GHG emissions for the fleet as soon as 2026. By 2040, emission reductions would reach 63% with respect to BAU, and the long-term benefits would be around 68% improved from the BAU case.
- A technology transition that combines diesel and a slower transition to BEBs would also offer GHG benefits. The incremental adoption of BEBs into the LLP fleet would result in 30% GHG reductions by 2040 and 50% after 2045.
- Euro VI buses provide only a marginal 5% long-term GHG reduction compared to baseline Euro V technology. The diesel available in South Africa today is a mix of crude oil refined products and coal to liquids (CTL). CTL-based diesel has more than twice the carbon intensity of crude oil-derived diesel. A reduction in CTL blends would reduce the overall carbon contribution from Euro VI diesel technologies.
- A transition to CNG could provide a wide range of GHG benefits depending on the fuel used. Fossil-based natural gas offers 26% GHG reduction beyond 2030. A phased displacement of fossil-based natural gas by biogas, at around 5% per year starting in 2027, could result in up to 54% GHG reductions by 2040 and 61% compared to the BAU scenario.
- With respect to local pollutants (nitrogen oxide [NOx] and PM) under the BAU scenario, retaining diesel Euro V buses as the baseline technology for the long term, including the fleet expansion to 101 buses, would increase annual NOx emissions from 19 t per year to 50 t per year.
- Today, LLP buses emit 0.16 t of particulate matter per year, which would nearly triple to 0.5 t per year after a fleet size expansion to 101 buses. Only a transition to alternative technologies would ensure future lower NOx and PM emissions from the fleet as it grows. A transition to any of the proposed technologies would achieve a 60% GHG reduction by 2030 and a GHG reduction of more than 95% reduction after 2032.
- Adoption of electric buses would achieve 100% elimination of tailpipe NOx and PM emissions from LLP buses in the long term.

Based on these findings, we recommend that the city adopt the following fleetwide targets and follow the proposed set of actions to implement them:

Target 1:	**Reduce fleetwide PM and NOx emissions to 80% below projected levels by 2035.**
Action 1.1	In the short term (1–3 years), require minimum Euro VI emissions certification in all future vehicle procurements.
Action 1.2	In the short term, limit sulfur content to a maximum of 10 parts per million in new diesel fuel supply contracts.
Target 2:	**Reduce fleetwide life-cycle GHG emissions by 20% within 12 months.**
Action 2.1	In the short term, ban coal-based feedstocks from existing and future diesel fuel supply contracts.
Target 3:	**Reduce fleetwide GHG emissions to 50% below projected levels by 2040.** Polokwane can achieve this target by applying different alternatives that the city should consider adopting in 4–6 years, coinciding with the Phase 1B bus procurement process.
Action 3.1.a	Starting in Phase 1B, procure only battery electric buses.
Action 3.1.b	For the Phase 1B bus procurement cycle, transition to a combined fleet of Euro VI diesel and BEB buses. Euro VI diesel would be phased out of the procurement cycles over time as BEBs increase their numbers in the fleet. BEB fleet shares would start at 10%, with Euro VI diesel fleet shares making up the rest at the beginning of Phase 1B procurement. BEB shares would increase every procurement cycle toward a goal of attaining 100% zero-emission bus purchases by 2040.
Action 3.1.c	For the Phase 1B bus procurement cycle transition to CNG buses, fossil-based natural gas alone would not achieve this target. Achieving Target 3 would require establishing a long-term purchasing agreement to develop and expand biomethane's share of gas supply by at least 5% annually starting in 2027. Relying on fossil-based natural gas would not enable Polokwane to meet this GHG target.
Target 4:	**Establish a Green Bus Team at Leeto la Polokwane to update the bus procurement process and meet environmental targets.**
Action 4.1	Establish an interdisciplinary team consisting of engineering, planning, public relations, and finance professionals. Seek technical support from independent advisory institutions.
Action 4.2	Grant the interdisciplinary team 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.

PROJECT BACKGROUND AND OBJECTIVES

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

The Climate Support Program (CSP), financed by IKI and 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. Transport is one focus of flagship programs, which support the City of Polokwane to promote green mobility for their brand new Leeto la Polkwane (LLP) transit system, as well as to protect the environment and increase safety for commuters.

ABOUT LEETO LA POLOKWANE AND ITS EMISSION GOALS

The Polokwane Local Municipality is one of the 10 cities identified to implement South Africa's Integrated Rapid Public Transport Network (IRPTN). LLP is an Integrated Public Transport System (IPTS) that offers passengers a safe, scheduled, and accessible transportation service. Leeto la Polokwane, which means "the Journey of Polokwane," derives its name from the Sepedi language and evokes the collective journey of the people of Polokwane. The LLP project was conceived in 2007 and began operations in 2021.

The mission of LLP is to provide citizens with a public transport service that is safe and fast, as well as affordable, efficient, and environmentally friendly. The project advances the city's socio-economic development through upgrades in public physical infrastructure. The project is also generating jobs while helping to create a clean, green, safe, and healthy city. Such improvements promote local business and stimulate investment.

LLP is funded by the Department of Transport in tranches through the Public Transport Network Grant (PTNG) and integrates Bus Rapid Transit (BRT) with non-motorized transport, progressive land-use approaches, and car restriction interventions. The program, which is to be implemented in phases, operates on fully or partially dedicated roads and feeder routes that connect to existing networks of minibus taxis and buses, and to walkways and cycling lanes. Over the past 10 years, the National Treasury has contributed R 167 billion toward integrated infrastructure and operation subsidies—support that has grown at an annual average rate of 18%.

LLP project phasing

The deployment of the BRT services in Polokwane is planned in several phases: Phase 1A and 1B cover the construction and operation of the BRT system between Seshego, Westernberg, and Flora Park, and will start service in October 2021. Phase 2 covers the Moletji area and is under construction. Phase 3 will service the Mankweng cluster, and is also under construction. Phase 4 will service the Aganang cluster and is currently being built.

Before the start of service, the system underwent a dry run in September 2021 to test the effectiveness of the system and to train drivers to run the buses efficiently. Phase 1A consists of developing two Trunk Extension Routes and two Complementary Routes that will serve the Seshego, Flora Park, and Westenburg areas. The complete system will feature dedicated bus lanes, the use of a travel card, bus stops, a control center, one median station, a layover facility, trunk extension routes, and complementary routes.

Construction of dedicated trunk route lanes along Nelson Mandela Drive from Zebediela Street to Seshego Circle have already been completed and will shorten travel times for passengers by separating buses from normal traffic. The median station and a bus depot are under construction. The station will be situated at the Central Business District (CBD) along General Joubert Street between Thabo Mbeki and Grobler Street. The bus depot, which is situated in Seshego, Zone 8 on New Era Drive Street, will host 36 LLP buses in Phase 1A. In the meantime, buses will drop and collect commuters only at bus stops. Buses will operate from the layover facility, which is located near the Itsoseng Center at the Corner of Fluorspar and Silicon Street.

LLP business model

LLP reports that its 36 buses have been purchased outright, without the use of a loan or long-term payment plan. The Polokwane Local Municipality plans to operate the 36-bus fleet over three years before transferring ownership and operations to a Vehicle Operating Company (VOC) named Esilux (Pty) Ltd.[1] After the takeover, the VOC will operate the bus service on behalf of the city for a period of 12 years.

PROVINCIAL AND NATIONAL TRANSPORT GOALS

Provincial goals

Limpopo province, where Polokwane is located, is working to build a low-carbon, climate-resilient economy that prioritizes sustainable use of natural resources while advancing the development prospects of Limpopo citizens. As a key initial step of this effort, the province developed the Limpopo Green Economy Plan (Limpopo Provincial Government, 2013). The plan includes the Limpopo Climate Change Response Strategy, which assesses the climate change risk and vulnerability of major sectors by profiling each sector's provincial-level GHG emissions and identifying high-level strategies to reduce them. The strategy identifies a set of initial mitigation and adaptation strategies for key sectors in Limpopo that a) are highly carbon-intensive (based on their GHG emission profiles), b) exhibit high levels of climate change vulnerability (based on the findings of a vulnerability assessment), or c) are critical to the province's economy.

According to Limpopo's Climate Change Response Strategy, the transport sector accounts for 29% of all energy consumption in the province (Limpopo Provincial Government, 2016). Within transport, diesel accounts for 54% of fuel used, while petrol accounts for 46%. Jet fuel and aviation gas contribute a combined 0.5%. Transport accounts for 29% of provincial GHG emissions and contributes substantially to local air pollution.

The provincial government has identified mitigation actions for transport centered on low-carbon travel choices (e.g., public transit, carpooling, walking, and biking), which are designed around smart growth land development and objectives that include reductions in fuel consumption, vehicle emissions, and vehicle miles travelled (VMT). The province promotes public transit to encourage and support transport modal shifts. By increasing the use of transportation options such as public transit, cycling, and carpooling, congestion on roadways and transport-related emissions are reduced, while providing health benefits like increased activity levels and improved air quality.

The investments in the LLP BRT system exemplify the commitment of provincial authorities to mitigate climate change by promoting a shift from minibus taxis to more efficient buses.

1 The VOC is a partnership of the three affected minibus taxi associations: Seshego Polokwane Taxi Association (SPTA), Flora Park Polokwane Taxi Association (FPTA), and Westenburg Taxi Association (WTA).

National goals

The government of South Africa also invests in green urban bus fleets. South Africa's National Climate Change Response Policy mandates that the Department of Transport lead a Transport Flagship Program that includes promotion of lower-carbon mobility (DFFE, n.d.). In addition, the Department's Green Transport Strategy (2018–2050) calls for specific actions to promote cleaner fuels and alternative fuels and sets forth specific short-term (5–7 years), medium-term (8–10 years), and long-term (11–20 years) emissions-relevant objectives.

Over the short term, the strategy calls for a modal shift of 20% of private vehicles to public transport; the conversion of 5% of the public transit and national government fleet (increasing by 2% annually) to fuel-efficient vehicles that run on cleaner fuels (and, ideally, are powered by renewable energy); and adoption of environmentally sustainable low-carbon fuels by 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 and the Department of Science and Technology.

Over the medium-term, the strategy calls for the 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. The strategy identifies 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.

The strategy references the Clean Fuels II regulation developed 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 fuels that are low in sulfur content but also relatively more carbon-intensive than traditional fossil-based diesel. The South African Department of Forestry, Fisheries and the Environment (DFFE) 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 for the availability of conventional Euro V diesel fuels, which are less carbon-intensive than CTL-produced Euro V diesel.[2]

Meanwhile, the South African government has pledged to limit economy-wide GHG emissions to 17%–78% above 1990 levels by 2030, excluding emissions from land use, land-use change, and forestry. This compares to current policy-based projections that estimate an 82% increase in emissions for the same term and baseline.[3] By 2050, the target for emissions ranges from 35% below to 25% above 1990 levels.[4] To help meet these goals, 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. Currently, 30% of gasoline and diesel fuels are generated from coal feedstocks.

2 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

3 GHG projections from https://climateactiontracker.org/countries/south-africa/current-policy-projections/

4 For nationally determined contributions (NDC) mitigation action please review: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/South%20Africa%20First/South%20Africa.pdf

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.

SYSTEM AND OPERATIONAL DESCRIPTION

The LLP system is designed around a trunk route that starts from the CBD Station situated on General Joubert Street and ends in Seshego (Figure 1). In Seshego, the service will proceed from Nelson Mandela Trunk into Trunk Extensions TE4 and TE5B in mixed traffic and back to the CBD. One median station is situated on General Joubert Street, as well as curbside stops along Landdros Mare, Jorissen, and Church Streets.

Figure 1. Leeto La Polokwane service map. *Reprinted from Leeto la Polokwane.*

The system is composed of trunk routes and complementary (feeder) routes. The trunk routes are the dedicated lanes that will only be used by the LLP buses. The lanes are painted red to indicate that they are bus-only lanes. Complementary routes and trunk extension routes provide a direct service between two nodes or major areas. These routes will operate like other bus services, in which buses use normal lanes and operate in mixed traffic. Passengers will be picked up and dropped off at branded pavement stops.

The system includes a network of median stations and bus stops. Median stations are the bus stations that are specially built for the LLP service and are situated in the middle of the road. Bus stops and curbside stops are those situated on the curbs (pavement) and are easily identified by the branded poles of LLP.

The system also takes into account the needs of non-motorised transport. LLP has provided paved walkways next to the road for safe walking, running, and cycling. These walkways will also be placed along the LLP route to ensure safe travel to and from the station.

Figure 2. Leeto la Polokwane bus (above) and trunk corridor (below). *Reprinted from Leeto la Polokwane*.

COMPARATIVE TECHNOLOGY AND FUEL ASSESSMENT

TECHNOLOGY POTENTIAL

Diesel engines are the most common power train technology in South Africa. But the country has been slower than many major vehicle markets to advance 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 implementing Euro VI emission standards for buses and other heavy-duty vehicles (Miller and Jin, 2019). 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 standard is the best available control technology for protecting public health from combustion engine emissions.

Today, the South African national government mandates Euro II emission standards, which puts South Africa more than 20 years behind the European Union in emission regulation. The availability of commercial diesel fuel, with a maximum sulfur content of 50 parts per million (ppm), opens the immediate possibility for the national government to implement Euro IV emission standards and bring the country to within 13 years of European standards. 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 and natural gas in Mossel Bay. While this fuel reduces reliance on imported energy, its combustion produces some of the highest rates of carbon dioxide (CO_2) emissions of any transport fuel available. The life-cycle carbon emission of coal to liquids (CTL)-based diesel fuel is more than twice the carbon emissions from crude oil-based diesel. The transition to a locally produced fuel source that is clean and low carbon would bring additional GHG benefits in Polokwane. The technologies proposed here reflect these benefits.

LEETO LA POLOKWANE FLEET

The current LLP fleet is composed of 36 buses of 12-m and 9-m lengths. The buses are powered by diesel fuel and are certified to meet Euro V emission standards. Table 1 presents a description of the LLP fleet composition, according to public records

Table 1. Leeto la Polokwane bus fleet, 2020.

Bus type	Number of buses	Engine	Manufacturer	Emission standards	Fuel
12-m	21	6-Cylinder Diesel, 8.9 L, 209 kW	Cummins	Euro V	Diesel
9-m	15	6 Cylinder Diesel, 6.7L, 151 kW	Cummins	Euro V	Diesel

ALTERNATIVE TECHNOLOGIES

The bus market today features a wide array of technologies that reduce impacts on public health and climate. The ambition for LLP and other fleets throughout South Africa should be to deliver soot-free transport using low-carbon, domestically produced energy sources like biogas and renewable based electricity, in line with domestic climate goals. This section reviews four bus technologies that can help achieve that goal: Euro VI diesel buses, Euro VI compressed natural gas (CNG) buses, Euro VI Hybrid buses, and battery electric buses (BEBs).

Euro VI diesel buses

Buses designed to meet the Euro VI emission standards achieve substantial reductions in emissions of particulate matter (PM) and nitrogen oxides (NOx) in the real world while improving fuel economy and reducing 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 for emission control systems, and a variety of measures to ensure that emissions are controlled in the real world throughout the useful life of the vehicle.

Diesel vehicles are known for high PM and NOx emissions. NOx is a precursor to the formation of secondary particles and ozone in the atmosphere. Diesel PM consists mainly of black carbon (BC), the second-largest contributor to human-induced warming. 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 emissions control technologies which the Euro VI standards make mandatory:

- 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 NOx emissions so effectively that the engines can be calibrated to generate higher NOx emissions to improve thermal efficiency and reduce fuel consumption. As an additional safeguard under the Euro VI emission certification program, the diesel engines are tested under real-world emission conditions. These certification tests employ portable emissions measurement systems to ensure that the vehicles on the road are meeting the emission standards on the road. Vehicles in non-compliance face recalls and penalties, making the Euro VIthe most robust emission standard program in ensuring that only the cleanest diesel buses are in use.
- Exhaust gas recirculation technology incorporates additional controls on NOx and particles before the SCR and DPF are engaged. Exhaust gas recirculation achieves more reliable reductions of NOx at low engine loads, but reductions are less reliable at medium and high loads.

Euro VI diesel buses require diesel fuel with a maximum sulfur content of 10 ppm, ensuring that very little sulfur exits the engine and is deposited in the emission control systems, especially the SCR systems that control NOx. Otherwise, excessive deposits of sulfur from diesel with higher sulfur content may disrupt the NOx reduction processes in the SCR and may damage it over time.

Euro VI gas buses

For many years, CNG has served as a substantially cleaner option than diesel, especially when ultra-low sulfur diesel fuel was unavailable. Nevertheless, the level of tailpipe emissions control depends on the emissions standard. Modern Euro VI CNG engines use a three-way catalytic converter capable of virtually eliminating NO_x, hydrocarbon, and carbon monoxide emissions. CNG naturally has lower PM emissions than diesel; its emission level is similar to but in general not as low as what can be achieved with a diesel Euro VI engines with DPF.

Fortunately, the adoption of Euro VI emission standards for vehicles fueled with CNG present no barriers related to fuel because this switch requires no changes in natural gas quality. The larger barrier for CNG is the availability of fueling infrastructure in a vehicle market dominated by diesel.

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, it is important to note that CNG has a 10% energy consumption penalty compared with diesel. Furthermore, methane is a potent GHG and can leak from poorly sealed gas engines and valves. Even a small amount of supply chain leakage and vehicle emissions can negate CNG's low-carbon advantage.

Although the initial price of a CNG bus is substantially higher than that of a diesel bus, local CNG costs can be much lower than the cost of diesel on a liter-equivalent basis. Estimates of maintenance costs vary significantly but generally suggest that newer-generation CNG engines are 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 CNG engines for buses can also be fueled with biogas. Biogas, also known as renewable natural gas, landfill gas, or digester gas, 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 production of biogas into vehicular biogas fuel, or compressed biogas, requires a number of gas separation processes to reach the right quality of methane-rich biogas needed for use in vehicles, through what is called biogas upgrading.

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 that South Africa and other nations require to meet their national climate targets. To achieve substantial GHG benefits, buses need to abandon fossil diesel in favor of low-carbon, non-fossil fuels like biogas or renewable electricity.

Hybrid buses

Hybrid buses are a technology midway between a conventional bus with an internal combustion engine (ICE) and a dedicated electric-drive bus. Hybrid powertrains for buses consist of a traditional diesel engine; an electric motor to assist or directly power the wheels; and a battery to store energy during braking in a process 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, 2014).

Diesel hybrids offer substantial reductions in CO_2 emissions and modest reductions in pollutant emissions without significant changes in operations or maintenance. These vehicles obtain optimal fuel savings 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 tailpipe air pollution reduction benefits.

While traditional hybrid vehicles do not require infrastructure or—strictly speaking—specific operational changes, 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 hybrids will necessarily include the diesel propulsion system and the aftertreatment system, and their price will not necessarily decrease substantially with the drop in battery costs. In the not-too-distant future, it is expected that BEBs will be cost-equivalent to or less expensive than hybrids (CARB, 2018).

Battery electric buses

BEBs are powered by electric motors that receive electricity from rechargeable batteries. In contrast to hybrid buses, BEBs require no ICE to operate. They produce zero tailpipe emissions, are highly efficient, and have the potential to achieve lower life-cycle CO_2 emissions than a fossil 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.

BEBs carry significantly lower operating costs than diesel and CNG, which offset, over the life of the vehicles, the higher initial cost of electric buses. The electric motor that a battery powers is much simpler than an engine and requires much less maintenance. It is also much more efficient and reduces the energy needed to run the bus by 70%–80% compared with hydrocarbon fuels.

While fleets around the world are adding electric buses, barriers to adoption exist in many cities. These barriers 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, beginning with a pilot fleet to gain experience. Fleet managers should design charging infrastructure plans to be scalable to fit a growing fleet of electric vehicles.

Route planning requires modeling fleet operations by route. Route planners must 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 necessary size of batteries. If new electric buses do not have enough range to cover the full daily route of existing buses under all operating conditions, the needed replacement rate will exceed one unit, increasing acquisition costs.

BEBs can benefit from a wide range of charging strategies, including 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. The best deployment strategy will depend on infrastructure needs, investment costs, and the structure of the electricity tariff.

ENERGY CONSUMPTION OF ALTERNATIVE TECHNOLOGIES

Alternative technologies can provide lower fuel and energy consumption than the Euro V technology currently used in LLP buses. Below, we compare the performance of the Euro V 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 BEBs. To our knowledge, these technologies have not been used in LLP. Due to the lack of Polokwane-specific data, our approach here is to present information about how 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 3, which shows energy consumption for four soot-free and zero-emissions transit bus technology types across six different driving cycles.

We source energy consumption data from testing conducted by the Altoona Bus Research and Testing Center in the United States. Average energy consumption values are presented in Figure 3 by bus technology and driving cycle parameters (e.g., road type, average speed, and prevalence of stop-and-go driving), with driving cycles ordered from left to right in order of increasing kinetic intensity. Kinetic intensity compares energy use across different driving cycles and is used to identify duty cycles where regenerative braking in hybrids and BEBs 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.

Energy consumption can vary considerably by driving cycle. For buses with ICEs such as diesel, hybrid, and CNG, energy consumption tends to increase with higher cycle kinetic intensity. These buses will consume less fuel per kilometer when deployed on routes with higher average speeds and fewer stops than on routes with high levels of congestion or low-speed, stop-and-go driving conditions.

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, which maximize the efficiency benefits of regenerative braking systems on hybrid buses. With respect to energy consumption, hybrid buses are less sensitive to driving conditions and route type than conventional diesel or CNG buses.

These data from Altoona 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. Conversely, 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% greater for high-intensity cycles.

BEBs offer significant efficiency benefits relative to buses using ICEs across all driving cycles. BEBs use between 70% and 80% less energy per kilometer than conventional diesel buses via regenerative braking, significantly less waste heat generation, more efficient motors, and more efficient transmissions.

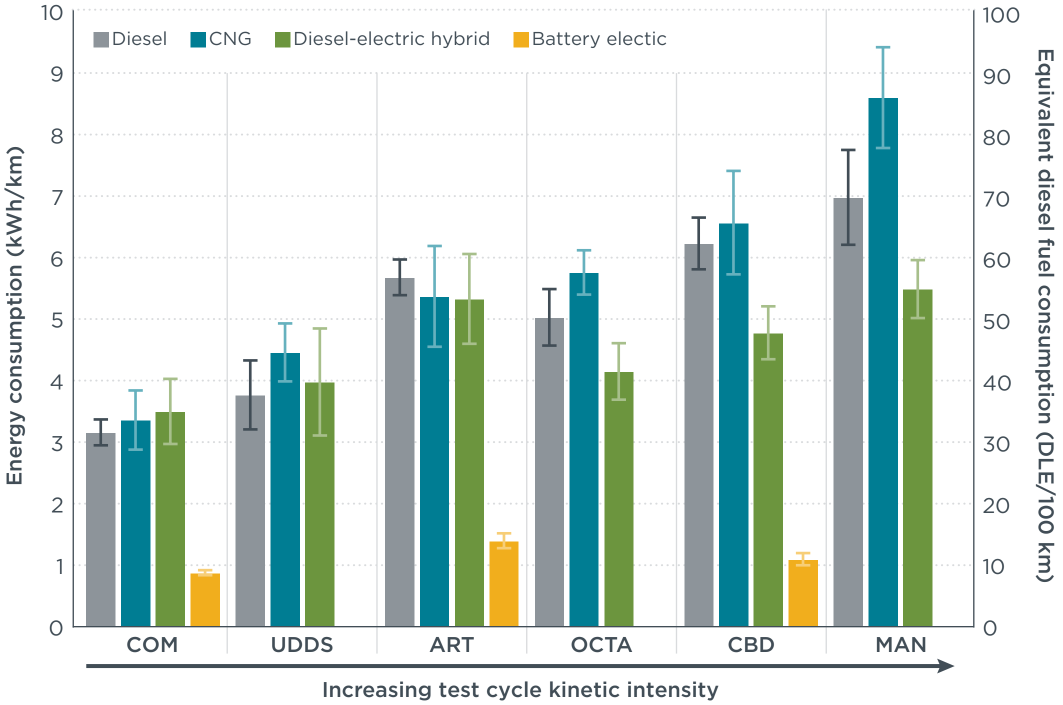

Figure 3. Average energy consumption by powertrain type and driving cycle for 2010 and newer model year buses tested at the Altoona Bus Research and Testing Center. The right vertical axis shows fuel consumption in terms of energy equivalent of a liter of diesel fuel, referred to as diesel liter equivalent (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, Du, & Minjares, 2017).

We summarize energy consumption findings in Table 2 and group results for individual driving cycles 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 the findings of other recently published transit bus technology assessments (Lajunen & Lipman, 2016; Asian Development Bank, 2018).

Table 2. Energy consumption for alternative powertrains relative to baseline diesel for three route types (Dallmann, Du, & Minjares, 2017).

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

In general, these results 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 in order to reduce fuel consumption, operating costs, and GG emissions.

The results in Table 2 provide a general perspective of the energy consumption for alternative transit bus technologies. A more robust comparison could be developed by pilot testing these technologies on LLP routes or by performing energy consumption modeling using detailed information about the operating conditions on selected routes. The International Energy Agency's Advanced Motor Fuels Technology Collaboration Program conducted a study using these strategies in Santiago, Chile, in order to promote transitions to cleaner and more efficient bus technologies (Castillo et al., 2018).

The ICCT is currently developing similar modeling capabilities. While beyond the scope of this study, these methods could be used in a follow-up study to provide a more detailed analysis of the energy consumption of alternative bus technologies in Polokwane. LLP could take an initial step in support of this type of assessment by deploying GPS units throughout the fleet to collect detailed operating information such as vehicle speed, acceleration, and elevation.

WELL-TO-WHEEL GHG EMISSIONS OF ALTERNATIVE TECHNOLOGIES

Life-cycle GHG emissions can be calculated as the product of the carbon intensity of a fuel and the energy consumption of the vehicle using it. The carbon intensity of fuels used in transit buses represents tailpipe GHG emissions from the combustion of fuels as well as 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 emissions values yields well-to-wheel (WTW) emissions, which are the focus of this analysis. This carbon intensity metric includes emissions of CO_2, 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 carbon dioxide-equivalent (CO_2e).

We estimate energy consumption for alternative technologies using average fuel consumption values for the Metrobus fleet as representative for Polokwane, alongside the relative energy consumption levels reported in Table 2. In this formulation, energy consumption is expressed in units of energy consumed per distance traveled, such as kilowatt-hours per kilometer (kWh/km), and fuel carbon intensity is expressed in units of mass CO_2e 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 technology, Euro V buses using commercial CNG, and diesel fuels. We report results for three representative route types.

Figure 4 shows estimates of WTW carbon intensities for transit bus fuels produced completely or partly 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. Figure 4 also provides an estimate for the average South African diesel mix. This value assumes that 12.5% of the diesel fuel consumed in the country is supplied by CTL fuels, with the remainder produced from crude oil feedstocks from national refining and imports. Data for the carbon intensity values for diesel fuels and national diesel supply mix come from the DEA GHG Mitigation Potential Analysis Report (Department of Environmental Affairs, 2014).

The WTW carbon intensity of CTL diesel is more than twice the carbon intensity of crude oil-derived diesel, which means that any CTL-derived diesel in the fuel mix for the LLP fleet will considerably increase the WTW GHG emissions of diesel buses operating in the city. For our modeling of the baseline Euro V technology buses, we assume diesel fuel consumed has a carbon intensity of 392 gCO_2e/kWh, borrowing from the value reported for the average South African diesel supply mix.

In Figure 4, we source fossil CNG carbon intensity values from the U.S. Argonne National Laboratory (ANL) GREET model as reported in the ANL AFLEET tool (2018). The carbon intensity of fossil CNG fuel is sensitive to assumptions regarding methane leakage across the natural gas supply chain of production, processing, transmission, and compression, as well as vehicle use. 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 the recent findings of an extensive experimental program to measure CH_4 emissions from the natural gas supply chain in the United States (Alvarez et al., 2018). Finally, we estimate a high CH_4 leakage case 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 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.

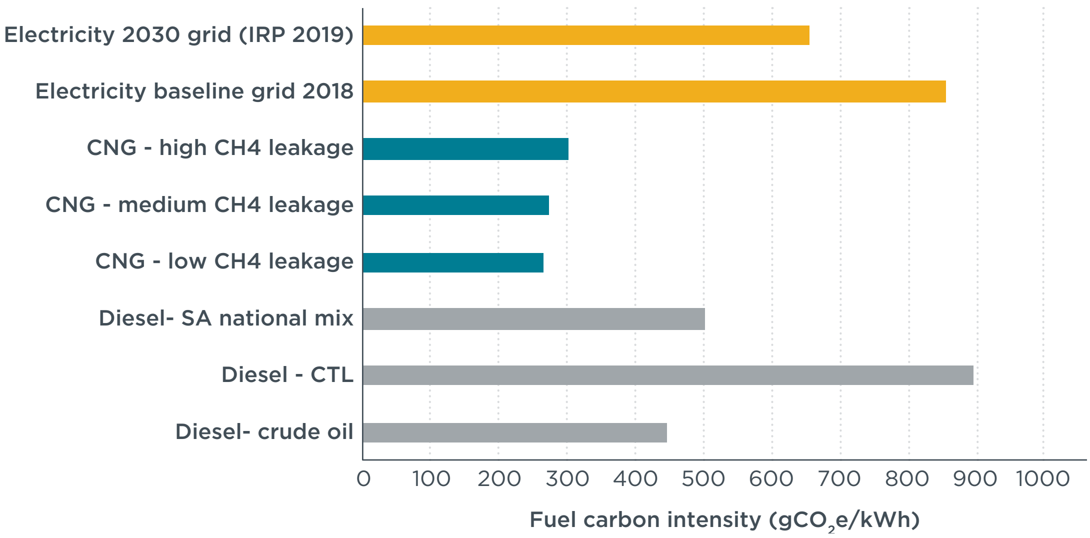

Figure 4. Fuel WTW or life-cycle carbon intensities for fossil diesel, fossil CNG, and electricity.

We estimate the carbon intensity of the electricity used to power battery electric buses using the AFLEET model and data on national-level electricity production by generation source type for the baseline year, 2019, and on projections for future years provided in the Department of Energy (DOE) Integrated Resource Plan from the South Africa Department of Mineral Resources and Energy, (IRP, 2019). The assumed share of electricity generation by fuel type for each scenario is reported in Table 3. The year 2018 generation mix is dominated by coal, resulting in a relatively high grid carbon intensity. DOE's IRP of 2019 foresees an increase in renewables adoption and a reduction in reliance on coal generation. The IRP 2019 trajectory results in a 52% reduction in grid carbon intensity relative to the 2018 baseline.

Table 3. Share of electricity generation by fuel in South Africa in the 2019 Integrated Resource Plan (IRP 2019).

Electricity source	Generation in 2018	Planned generation in 2030 (IRP 2019)
Coal	75.5%	45.8%
Gas and Diesel	7.8%	8.7%
Nuclear	3.8%	2.6%
Renewables	8.6%	36.6%
Hydroelectric	4.3%	6.3%
Estimated grid carbon intensity (gCO_2e/kWh)	856	654

The carbon intensity of biomethane heavily depends on the type of feedstock and production process used to make the fuel. To illustrate the variability in biomethane carbon intensity, Figure 5 shows carbon intensities for biomethane fuels certified under the State of California's Low Carbon Fuel Standard. For each biomethane fuel, we conducted a life-cycle assessment 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 production 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 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 (CARB) Temporary Pathways table for biomethane produced from landfill or digester gas (Clean Air Resources Board, 2019).

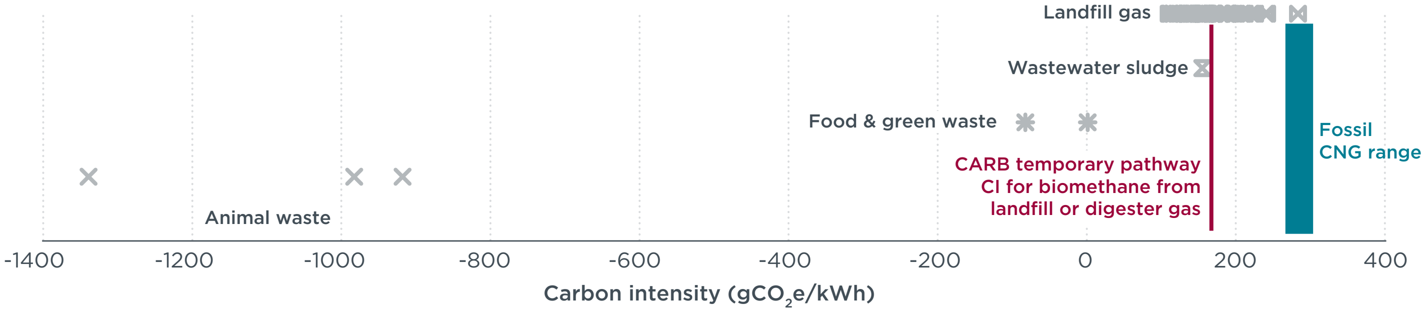

Figure 5. Carbon intensity for biomethane by feedstock. Reproduced from data made available by California Air Resources Board (2019).

We combined life-cycle fuel carbon intensities and energy consumption estimates in order to estimate WTW GHG emissions performance of alternative powertrain and fuel combinations compared against the baseline LLP technology and fuel, i.e., a Euro V bus operating with commercial diesel fuel, 12.5% from CTL and 87.5% from crude oil. Figure 5 presents the WTW GHG comparison for medium-speed route types characterized by an average speed of around 20 km per hour.

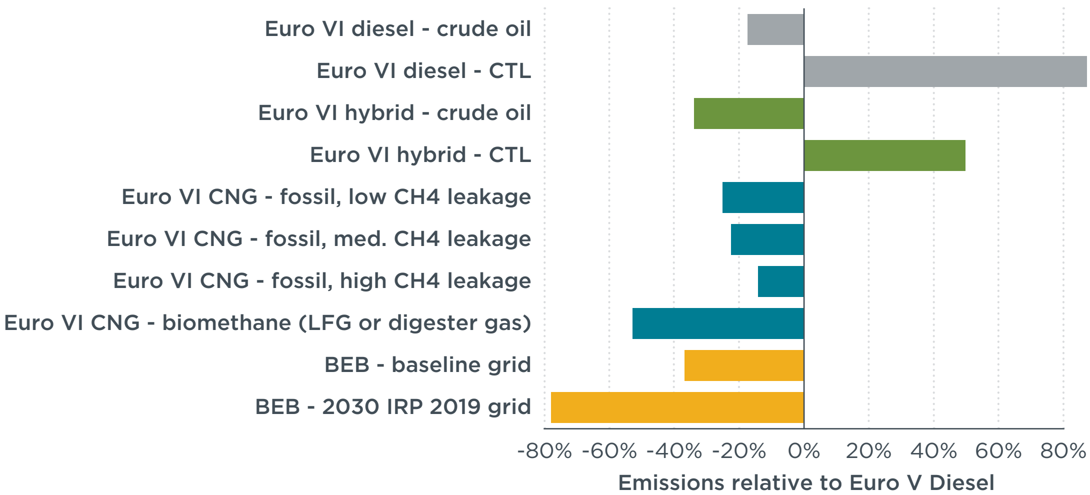

Figure 6. WTW GHG emissions relative to Euro V baseline for buses operating in medium-speed urban driving conditions.

In medium-speed conditions, BEBs 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 that assume low or medium methane leakage from the natural gas supply. 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.

Several conclusions can be drawn from this WTW comparison:

- With the exception of diesel buses and hybrid buses fueled with CTL diesel, all technology and fuel options provide WTW GHG emissions savings relative to the baseline technology. If Euro VI diesel buses, or hybrid buses fueled with low-sulfur CTL diesel fuel, were to replace buses on routes with these driving conditions, life-cycle GHG emissions could increase by 70%–80%.
- Hybrid and diesel buses fueled with crude oil-derived diesel fuel and battery electric buses (assuming today's grid carbon intensity) provide similar WTW GHG emissions performance. In each case, GHG emissions are about 35% lower than those for the baseline Euro V bus technology for medium-speed urban driving conditions.
- Efficiency penalties for CNG engines are minimized under suburban/commuter operating conditions, leading to better GHG emissions performance than other alternative technologies in cases that assume low natural gas supply chain leakage. 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 BEBs powered by decarbonized grid electricity provide the greatest GHG emissions benefits, with reductions of 60%–70% relative to the baseline.

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**. CTL-derived fuels have a very high carbon intensity and, consequently, much greater GHG emissions relative to other technology and fuel options. If LLP were to consider Euro VI diesel technologies, it would need to procure a dedicated supply of low-sulfur diesel fuel and ensure that the fuel would 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. We estimate CNG buses to perform moderately better under suburban/commuter driving conditions and estimate diesel buses to 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. 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: We estimated WTW GHG emission savings of 50%–60% relative to the baseline. If biomethane were produced from lower-carbon feedstocks, such as animal or food waste, GHG emission savings could be much greater.

BEBs 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, we estimate WTW GHG emissions to be similar to those 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 emissions benefits of BEBs are even clearer under the grid decarbonization scenarios, where the technology is estimated to reduce emissions by 65%–85% relative to a baseline Euro V bus.

AIR QUALITY IN POLOKWANE

The city of Polokwane is home to over 1.3 million residents and accommodates millions of additional commuters on a daily basis. According to IQAir, the city has a moderate level of pollution of 51 US Air Quality Index (AQI) that nevertheless may be a risk for some people, particularly those who are unusually sensitive to air pollution (IQAir.com, 2021). The city's main pollutant is fine particulate matter (PM2.5), with a reported concentration density of 12.1 $\mu g/m^3$. By comparison, the AQI of Johannesburg, whose population is six times greater than Polokwane, is only twice as high (105 US AQI, considered unhealthy for sensitive groups), while the concentration density of PM2.5 is only three times greater (37.2 $\mu g/m^3$). Polokwane would benefit from prioritizing action against unhealthy levels of air quality.

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

Figure 7 demonstrates the improvement in PM and NO_x emissions performance of diesel and CNG buses through the development of the European regulatory program for heavy-duty vehicles. We present emission factors for each pollutant by engine type and Euro standard, beginning with Euro I and ending with the current Euro VI standard. National standards for heavy-duty vehicles in South Africa are currently equivalent to Euro II standards. We use emission factor data from the Handbook Emission Factors for Road Transport, a European emission factor model widely used in emissions inventory development applications (Handbook Emission Factors for Road Transport, 2019).

Euro VI technologies have clear emissions benefits. We estimate the PM emission factor for Euro VI buses to be 99% lower than for Euro I buses and 90% lower than for buses certified to Euro V emission standards. We report similar reductions 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 that Euro VI technologies offer is only slightly less than that of zero-emission technologies such as BEBs.

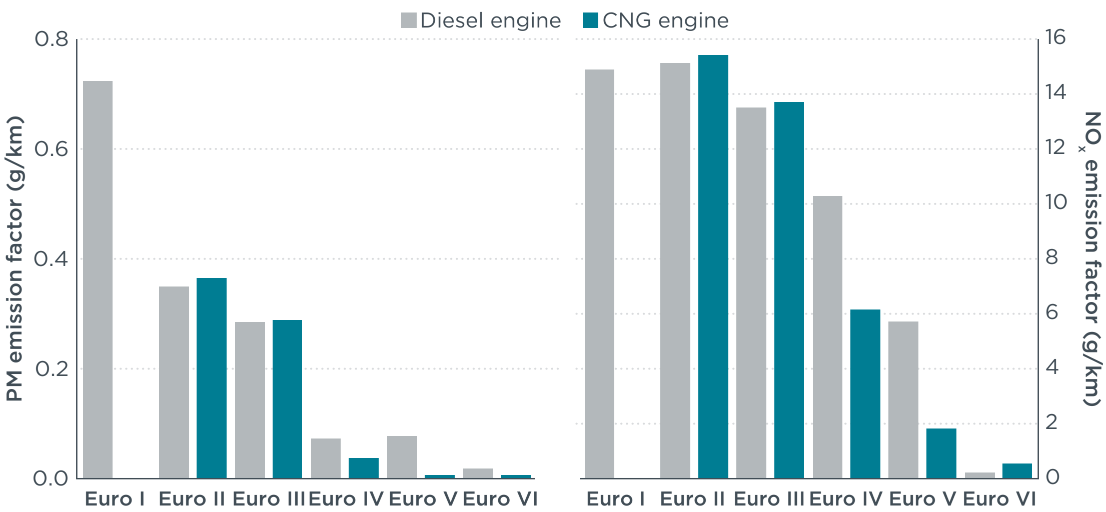

Figure 7. PM and NO_x emission factors for standard-sized diesel urban buses by emissions control standard and engine technology. Data sourced from Handbook Emission Factors for Road Transport (2019).

Euro VI engines are also effective at controlling particle number and BC emissions. Particle number is associated with the detrimental health impacts of vehicular PM emissions, while BC is a major component of diesel PM and an impactful short-lived climate pollutant. Up to 75% of diesel PM emitted from older-technology engines contains BC. However, Euro VI engines reduce diesel BC emissions by 99%, primarily through the application of a DPF. The DPF also effectively controls particle number emissions, as demonstrated in Figure 8. The particle number emission factor for Euro VI diesel buses is two to three orders of magnitude lower than for 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.

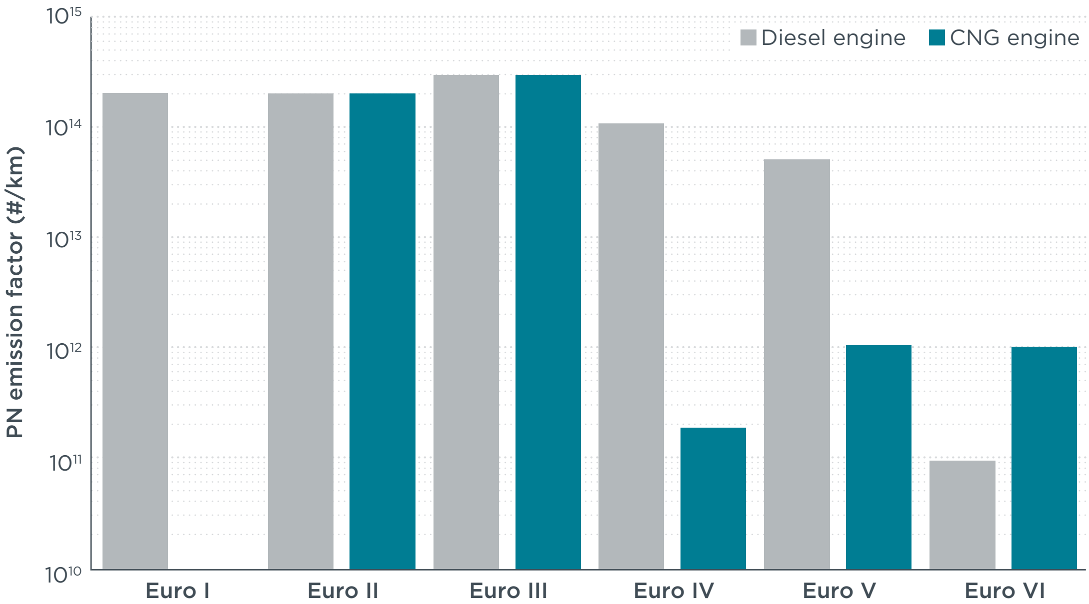

Figure 8. Particle number emission factors for standard-sized diesel urban buses by emissions control standard and engine technology. Data sourced from the Handbook Emission Factors for Road Transport (2019).

In addition to more-stringent emission standards, the Euro VI regulation also introduced provisions that significantly improve real-world emissions performance for heavy-duty engines. Among the new provisions are the introduction of certification test cycles that better represent real-world driving conditions by 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 9, which shows estimates of real-world NO_x emissions from buses by emissions control level for four major vehicle markets. The European Union achieved little real-world improvement in NO_x emissions between Euro II and Euro V standards. Only with the implementation of Euro VI standards did the European Union effectively control real-world NO_x emissions. Similar trends exist for emission estimates in other regions.

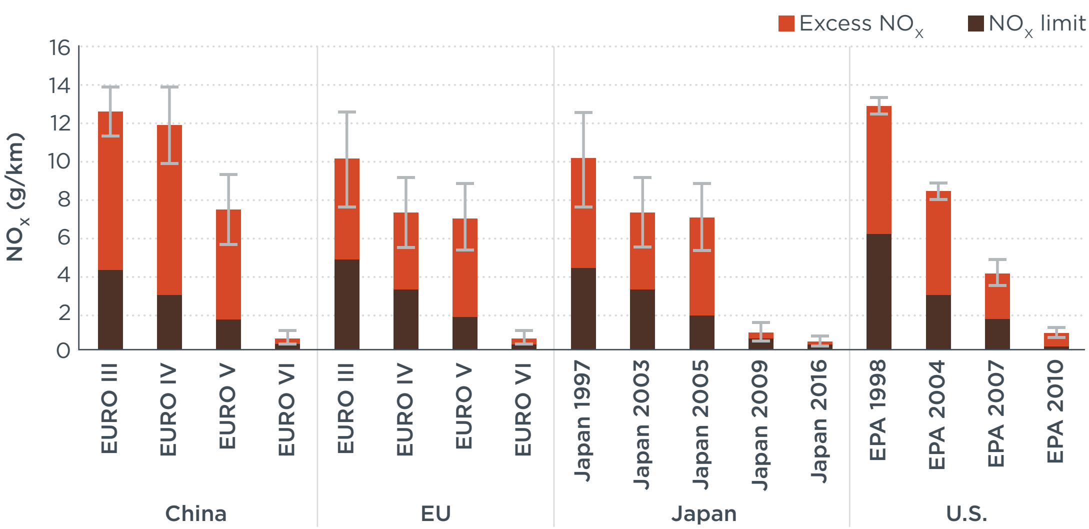

Figure 9. Real-world NO_x emission factors for buses, by vehicle emissions standard (Anenberg et al., 2017).

The effectiveness of Euro VI diesel engine emission systems in controlling real-world NO_x emissions is further demonstrated in Figure 10, which shows results from a recent on-road vehicle testing campaign conducted in London using remote sensing technology. 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 10. Average emission factors for London buses. 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

Existing procurement and contracting practices often favor or require purchase of the bus technology with the lowest purchase price. Purchase price, 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 creates a bias against hybrid, battery electric, and other alternative and clean bus technologies that may have a higher purchase price but substantially reduce operating and maintenance costs and in some cases reduce costs over the lifetime of the bus (Miller, Minjares, Dallmann, & Jin, 2017).

A better metric for comparing the costs of bus technologies is the total cost of ownership (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 11 summarizes the components of the TCO. In this section, we evaluate the TCO of alternative transit bus technologies for representative 12-meter and 9-meter buses operating in the LLP fleet.

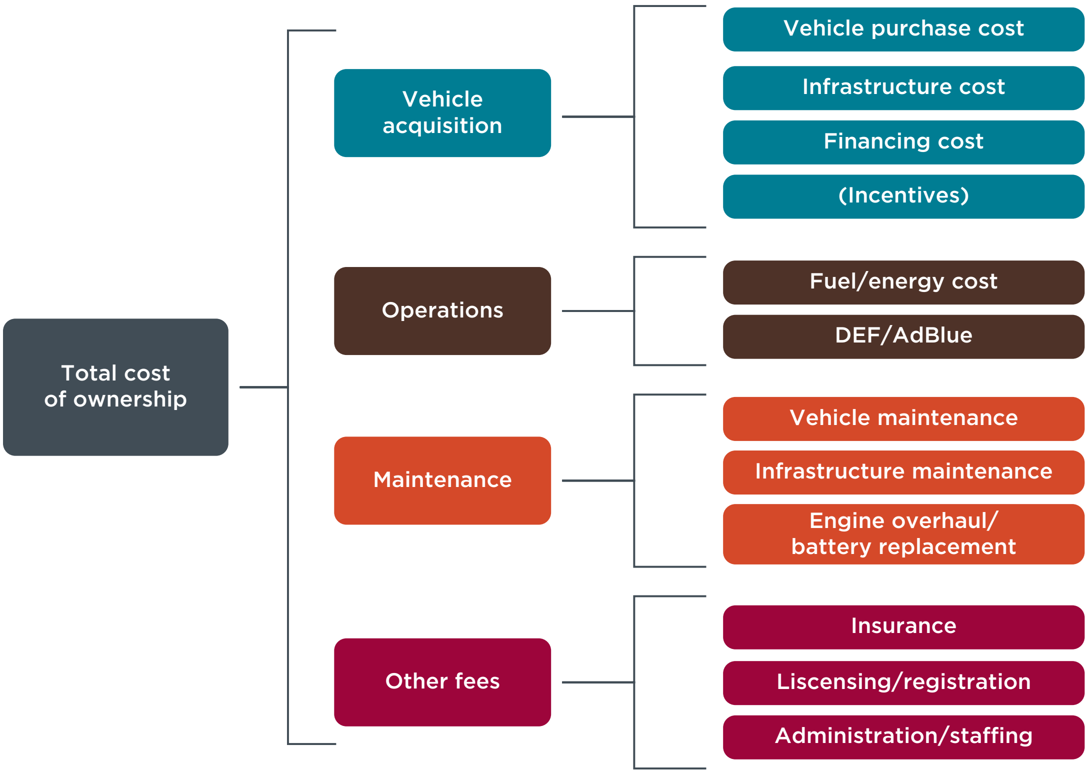

Figure 11. Total cost of ownership components, including resale value at end-of-life.

Table 4 summarizes the components of TCO that we consider in this analysis. Our objective is to evaluate costs that differ with the bus technology selected, so we do not evaluate the extraneous fees indicated in Figure 11; including those costs would not be expected to change the outcome of the analysis.

Table 4. Components of the 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	Positive cash flow attained for depreciated vehicles in instances where the duration of planned operation is shorter than the bus service life.
Operation and maintenance	**Fueling**	Annual cost to fuel the vehicle determined by vehicle efficiency, distance traveled, and fuel price.
	Other operational	Cost of diesel exhaust fluid for diesel buses with selective catalytic reduction systems (typically Euro IV+).
	Bus maintenance	Cost of regular bus maintenance, including tires, parts, lubricants, etc.
	Infrastructure maintenance	Cost of infrastructure maintenance and operations not already represented in the retail fuel price.
	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 its analysis of the cost of soot-free transit bus fleets in 20 megacities across the globe. Slowik et al. further developed these methodologies in a case study for São Paulo (2018). TCO results are presented for a base modeling scenario that reflects our current best estimates of input values for cost components. Because neither Polokwane nor elsewhere in South Africa has deployed most of the technologies we consider here, some uncertainty exists in the TCO modeling assumptions. To help address uncertainties and explore the influence of individual cost components on TCO estimates, we conduct a sensitivity analysis.

The baseline technologies are 12-meter and 9-meter buses certified to meet Euro V diesel standards. LLP provided some financial information about the procurement of these Euro V buses. Alternative technologies considered in the TCO assessment include Euro VI diesel, CNG, hybrid, and BEBs.

In Table 5, we estimate purchase prices of alternative technologies assuming a set price difference relative to the baseline technology. We follow this approach due to the lack of robust cost information for alternative technologies in South Africa. Relative price differences among technologies come from cost data for alternative transit bus technologies compiled by the CARB (Clean Air Resources Board, 2017) and equal the values used in previous TCO modeling assessments that the ICCT has conducted. Where information from Polokwane is not available, we take relevant cost numbers and important parameters from the bus fleet strategy work performed with Metrobus in Johannesburg (Dallmann, 2020).

Table 5. Bus purchase price for 12 m and 9 m bus sizes.

Bus technology	Assumption	12-meter bus value used for TCO modeling (R)	9-meter bus value used for TCO modeling (R)	Source
Euro V (baseline)	Reported by Leeto la Polokwane	4,312,622	4,170,063	Leeto la Polokwane
Euro VI diesel	+2% relative to baseline technology	4,398,874	4,253,464	California Air Resources Board, 2017
Euro VI hybrid	+50% relative to baseline technology	6,468,933	6,255,095	California Air Resources Board, 2017
Euro VI CNG	+12% relative to baseline technology	4,830,137	4,670,471	California Air Resources Board, 2017
Battery electric bus	+75% relative to baseline technology	7,547,089	7,297,610	ICCT bus databases

Other capital expenses for alternative technologies include fueling infrastructure costs. We consider these costs for CNG and BEBs. Table 6 shows estimates of the per-bus infrastructure acquisition costs we use for the base TCO modeling assessment. Estimates for CNG fueling infrastructure come from discussions with Johannesburg's Metrobus and an independent consultant previously contracted to conduct financial assessments of alternative transit bus technologies for the Rea Vaya fleet in Johannesburg. For the purposes of this assessment, we assume that the BEB will be charged overnight at a depot and that each bus will require its own charging station. We estimate the cost for a single charger to be R 715,000 ($50,000 USD). Grid connection costs are not included.

Table 6. Infrastructure costs by bus technology.

Bus technology	Assumption	Source
Euro VI CNG	R 230,000/bus	Metrobus, Johannesburg
Battery electric bus	R 715,000/bus Calculated assuming depot charger servicing 1 bus costs $50,000	CARB, 2017

[a]The currency conversion rate is $1 = R 14.5.

Table 7 provides our calculations of fueling costs on a per-kilometer basis using estimates of energy consumption in diesel liter equivalents (DLE) and the price of fuels. We calculate energy consumption values for alternative technologies assuming medium-speed urban driving conditions. The effect of route type and driving conditions on TCO estimates is explored further in the sensitivity analysis. We also calculate the cost of urea needed for NO_x control systems for Euro VI diesel and Euro VI hybrid buses.

Table 7. Fueling costs by technology for 12 m and 9 m buses

Bus technology	Fuel price (R/DLE)	Energy consumption (DLE/km)		Fueling cost (R/km)	
		12-m bus	9-m bus	12-m bus	9-m bus
Euro V diesel	15.1	0.62	0.50	9.4	7.6
Euro VI diesel	15.4	0.59	0.48	9.1	7.3
Euro VI hybrid	15.4	0.47	0.38	7.3	5.9
Euro VI CNG	7	0.65	0.52	4.6	3.7
Battery electric bus	15.3	0.18	0.14	2.7	2.2

Note. Assumed price is R 15.1 per diesel liter equivalent (DLE) for diesel and R 7.0/DLE for CNG, based on CNG prices from Metrobus Johannesburg. Electricity price is estimated from Leeto la Polokwane Power tariffs averaged for industrial users and residential users at 153.4 c/kWh.

Table 8 presents maintenance cost estimates sourced from Johannesburg's Metrobus, a representative fleet of public transit buses in South Africa. LLP started operations in 2021, making it impossible to source long-term maintenance values for the city. For the baseline technology, we estimate per-kilometer costs 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. We calculate per-kilometer maintenance costs for alternative technologies using information on the relative maintenance costs of these technologies reported by CARB (2017).

Table 8. Maintenance costs by technology for 12-m and 9-m buses.

Bus technology	Assumption	Values used for TCO modeling (R/km)	Source
Euro V (baseline)	Calculated form Metrobus service contract for chassis and body maintenance, with an 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	

The following are additional assumptions related to the estimates of TCO in the base assessment:

- A discount rate of 8.2% applied to future costs (DOE, 2018)
- A bus service life of 12 years
- Annual activity per bus:
    - for the 12-m buses: 68,000 km per year
    - for the 9m buses: 52,000 km per year
- Baseline technologies (Euro V diesel buses) purchased upfront. For alternative technologies, 50% down payment for bus and infrastructure acquisition; remaining expenses covered by a 5-year loan at a real interest rate of 7%.
- 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.
- Energy prices, calculated as the average of the industrial and domestic tariff at 153.3 c/kW.
- Interest rate, reflecting a prime lending rate of 7% from March 10, 2021, as published by the South African Reserve Bank.

TCO RESULTS

We calculated TCO values for standard 12-m and medium-size 9-m buses for two different sets of vehicle activity (average kilometers traveled per bus per year, or vehicle-kilometers traveled [VKT]). The first value corresponds to expected VKT to be achieved by the LLP once fully operational. The second value matches the average VKT from the Metrobus fleet in 2019 (i.e., 36,000 km per year).

TCO for 12-m buses

The results from the TCO evaluation for the standard 12-m buses are shown in Figure 12. The expected activity in VKT for LLP buses would result in lower cost per kilometer across vehicle technologies. Euro VI diesel and Euro VI CNG present consistent cost reductions independent of the assumed VKT. TCO evaluations for hybrids and BEB technologies are dependent of VKT assumptions. We estimate the TCO for the baseline Euro V diesel bus at R 14.8km for the design VKT case and R 18.8/km for the lower VKT case (equivalent to Metrobus' VKT). Fueling is the largest cost component in the high VKT case. In the lower VKT case, the capital cost of the bus is the largest cost component for TCO on a Rand/km basis.

The TCO and cost breakdown for the EURO VI diesel bus are similar to those of the EURO V bus. The slightly higher technology cost of the Euro VI bus is offset by the higher efficiency of the Euro VI technology. In the base case, we assume the diesel fuel price for the Euro VI bus to be R 0.3/L more expensive than the 50 ppm sulfur diesel fuel that LLP buses currently use. Euro VI buses would result in lower TCO values under both expected and lower VKT values. The reduction was estimated at 2.3% and 1.4% for designed and lower VKT values, respectively.

Diesel hybrid technology results in one of the most expensive options. Under the expected operational activity of 68,000 km per year, a hybrid bus would be 1.3% more expensive per kilometer than the baseline diesel Euro V technology. Reducing the activity to 36,000 km would increase the hybrid technology TCO to 12.5%. The hybrid technology is more expensive than diesel Euro V, and fuel savings provided by hybrid powertrains are insufficient to cover the incremental cost.

The CNG Euro VI solution provides the lowest TCO under the two activity values assumed here. The design VKT would result in a TCO reduction of 15% with respect to the diesel Euro V technology. Under lower VKT operations, the TCO would still be 7.3% below baseline. These positive TCO evaluations for CNG buses result from our assumption of CNG fuel prices from Metrobus that are 50% lower than the diesel fuels on a per-liter basis.Metrobus has an ongoing supply of CNG for its operations. It is unlikely that CNG in Polokwane would be as inexpensive as the CNG in Johannesburg, considering that Polokwane has no immediate access to natural gas pipelines today.

The evaluation of TCO for BEB technology shows positive results under the high activity assumption, and negative results for lower activity assumptions. Under expected activity (VKT = 68,000 km per year) the BEB solutions would be 8.6% less expensive than the baseline diesel Euro V. Under lower activity assumptions (VKT = 32,000 km per year), the BEB would be 15% more expensive than the baseline diesel technology. The higher costs for BEB result from the combination of higher capital cost for buses and infrastructure. Savings are realized in the longer VKT case by the higher energy efficiency of BEBs.

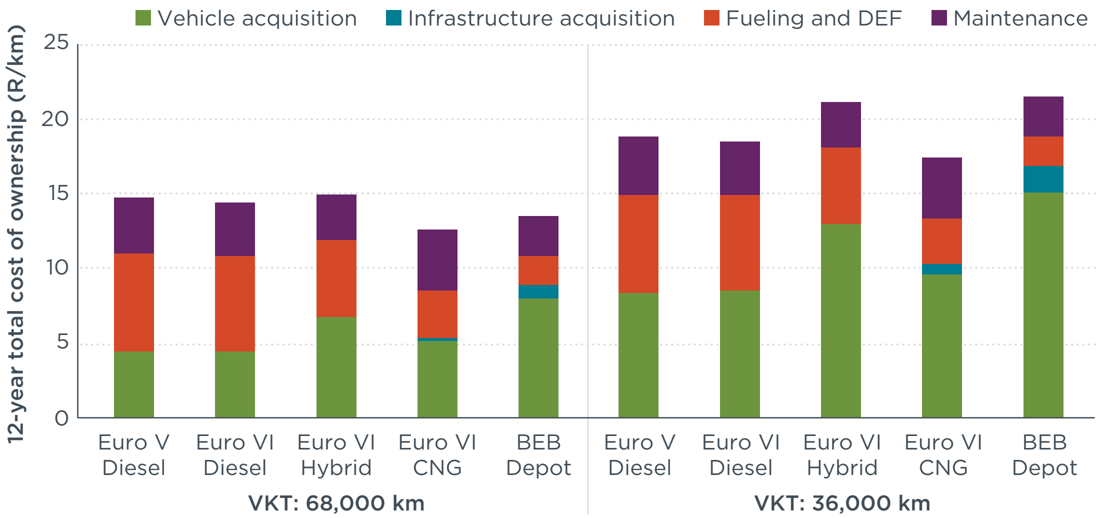

Figure 12. Total cost of ownership for 12-m buses over 12 years for baseline and alternative technology in Polokwane under two bus activity cases.

TCO for 9-m buses

We present results of the TCO evaluation for the 9-m buses in Figure 13. The baseline technology shows a TCO of R 14.7/km for the design VKT value (52,000 km per year), increasing to R 17.2/km for the lower VKT case. For the 9-m bus, vehicle purchase is the largest component of the TCO for both VKT cases.

As observed in the 12-m bus results, the Diesel Euro VI and CNG provide the lowest TCO values. Diesel Euro VI provides lower TCO values than baseline technology by about 2% due to lower fuel costs accrued over time. We estimate the CNG bus fueled with commercial fossil CNG fuel at R 7/L to have the lowest TCO of any of the alternative technologies considered in the baseline assessment. That vehicle's TCO is 9% lower than the TCO of the baseline Euro V diesel bus for the high VKT case and 4.6% lower for the low VKT case. While capital expenses for the CNG bus are greater than for the diesel bus, the low price of natural gas that we assume in this study results in considerable operational savings of R 1.3 to R 0.8 per kilometer traveled.

In contrast to the 12-m bus, both the Euro VI diesel-electric hybrid and the BEB for the 9-m bus are estimated to have a higher TCO than the baseline Euro V bus and other alternative-technology buses. Relative to the high and low VKT scenarios, the TCOs for the hybrid bus are 7.8% and 14.4% higher, respectively, than the baseline technology. For BEBs, the TCO evaluation shows 6.5% and 20.2% higher-than-baseline TCO values for high and low VKT cases, respectively. High capital expenses drives this increase in hybrid buses, while infrastructure acquisition increases the cost of BEBs. Operational cost savings are realized for each technology; however, due in part to the relatively few kilometers that LLP vehicles are driven each year, these savings are insufficient to offset the higher capital expenses. We explore further the effect of vehicle useful life and annual activity on TCO estimates in the sensitivity assessment.

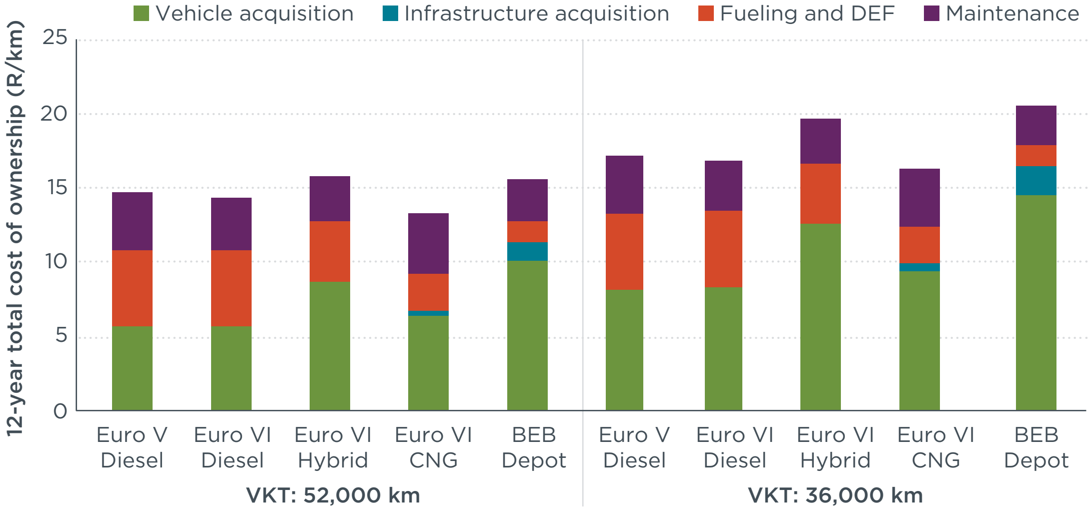

Figure 13. Total cost of ownership for 9-m buses over 12 years for baseline and alternative technology in Polokwane for two bus activity cases.

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 key TCO modeling input variables: bus activity, battery electric bus purchase price, energy price, ownership period, depreciation or resale value, and interest rate. Bus activity is studied in detail first, followed by the other inputs as overall impacts.

SENSITIVITY ANALYSIS TO BUS ACTIVITY (VKT)

Bus activity impacts the financial benefit of capital-intensive technologies like BEBs, which offer operational cost savings relative to the baseline Euro V technology. Because of the relatively high capital expenses of these technologies, high utilization rates are necessary to make them competitive with conventional technologies on a TCO basis. Utilization can be increased through greater annual activity or longer contract periods.

Figure 14 shows the estimates of the 12-m bus TCO sensitivity for diesel, CNG, hybrid, and BEBs relative to a wide range of annual activity. In all cases, the per-kilometer TCO decreases as annual utilization rises. This trend is most pronounced for the BEB. BEB technology matches the diesel baseline TCO values at 54,000 km per year for the 12-m bus. The hybrid Euro VI bus would match baseline TCO values after 76,000 km per year. The CNG Euro VI bus offers benefits after 22,000 km per year, but only if the cost of natural gas is about 50% of the price of diesel.

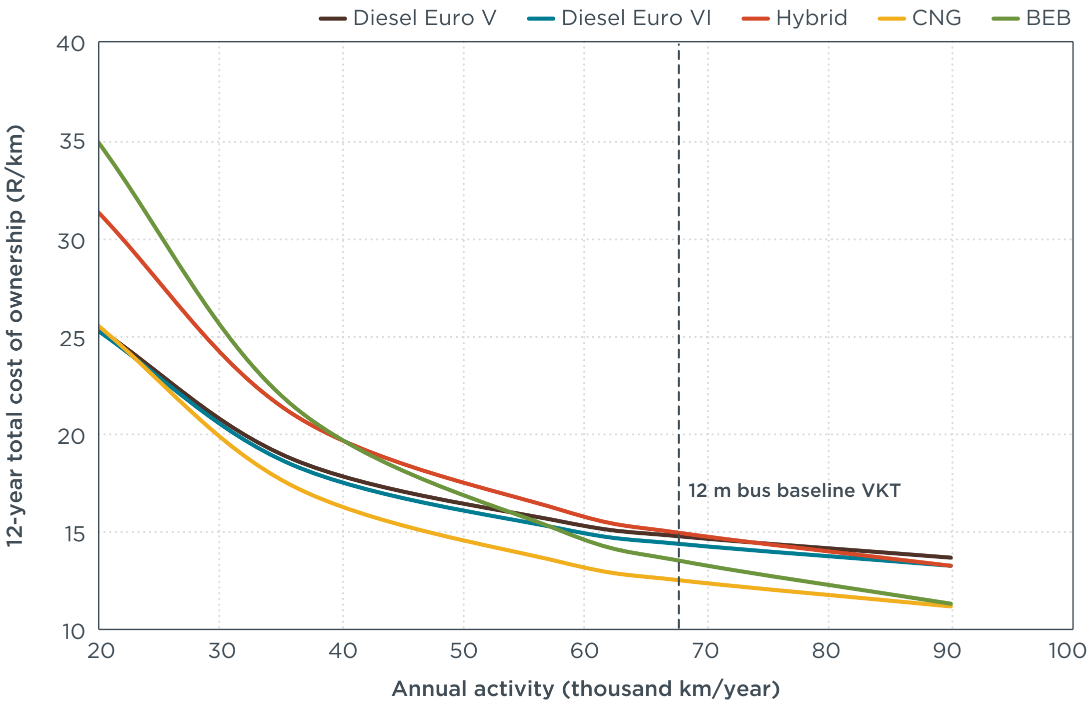

Figure 14. TCO sensitivity to 12-m bus activity in vehicle kilometers traveled (VKT).

For the 9-m bus, the TCO response to VKT is similar to the 12-m bus. The 9-m BEB would generate lower TCO values if operated above 55,000 km per year. The hybrid would require at least 68,000 km per year to match baseline TCO values. The 9-m CNG Euro VI bus would match the baseline TCO at 24,000 km.

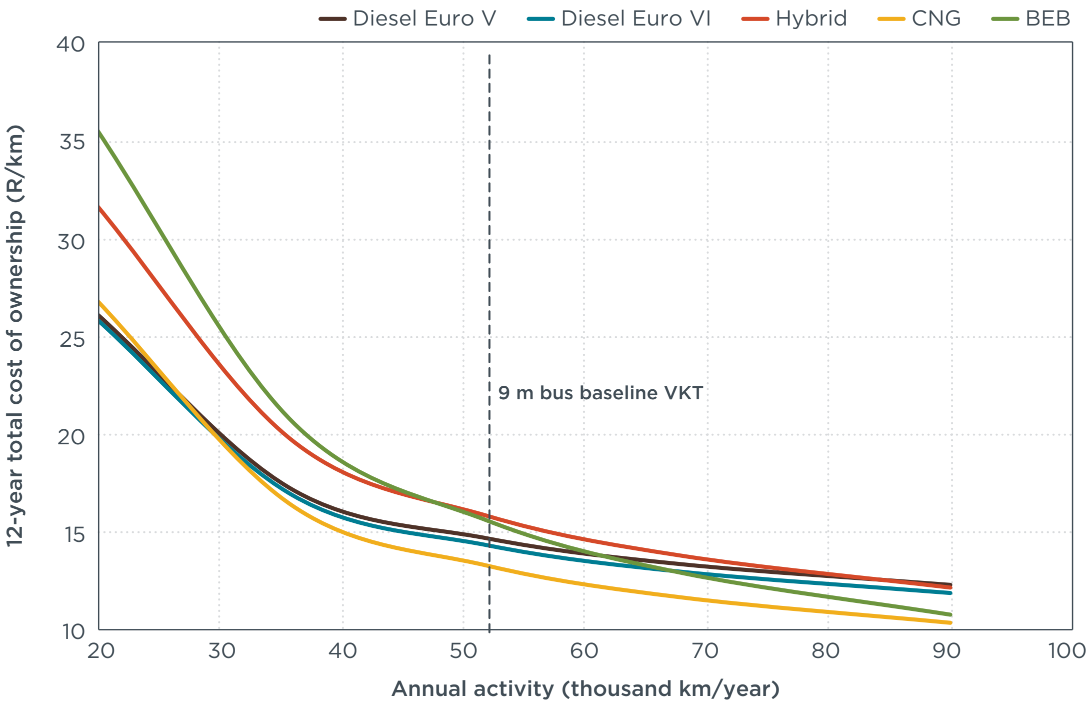

Figure 15. TCO sensitivity to 9-m bus activity in vehicle kilometers traveled (VKT).

SENSITIVITY ANALYSIS FOR OTHER VARIABLES

We perform a sensitivity analysis limited to soot-free and zero-emission bus technologies. We define multiple sensitivity cases in which the variable is changed from its baseline value. We then calculate the single bus TCO using the modified input variable, with all other cost modeling inputs set to their baseline levels. Table 9 summarizes all sensitivity cases considered here.

Table 9. Overview of sensitivity cases.

TCO component	Sensitivity case	Description
Alternative technology bus purchase price	Low prices for alternative technology	Bus purchase price reduced by 25% for all alternative technologies—baseline is not changed
	Baseline	Default baseline bus prices
	High prices for alternative technology	Bus purchase price increased by 25% for all alternative technologies—baseline is not changed
Energy price	Fuel/energy price -25%	Fuel/energy prices for each of default diesel, CNG, and electricity prices decrease by 25%
	Baseline	Default diesel, CNG, and electricity prices
	Fuel/energy price +50%	Fuel/energy prices for each of default diesel, CNG, and electricity increase by 50%
Bus ownership period	10-year	10-year ownership period
	Baseline	Default 12-year ownership period
	15-year	15-year ownership period
Interest rate	Low interest rate	Interest rate of 5% assumed
	Baseline	Default interest rate of 7% assumed
	High interest rate	Interest rate of 10% assumed

Figure 16 summarizes the results of the sensitivity analysis for the TCO for a standard 12-m bus. The sensitivity to alternative technology purchase price case is shown in the leftmost panel. As BEBs have only recently been commercialized, a fair amount of uncertainty is still associated with the purchase price for this technology in regions where they have not yet been commercially deployed. In our base assessment, we assume a purchase price equal to 1.75 times the price of the baseline Euro V diesel technology. Increasing this factor by 25% results in an increase in TCO for BEBs to match the TCO of the baseline technology.

On the other hand, decreasing the cost premium relative to the Euro V diesel bus by 25% brings the TCO of the BEB below CNG options. The low BEB price sensitivity case reflects the projected purchase price reductions over the next 10 years in response to declining battery prices. The price of BEBs will decline over time as battery cells and packs fall in price. The ICCT's review of battery electric vehicle prices show that as battery pack costs drop from about $160/kWh in 2018 to approximately $104/kWh in 2025 and $72/kWh in 2030, electric vehicle cost parity with conventional vehicles is likely to occur between 2024 and 2028 depending on vehicle size (Lutsey, 2019). Chinese manufacturers have already announced battery packs for buses that cost below $100/kWh (Bloomberg New Energy Finance, 2020).

Thus, while this technology may have a higher TCO than conventional buses today, projected technological developments should reduce capital expenses for electric bus technologies and make them more competitive on a TCO basis (CARB, 2017).

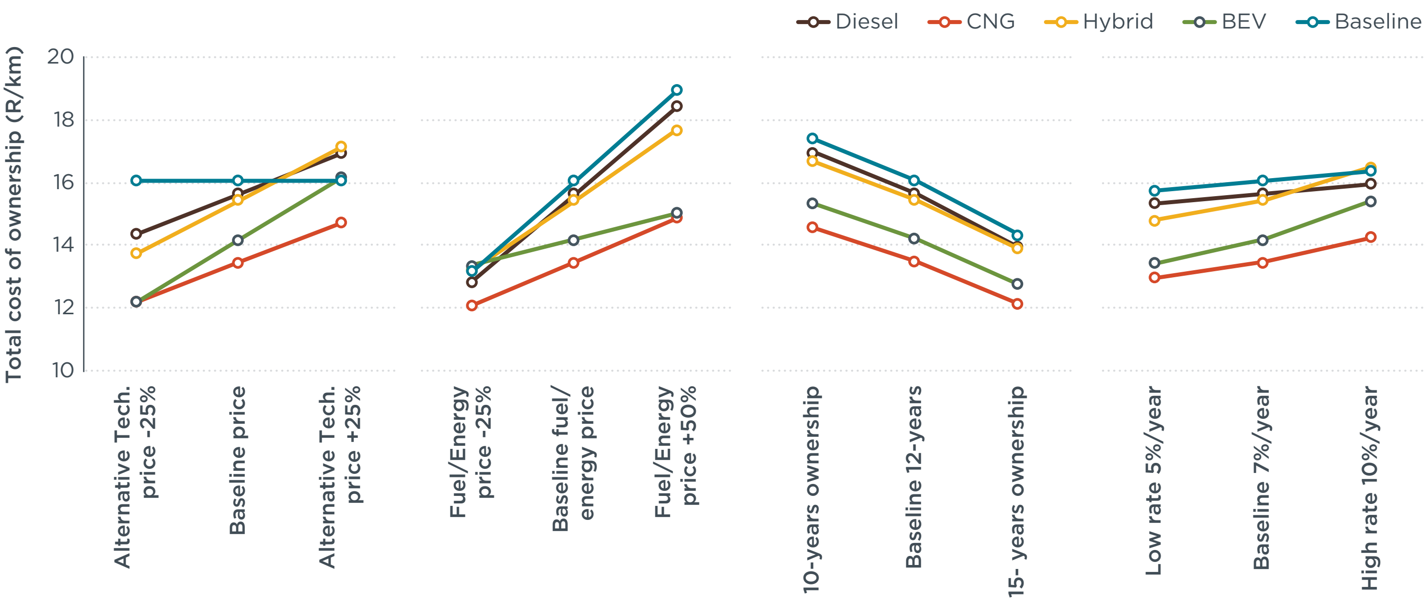

Figure 16. Sensitivity analysis for total cost of ownership of a standard (12-m) bus.

Of the technologies considered here, fueling costs constitute the largest portion of lifetime costs for all ICE bus technologies. As such, the TCO for diesel and CNG technologies is most sensitive to changes in fuel/energy prices. Increasing the cost of diesel fuel by 50% sharply raises the TCO estimate for all ICE technologies. For the Euro VI diesel bus, the 50% increase in fuel prices increases the TCO by 18%. The TCO of the BEB is the least sensitive to changes in the energy price. An increase of 50% in electricity prices would only increase the TCO by 6%.

A longer ownership period also serves to reduce the TCO across technologies, especially those with high capital investments. The analysis confirms that longer ownership periods make electric bus technologies more competitive with regard to TCO. Because of the relatively high capital expenses for these technologies, high utilization rates are needed to make electric bus technologies more financially competitive with conventional technologies on a TCO basis. Utilization can be increased through extended ownership periods or greater annual activity. Figure 16 considers the sensitivity of TCO estimates for each bus technology to assumed ownership period. For BEBs, extending the ownership period from 12 years to 15 years reduces the TCO by R 1.4/km, or 10%.

Interest rate assumptions influence the capital expenses estimated for transit bus technologies. As such, TCO estimates for vehicle types like battery electric and hybrid buses, for which bus and infrastructure acquisition costs account for relatively higher fractions of total lifetime expenses, are most sensitive to this variable. Under the financing terms assumed here, lowering the interest rate for BEB capital expenses from the baseline of 7% to the low-rate scenario of 5% would result in a 6% decrease in the TCO and would make this technology more financially competitive with other bus types.

FLEET GREENING ROADMAP

Comparing the various technology and fuel pathways reveals their relative contributions to long-term economic, environmental, and energy objectives. This section defines the long-term technology pathways and investments that will optimize the performance of the LLP fleet. We first consider the current state of technology of the LLP fleet and then project how the fleet composition is expected to change in the coming years.

We consider several fleet greening roadmaps to evaluate alternative options for the transition to a soot-free and low-carbon LLP fleet. For each procurement pathway, air pollutant and GHG emissions are modeled and compared against a business-as-usual (BAU) procurement scenario in which no changes are made to existing technology procurement practices. Finally, for the recommended procurement pathways, we consider challenges and opportunities for incorporating alternative technologies into the LLP fleet, including local variables regarding fuel and electricity availability.

EXISTING FLEET IMPLEMENTATION AND EXPANSION PLANS

The establishment of a decarbonization roadmap for the LLP fleet requires an understanding of the engine technologies and fuels currently in use, as well as the projected changes in the size and composition of the fleet. As of April 2021, the LLP fleet consisted of 36 Euro V diesel buses. These buses are deployed in four routes, as presented in Table 10. LLP deploys the standard 12-m buses in the BRT trunk routes and the 9-m buses in feeder routes.

Table 10. Phase 1 of Leeto la Polokwane bus operations.

Route	F1 (Flora Park)	F4B (Westenberg)	TE4 (Seshego-C)	TE5B (Seshego-A)
Route type	Feeder	Feeder	Trunk	Trunk
Bus type	9-m	9-m	12-m	12-m
Number of buses	9	3	8	13

We estimated future fleet growth by reviewing potential route extensions that could be incorporated into the existing system. LLP would decide on these Phase 1B additional routes after evaluating the financial performance of Phase 1 service (Table 11). Thus, the fleet growth numbers we present and model here are to be understood as indicative of potential emissions benefits while considering technology options. The different routes would extend the fleet to an estimated 65 buses, 35 of which would be 9-m and 30 of which would be 12-m.

Table 11. Potential expansion of Leeto la Polokwane service under Phase 1B.

Route	TE1	TE2	TE3	TE5a	TE6	F2A	F2B	F3	F4A	F5	F6A	F6B	F6C
Route type	Trunk	Trunk	Trunk	Trunk	Trunk	Feeder	Feeder	Feeder	Feeder	Feeder	Feeder	Feeder	Feeder
Bus type	12-m	12-m	12-m	12-m	12-m	9-m	9-m	9-m	9-m	9-m	9-m	9-m	9-m
Number of buses	5	5	4	4	12	3	6	3	3	4	9	6	1

We designed a tentative long-term new bus procurement schedule using the current fleet parameters and fleet growth projections (Table 12). The long-term procurement schedule describes when new buses would be incorporated into the LLP system. New buses would enter the fleet to expand the service in 2026 under a tentative Phase 1B expansion and replace buses that achieve the assumed full contract life (12 years). These new buses represent the opportunity to shift from baseline technology (diesel Euro V) to alternative soot-free and zero-emission technologies.

Table 12. Study assumptions for new bus procurement schedule for LLP buses.

New Bus purchase	2020	2025	2032	2037	2044
Description	New Fleet Phase 1	Add buses to service Phase 1B	Retire and replace 2020 buses	Retire and place 2025 buses	Retire and replace 2032 buses
Number of 9-m buses	15	30	15	30	15
Number of 12-m buses	21	35	21	35	21

The total LLP fleet would increase from 36 buses to 101 buses (Figure 17). The technology selected for each of the new bus procurement cycles has a direct impact on emissions, which we explain in the next section.

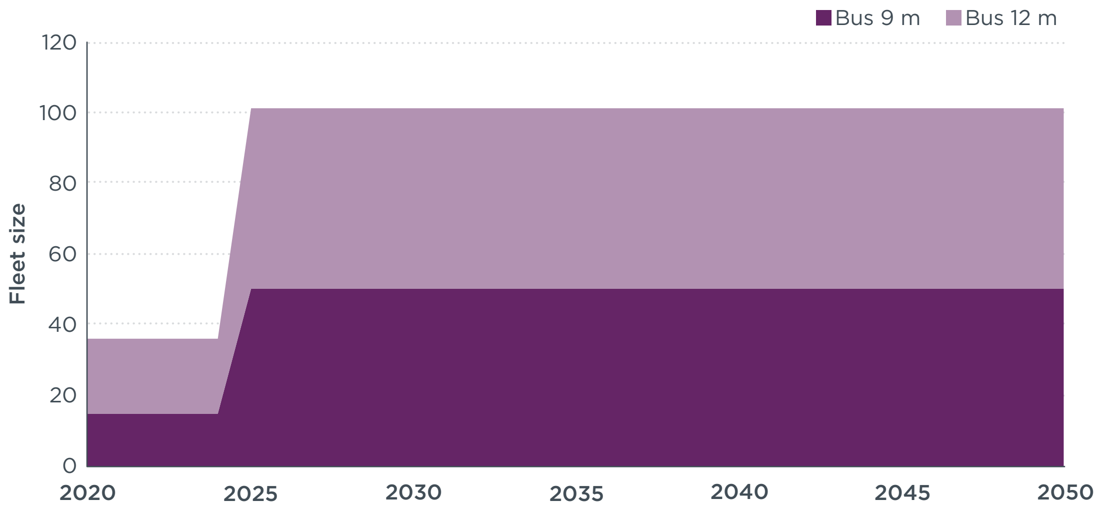

Figure 17. Leeto la Polokwane fleet size projections.

POTENTIAL TECHNOLOGY PROCUREMENT PATHWAYS

In this section, we consider alternative technology procurement pathways for the LLP fleet and compare them against a BAU scenario in which no changes are made to existing technology procurement practices. In each case, modeled procurement follows the schedule presented in Table 12.

We consider scenarios for the adoption of cleaner technologies for which TCO were evaluated previously: diesel Euro VI, diesel hybrid Euro VI, CNG Euro VI, and BEBs. The scenarios are presented in Table 13 and reflect potential adoption rates of advanced technologies. The baseline scenario assumes that all new buses are Euro V diesel. In this analysis, the carbon intensity of the electric grid changes over time according to the 2019 South African IRP, as developed by the Department of Mineral Resources and Energy (DMRE, 2019).

Table 13. Potential technology transition scenarios for Leeto La Polokwane buses.

Scenario	Description
Business as usual (BAU)	100% of new buses are baseline Euro V Diesel.
Scenario 1 - Euro VI	100% of new buses are Euro VI Diesel.
Scenario 2 - CNG	100% of new buses are Euro VI CNG.
Scenario 2B - CNG + Biogas	100% of new buses are Euro VI CNG with increased Biogas share. Biogas increases at 5% per year starting 2027.
Scenario 3 - Euro VI + BEB (IRP 2019)	Battery electric buses (BEBs) account for: 10% of new buses purchased in 2025, 25% in 2032, 50% in 2037, 100% in 2044; all other new buses are Euro VI diesels. Grid decarbonization according to IRP 2019.
Scenario 4 – BEB (IRP 2019)	100% of new buses are BEB. Grid decarbonization according to IRP 2019.

Figure 18 presents the progressive adoption of alternative technologies. In Scenario 1, we assume that all new buses are cleaner Euro VI diesel buses, which provides significant NOx and PM emission reductions. For Scenario 2 and 2B, we assume purchase of CNG buses that are certified to meet Euro VI standards; scenario 2B adds the progressive adoption of biogas and displacement of fossil-based natural gas as an additional GHG mitigation action. In Scenario 3, we assume a combined adoption of Euro VI and BEBs. In this case, the share of BEBs increases over time to reach 100% in 2044, for the last tendering process. Under Scenario 4—the most ambitious scenarios—every new bus entering the LLP fleet would be battery electric.

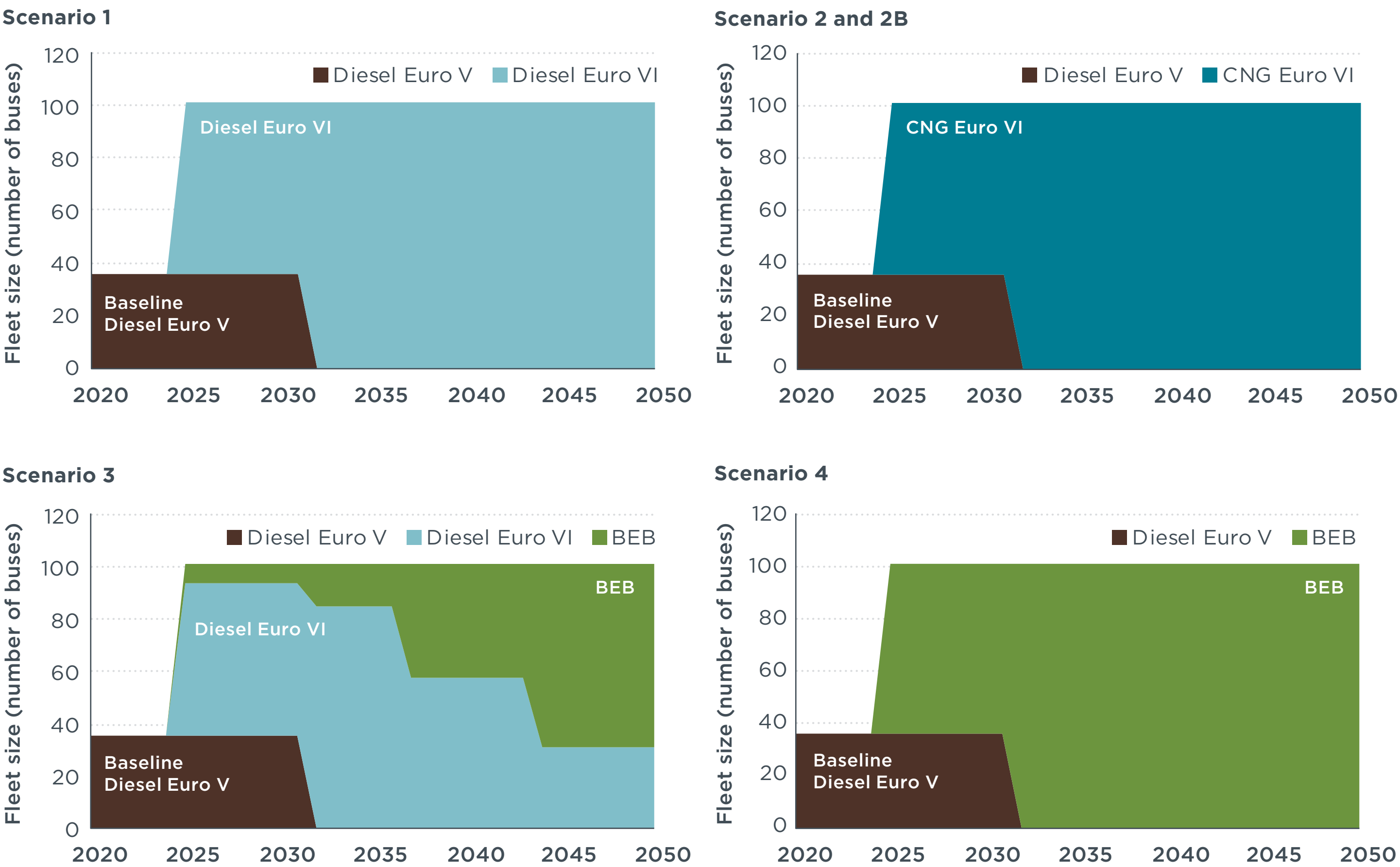

Figure 18. Fleet technology evolution under different bus procurement pathways for estimated fleet growth projections

EMISSIONS MODELING RESULTS

We applied a transit bus emissions model developed by the ICCT 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 68,000 km per year for 12-m buses and 52,000 for 9-m buses in the LLP fleet. Emissions are modeled for the 2020–2040 period, with 2020 as the baseline year for the assessment.

GHG emission projections under each of our scenarios are presented in Figure 19. GHG emissions reflect fuel life-cycle emissions and include both upstream and tailpipe emissions of CO_2, CH_4, and N_2O. We estimate baseline GHG emissions for the LLP fleet to be approximately 5,000 t CO_2e per year in 2020. Under the BAU scenario, GHG emissions grow with the introduction of an additional 60 buses to the fleet in 2025, to 13,500 t CO_2e per year.

The adoption of alternative technologies for new buses in the coming years would generate significant GHG reductions. Under Scenario 1, a transition to cleaner Euro VI buses provides a long-term marginal GHG reduction of only 5% with respect to baseline Euro V technology. A transition to CNG (Scenario 2) offers a range of GHG benefits depending on the fuel used. Fossil-based natural gas offers a 25.6% reduction in GHGs in the long term after 2032, when the last Euro V diesel is removed from the fleet. A phased displacement of fossil-based natural gas by biogas at around 5% per year starting in 2027, as presented under Scenario 2B, can result in GHG reductions of up to 61% with respect to the BAU scenario.

Electrification of the LLP provides the largest long-term GHG benefits as shown in the results for Scenarios 3 and 4. Under Scenario 3, the incremental adoption of BEBs into the LLP fleet would result in a 50% reduction in GHGs after 2045. Achieving the full GHG reduction potential of electric buses would require an accelerated adoption of BEBs for the bus fleet. Under Scenario 4, early acquisition of BEBs would result in the lowest GHG emissions for the fleet as early as 2026. By 2040, emission reductions would reach 63% with respect to BAU, and the long-term benefits would be around 68% compared with the BAU case. The GHG emission values for the 101 buses in 2040 would be 15% lower than current emissions values in 2020 from 37 buses.

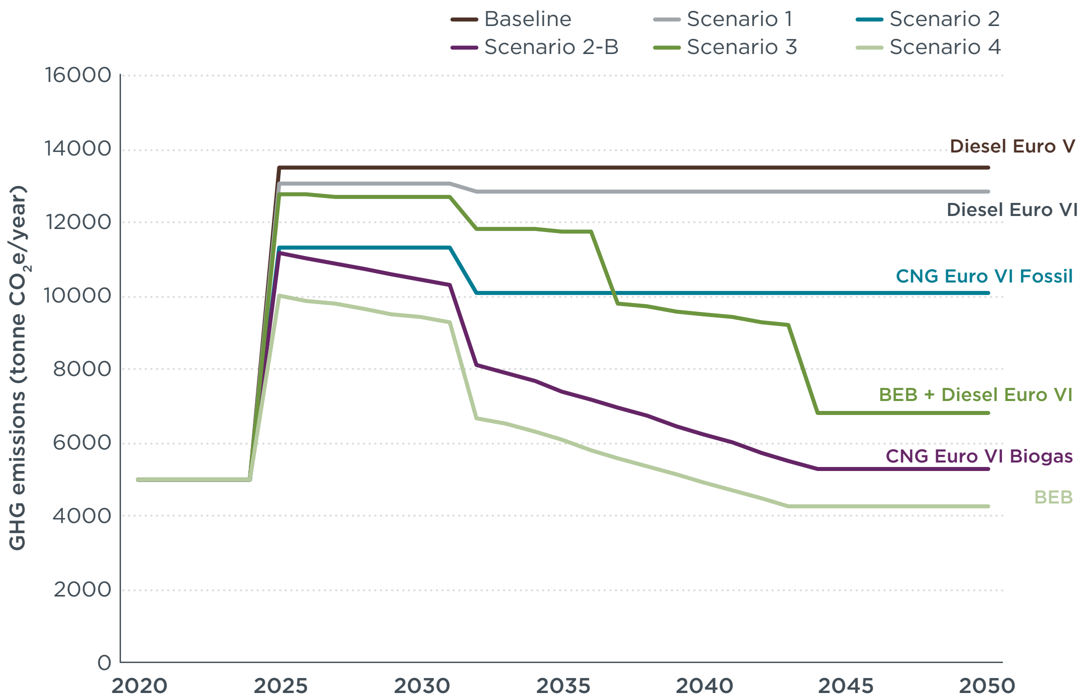

Figure 19. Annual greenhouse gas emission projections under scenarios considered.

We also explored the tailpipe emissions benefits of a transition to soot-free bus technologies for local NOx and PM. Under the BAU scenario, the LLP fleet would increase annual NOx emissions from 19 t per year to 50 t per year after a transition to Phase 1B service numbers (101 buses). Today, LLP buses emit 0.16 t per year of PM , which will nearly triple to 0.45 t per year under Phase 1B operations of increased fleet size. Only a transition to alternative technologies would ensure lower future NOx and PM emissions from the fleet.

Figure 20 presents the benefits of adopting alternative bus technologies for future new bus acquisitions in LLP. The values correspond to the annual contributions of 12-m and 9-m buses operating at their corresponding activity levels. The emissions benefits of a transition to Diesel Euro VI or CNG Euro VI (fossil or biogas) standards illustrated in Scenarios 1, 2, and 2B are very similar. The data show Euro VI technology for diesel and CNG to be a large improvement over Euro V technologies. However, only Scenarios 3 and 4, which present a large share of BEBs, can provide near-zero and zero-emission levels at the tailpipe.

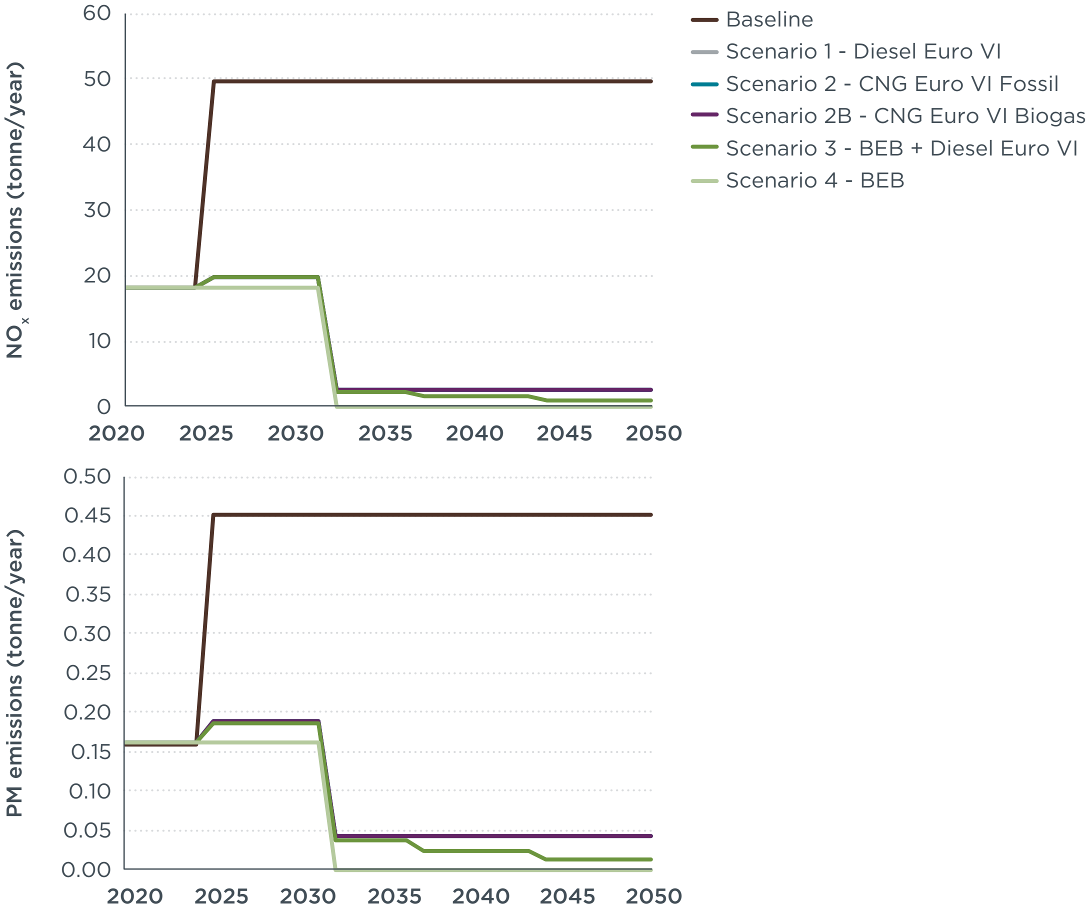

Figure 20. Annual tailpipe emission of NOx and PM from potential Leeto la Polokwane bus technology scenarios.

Table 14 presents cumulative emissions of GHG, NOx, and PM. Alternative technologies provide large benefits over the long term: NOx and PM emissions are greatly reduced in most of the scenarios, driven by the good performance of Euro VI emission control technology. Most benefits double in the 2020–2050 period compared to the 2020–2030 period. In Scenario 4, GHG emissions are reduced by 50% over a 30-year period. CNG with biogas sources provides the second-best GHG reduction. Scenario 2 (fossil CNG) and Scenario 3 (diesel Euro VI buses and BEBs) provide similar GHG emissions reductions in the long term of around 21-23%. The transition to Euro VI diesel provides the fewest GHG benefits of around 4% over the long term.

Table 14. Cumulative emissions and relative benefits with respect the business-as-usual over 10-, 20-, and 30-year evaluation periods.

Emissions	Period	BAU Diesel Euro V	Scenario 1 Diesel Euro VI	Scenario 2 CNG Euro VI	Scenario 2B CNG Euro VI + Biogas	Scenario 3 BEB + Diesel Euro VI	Scenario 4 BEB
GHG (tonne CO_2e)	2020–2030	106028.0	103474.6	92962.8	89795.8	101322.4	83175.7
	2020–2040	241158.0	232102.1	194839.2	164792.9	211582.0	144936.8
	2020–2050	376288.0	360480.1	295440.2	219007.2	287437.7	188421.8
NO_x (tonne)	2020–2030	389.4	210.2	210.2	210.2	209.2	200.4
	2020–2040	886.5	253.6	253.6	253.6	245.9	218.6
	2020–2050	1383.6	279.7	279.7	279.7	255.9	218.6
PM (tonne)	2020–2030	3.5	1.9	1.9	1.9	1.9	1.8
	2020–2040	8.0	2.5	2.5	2.5	2.4	1.9
	2020–2050	12.5	3.0	3.0	3.0	2.6	1.9
Emissions Reductions							
GHG	2020–2030		2.4%	12.3%	15.3%	4.4%	21.6%
	2020–2040		3.8%	19.2%	31.7%	12.3%	39.9%
	2020–2050		4.2%	21.5%	41.8%	23.6%	49.9%
NOx	2020–2030		44.5%	46.0%	46.0%	46.3%	48.5%
	2020–2040		70.1%	71.4%	71.4%	72.3%	75.3%
	2020–2050		77.3%	79.8%	79.8%	81.5%	84.2%
PM	2020–2030		43.7%	44.5%	44.5%	45.0%	49.2%
	2020–2040		65.4%	68.5%	68.5%	70.1%	75.8%
	2020–2050		74.9%	76.4%	76.4%	79.5%	84.5%

TECHNOLOGY POTENTIAL: RISKS AND OPPORTUNITIES

The previous sections in this technology greening roadmap evaluated the environmental benefits and cost implications for each of the available bus technologies as potential options for future bus acquisitions in Polokwane. Given the early stage of the BRT system operation and the uncertainty regarding fleet expansion and availability of alternative fuels in Polokwane or Limpopo, an analysis of risks and opportunities is an appropriate means of informing the technology discussion.

In Table 15, we discuss each of the technology adoption scenarios, highlighting their risks and opportunities for Polokwane. Key variables include fuel and energy availability in present and future plans, as well as cost assumptions in the TCO that greatly impact the results but carry significant uncertainty. We also review electric grid considerations and incorporate feedback and local data from Polokwane authorities to strengthen our analysis.

Table 15. Risks and opportunities in Polokwane, by scenario.

Scenario	Risks	Opportunities
Diesel Euro VI	A transition to Diesel Euro VI presents the fewest risks across alternative technologies. It provides insignificant TCO margins with respect to baseline diesel Euro V technologies. It provides the fewest GHG and pollution reduction benefits. The retrofit of Diesel Particulate Filters (DPFs) to Euro V buses is not recommended in light of the risk of affecting the control of other pollutants, which could lead to higher fuel consumption and GHG emissions.	Diesel Euro VI buses are the least sensitive technology to bus utilization (i.e., activity or vehicle-kilometers traveled [VKT]). If demand is lower than the expected VKT, this technology would have a lower impact on total cost per kilometer traveled than other bus technologies. South Africa's diesel in the market today is a mix of crude oil-refined products and coal to liquids (CTL). Because the lifecycle carbon intensity of CTL diesel is more than twice the carbon intensity of crude oil-derived diesel, a reduction in CTL blends would reduce the overall carbon contribution from Euro VI diesel technologies.
Hybrid Euro VI	Presents the highest TCO and a significant initial purchase price. Environmental benefits are limited, as fuel consumption is reduced by only 25%. Hybrid buses are the most sensitive TCO to bus utilization VKT values. If the operational values are below planned VKT, the TCO increases at a faster rate than other technologies.	Does not require infrastructure changes.
CNG Euro VI	Presents a challenge in the availability of natural gas or biogas. Currently, there is no supply of natural gas from pipelines into Polokwane. Bringing the natural gas via road transport can be done usually via liquified natural gas (LNG) transport, but this requires additional gasification infrastructure and a business model that ensure natural gas demands beyond what the LLP fleet can provide. The TCO values calculated for 12-m and 9-m buses were based on CNG prices from Metrobus in Johannesburg. It is highly unlikely that the prices of CNG in Polokwane would be as low as the CNG prices that Metrobus contracts. A re-evaluation of TCO results for CNG buses would be required once Polokwane identifies a natural gas supplier. Initial purchase price is higher than Diesel Euro VI with similar environmental benefits. GHG reductions are significant if natural gas comes from renewables feedstocks (e.g., waste-based biogas). The price of biogas is uncertain and would require tariff support from local or national government green funding sources.	The main opportunity offered by a transition to CNG bus technology in Polokwane is to incentivize the development of biogas infrastructure and related jobs. The government of South Africa is interested in supporting biogas development as part of the Green Transport Strategy and its commitment to meet national NDC targets (South Africa Department of Transport, 2018).
BEB Euro VI	The higher capital cost of BEBs is one of the main risks in BEB deployments worldwide. TCO evaluations reflect higher upfront costs at low levels of bus operation (i.e., VKT). The grid may lack the reliability and flexibility needed to accommodate the increased load. Access to electricity is limited in Polokwane. According to the 2016 Polokwane Green Goal Energy Strategy Update and Implementation Plan, about 17% of households are not connected to the electric grid. Moreover, according to the city's 2021-2022 Independent Development Plan, there are no current plans to add more power to the grid. Thus, a potential adoption of BEBs would require additional analysis to better understand electricity availability and impacts to the local grid.	BEBs have the most long-term environmental benefits for GHG and local pollution reductions. The higher costs of BEBs today can be addressed in several ways, including adopting procurement practices based on TCO, rather than simply on upfront costs. If the TCO is still prohibitive, some progressive goverments (e.g., China and India) offer direct monetary incentives to public transit projects to reduce upfront costs of BEBs, covering the incremental price gap with respect to diesel technology. In addition, the price of BEBs will decline over time as battery cells and packs fall in price. Thus, LLP could request a review of TCO analysis with updated BEB prices and reevaluate the adoption of electric buses for their Phase 1B rollout. LLP could also plan a pilot project to better evaluate the performance of the technology in local conditions. One opportunity to overcome the challenges related to electric grid reliability and flexibility is to participate in the development of independently produced power. Renewable energy, like photovoltaic generating capacity, could feed the battery charging needs of a potential LLP BEB fleet.

CONCLUSION: THE WAY FORWARD

The LLP bus fleet started service in April 2021 to offer a superior transport alternative to traditional minibus taxis. The bus technology selected to start phase 1A of the BRT service is the best diesel technology currently available in South Africa. At the national level, new vehicle emission standards are set at Euro II, which means that Polokwane, with its Euro V diesel buses, already uses cleaner technologies than most new diesel vehicles entering service in South Africa today.

The new BRT service creates an opportunity for transit authorities and operators in Polokwane to consider new bus technologies that can provide large environmental and economic benefits in the long term. This study presents 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 LLP fleet. The results of the technology potential assessment, emissions modeling, and TCO analysis can be used to inform future procurement decisions by LLP. However, it is up to LLP, Polokwane transit authorities, and other stakeholders to select the desired technology pathway and take meaningful steps toward its implementation. While differences exist in the specific implementation steps for the various fleet renewal scenarios presented in this report, here we provide a general framework applicable to each pathway to guide long-term technology transitions. An example of the conceptual framework to plan and execute a technology transition is presented in Figure 21.

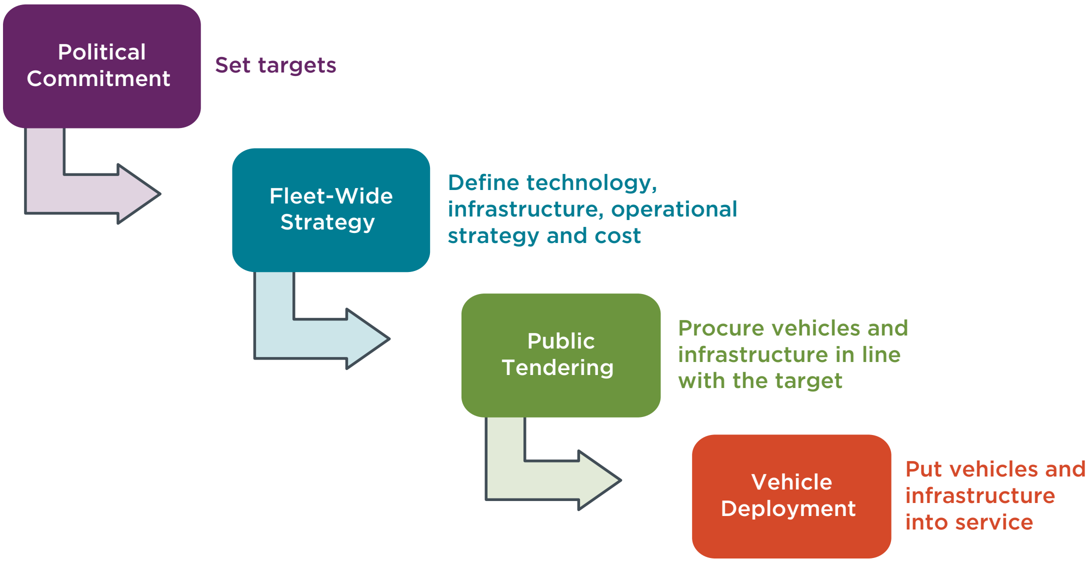

Figure 21. Framework for technology transition in urban bus fleets.

SECURE POLITICAL COMMITMENT AND SET TARGETS

Polokwane's first step is to make 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, as illustrated in case studies from several regions:

» In Los Angeles, California, the mayor's office and board of directors for LA Metro established a target for a zero-emission fleet. This commitment is now guiding LA Metro's long-term technology planning and procurement. Similarly, California has established a goal of achieving a full statewide transition to zero-emission buses by 2040: California expresses its political commitment through the Innovative Clean Transit regulation, which mandates 100% zero-emission bus purchases by 2029 for all transit agencies in the state.

- The city of 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 (AQMP) 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.
- The Climate Change Law of São Paulo, Brazil, as amended in 2018, set 10- and 20-year targets for fleetwide reductions in tailpipe emissions of fossil CO_2, PM, and NOx. Its ultimate aim is to eliminate emissions of fossil fuel-derived CO_2 and reduce emissions of PM and NOx by 95% from 2016 levels by 2038. São Paulo's political commitment takes the form of technology-neutral performance targets for the fleet.

Polokwane can set targets based on a share of alternative technology vehicles over time, or on a percent reduction in GHG or local pollutants. The scenarios discussed here provide an assessment of the benefits that increasing shares of CNG buses or BEBs can provide over time. Thus, a target of alternative bus technology share, or a target of percent reduction of GHG or NOx and PM, can also be designed to drive technology changes.

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

Target 1:	**Reduce fleetwide PM and NO_x emissions to 80% below projected levels by 2035.**
Action 1.1	Require minimum Euro VI emissions certification in all future vehicle procurements.
Action 1.2	Limit sulfur content to a maximum of 10 ppm in new diesel fuel supply contracts.
Target 2:	**Reduce fleetwide life-cycle GHG emissions by 20% 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	For the Phase 1B bus procurement cycle, transition to Euro VI diesel buses immediately and start a transition to BEBs from 10% in Phase 1B procurement. Increase BEB shares in every procurement cycle, with a goal of reaching 100% zero-emission bus purchases by 2040.
Action 3.1.b	For the Phase 1B bus procurement cycle transition to CNG buses, fossil-based natural gas alone would not achieve this target. Achieving Target 3 would require establishing a long-term purchasing agreement to develop and expand biomethane's share of gas supply by at least 5% annually starting in 2027.
Action 3.1.c	Starting with Phase 1B, procure only BEBs.
Target 4:	**Establish a Green Bus Team at Leeto la Polokwane to update the bus procurement process and meet environmental targets.**
Action 4.1	Establish an interdisciplinary green bus team consisting of engineering, planning, public relations, and finance professionals. Seek technical support from independent advisory institutions.

Action 4.2	Grant the interdisciplinary team 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 NO_x 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.

SET A FLEETWIDE STRATEGY

The second step in the technology transition framework is the development of a fleetwide strategy to implement the desired fleet-renewal pathway. Under this step, Polokwane would perform the detailed planning needed to support the transition through technical analyses, operational planning, financial assessment, training schedules, etc. Here is an example of the structure of a fleetwide strategy:

» A goal of a full transition to soot-free buses and low-carbon fuels, including target years for each.

» Identification of the types of soot-free bus technologies and low-carbon fuels the transit agency plans to deploy.

» A schedule for the construction of the facilities and infrastructure modifications or upgrades needed—including for charging, fueling, and maintenance facilities—in order to deploy and maintain soot-free buses. The schedule should specify the general location of each facility, the type of infrastructure, the service capacity of infrastructure, and the timeline of construction. Adoption of electric buses would require the early involvement of electric distribution companies to address any power demand gaps and challenges.

» A schedule for bus procurement. The schedule for bus procurement should identify bus types, fuel types, the emissions standard, and the number of additional buses needed.

» A schedule for the 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.

» A schedule for the deployment of soot-free buses by route and depot, as well as for the retirement of buses by route and depot.

» A training plan and schedule for bus operators and maintenance staff.

» Identification of potential funding sources and their application.

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

UNDERTAKE TENDERING AND DEPLOY BUSES

The final two steps of the implementation framework for Polokwane are to tender and deploy soot-free and low-carbon buses and supporting infrastructure. LLP should carry out tendering following the renewal pathway defined in the fleetwide strategy and international best practices for procuring alternative-technology buses and fuels, such as those developed by the International Association of Public Transport (2020).

IMPLEMENTATION TIMELINES

Implementation timelines depend on the availability of fuel and speed of infrastructure development. The transition to Euro VI presents the lowest challenge for fuel availability, because diesel with 10-ppm sulfur content is available today, according to regional fuel maps (SASOL, 2021). BEBs are second in line for adoption; the electric charging infrastructure can be deployed in 3-4 months. A transition to CNG presents many challenges due to the lack of immediate availability of natural gas in Polokwane.

Near-term actions LLP must perform to implement the Euro VI diesel/zero-emission fleet renewal pathway 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. From an operational perspective, Euro VI diesel buses should present little significant change relative to the diesel buses currently in the LLP fleet, though additional training of maintenance staff would most likely be necessary to ensure adequate performance of aftertreatment control technologies like DPFs.

In the near term, Polokwane will need to conduct more extensive study and planning to support the introduction of BEBs in the LLP fleet. A key near-term step to support a BEB transition is to carry out a pilot project. A trial of one or two buses would be necessary to evaluate the performance of more than one electric bus supplier. For example, depot charging could be demonstrated by more than one supplier, and LLP could evaluate these technologies along low-speed and high-speed routes. This would give LLP staff valuable new experience and capacity regarding the operation, maintenance, cost, and performance of such systems in Polokwane. Results from the pilot study could help 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 proposed fleet renewal pathways. In each case, the strategies should take into account current LLP 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 insight into how financing and business models can support the technology transitions proposed in the fleet renewal roadmap. Figure 22 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 BEBs. Capital expenditures account for a significant portion of the TCO for all three technologies. However, in the case of the BEB, costs for buses and supporting infrastructure account for nearly 59% of total lifetime costs, compared with 32% for the Euro VI diesel option and 41% for the CNG option. The relative capital expenditures for these two combustion technologies are similar to the proportion of total cost from capital expenditures of 30% estimated for Euro V 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 costs of BEBs and charging infrastructure.

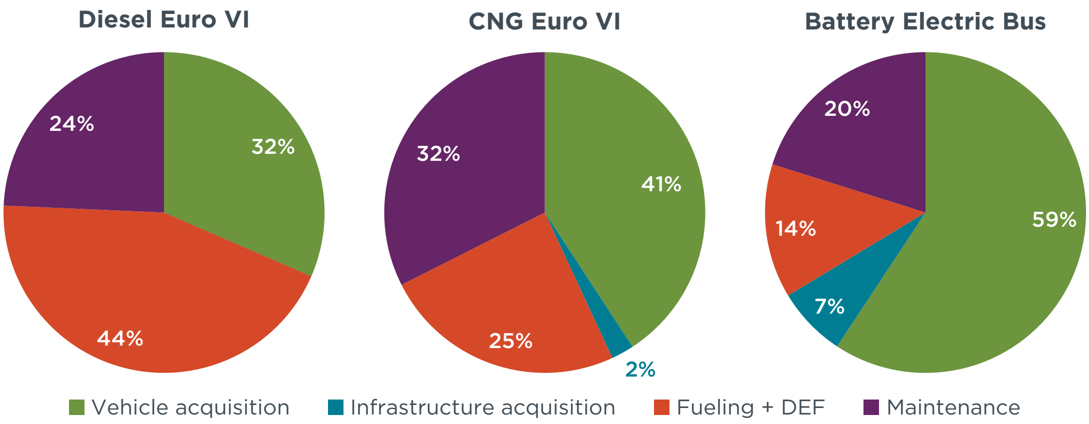

Figure 22. Relative contributions of individual cost components to TCO of Euro VI and zero-emission bus technologies. DEF means diesel emission fluid (urea consumed by the SCR).

CASE STUDIES OF FLEET TECHNOLOGY TRANSTIION

Other municipalities have developed and implemented new business models for procuring and deploying zero-emission buses. In Shenzhen, China, a new business model was developed to support the city's goal of a 100% electric bus fleet (which was achieved in 2018), featuring vehicle leasing, the separation of vehicle and battery costs, and the separate provision of charging infrastructure and maintenance (Zhang, 2019). Government subsidies 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, called the Faster Adoption and Manufacturing of Electric Vehicles (FAME) program, allocates $500 million to introduce 7,000 electric buses in Indian cities. Under the program, 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 dollars per kilometer for a minimum assured number of kilometers per year over a specified contract period. The bidder is then responsible for all expenses related to running the buses over the contract period, including the purchase of vehicles, cost of operation, electricity, drivers, fleet management, charging infrastructure, battery replacement, and vehicle maintenance. A profit margin is included on top of expenses the successful bidder incurs. In the GCC model, the risks associated with the introduction of new vehicle technologies are transferred from the transit authority to the contracted operator.

The city of Santiago, Chile, is considered a case of successful zero-emission bus deployment. As of 2018, the system had 6,756 buses, operated by six different companies on 380 different routes. The city currently has 776 electric buses, the largest electric bus fleet outside of China (Galarza, 2020). All of Santiago's electric buses are Chinese-made: 435 by BYD, 215 by Foton, 100 by Yutong, and 26 by King Long. In 2018, under a new administration, Santiago undertook a major revamping of its public transit system that split the ownership and operation of assets by separating fleet suppliers and bus operators and giving the transport authority management of depots. The revamped process also established Euro VI buses as a minimum emission standard and offered operating incentives for electric buses: Fleet suppliers can secure fleet contracts for 14 years for electric buses, compared to 10 years for ICE buses. Operators, who will lease buses from suppliers, will be granted 5-year contracts with potential extensions of up to five additional years based on performance. If the base operational fleet of these operators is more than

50% electric, contracts are granted for 7 years and are extendable for another 7 years, depending on performance.

Additional means of optimizing the cost of new technologies exist. 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.

REFERENCES

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., ... & Hamburg, S. P. (2018). Assessment of methane emissions from the U.S. oil and gas supply chain. *Science, 361*, 186–188. doi:10.1126/science.aar7204

Anenberg, S., Miller, J., Minjares, R., Du, L., Henze, D. K., Lacey, F., ... Heyes, C. (2017). Impacts and mitigation of excess diesel-related NOx emissions in 11 major vehicle markets. *Nature*, *545*, 467–471. doi:10.1038/nature22086

Asian Development Bank. (2018). *Sustainable transport solutions: Low-carbon buses in the People's Republic of China*. Retrieved from https://www.adb.org/publications/sustainable-transport-solutions-peoples-republic-china

Argonne National Laboratory. (2018). AFLEET Tool 2018. Retrieved from https://greet.es.anl.gov/afleet_tool

Bloomberg New Energy Finance. (2020). Battery Pack Prices Cited Below $100/kWh for the first time in 2020. Retrieved from https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/

California Air Resources Board (CARB). (2017). *Fifth Innovative Clean Transit Workgroup meeting: Cost data and sources (6-26-2017).* Retrieved from https://arb.ca.gov/msprog/ict/meeting.htm

California Air Resources Board (CARB). (2018). *Low income barriers study, part B: Overcoming barriers to clean transportation access for low-income residents*. Retrieved from https://www.arb.ca.gov/msprog/transoptions/sb350_final_guidance_document_022118.pdf

California Air Resources Board. (2019). *Carbon intensity values of current certified pathways.* Retrieved from https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm

Castillo, M., Galarza, S., López, G., Cádiz, A., & Nilo, F. (2018). *Sustainable bus system (phase 1)*. International Energy Agency Advanced Motor Fuels Technology Collaboration Programme Annex 53-1. Retrieved from https://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_53-1.pdf

Cidade de São Paulo. (2018). Diário Oficial Número 12, Lei N° 16.802. Retrieved from http://www.camara.sp.gov.br/wp-content/uploads/2018/01/dom_capa.pdf

Dallmann, T. (2019). *Climate and air pollutant emissions benefits of bus technology options in São Paulo*. Retrieved from the International Council on Clean Transportation, https://www.theicct.org/publications/climate-and-air-pollutant-emissions-benefits-bus-technology-options-sao-paulo

Dallmann, T., Bernard, Y., Tietge, U., & Muncrief, R. (2018). *Remote sensing of motor vehicle emissions in London*. Retrieved from the International Council on Clean Transportation, http://theicct.org/publications/true-london-dec2018

Dallmann, T., Du, L., & Minjares, R. (2017). *Low-carbon technology pathways for soot-free urban bus fleets in 20 megacities*. Retrieved from the International Council on Clean Transportation, https://www.theicct.org/publications/low-carbon-technology-pathways-soot-free-urban-bus-fleets-20-megacities

Elgowainy, A., Han, J., Ward, J., Joseck, F., Gohlke, D., Lindauer, A., ... & Sutherland, I. (2016). *Cradle-to-grave lifecycle analysis of U.S. light duty vehicle-fuel pathways: A greenhouse gas emissions and economic assessment of current (2015) and future (2025-2030) technologies* No. ANL/ESD-16/7. Argonne National Lab. Retrieved from https://greet.es.anl.gov/files/c2g-2016-report

Galarza, Sebastián. (June 2020). From Pilots to Scale: Lessons from Electric Bus Deployments in Santiago de Chile. Centro Mario Molina Chile. https://www.c40knowledgehub.org/s/article/From-Pilots-to-Scale-Lessons-from-Electric-Bus-Deployments-in-Santiago-de-Chile?language=en_US

Grutter, J. M. (2014). *Real world performance of hybrid and electric buses*. Grutter Consulting. Retrieved from http://slocat.net/sites/default/files/u10/report_hybrid_and_electric_buses.pdf

Handbook emission factors for road transport (HBFEA) (2019). Version 4.1. Retreived from: www.hbefa.net

International Energy Agency. (2018). Statistics. http://www.iea.org/statistics/

International Association of Public Transport. (2020). Bus Tender Structure Report 2020. Retrieved from https://www.uitp.org/publications/bus-tender-structure-report-2020/

IQAir (2021). IQAir.com

Lajunen, A., & Lipman, T. (2016). Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy, 106*, 329–342, doi:10.1016/j.energy.2016.03.075

Limpopo Provincial Government (2013). Limpopo Green Economy Plan Including Provincial Climate Change Response. Department of Economic Development, Environment and Tourism. Retrieved from: https://www.environment.gov.za/sites/default/files/docs/limpopogreen_economyplan.pdf

Limpopo Provincial Government (2016). Limpopo provincial climate change response strategy 2016-2020. Retrieved from: http://policyresearch.limpopo.gov.za/bitstream/handle/123456789/1251/Limpopo_Climate_Change_Response_Strategy__2016_2020_Final_%284%29.pdf?sequence=1

Miller, J., Minjares, R., Dallmann, T., & Jin, L. (2017). *Financing the transition to soot-free urban bus fleets in 20 megacities*. Retrieved from the International Council on Clean Transportation, https://www.theicct.org/publications/financing-transition-soot-free-urban-bus-fleets-20-megacities

Miller, J., Jin, L., (2019). Global progress toward soot-free diesel vehicles in 2019. Retrieved from https://theicct.org/publications/global-progress-toward-soot-free-diesel-vehicles-2019

SASOL (2021). 10ppm Diesel. Store Locator. https://locator.sasol.com/#/

Searle, S., & Bitnere, K. (2018). *Compatibility of mid-level biodiesel blends in vehicles in Indonesia*. Retrieved from the International Council on Clean Transportation, https://theicct.org/publications/compatibility-mid-level-biodiesel-blends-vehicles-indonesia

Slowik, P., Araujo, C., Dallmann, T., & Façanha, C. (2018). *International evaluation of public policies for electromobility in urban fleets*. International Council on Clean Transportation and Gesellschaft für International Zusammenarbeit. Retrieved from https://www.theicct.org/publications/international-evaluation-public-policies-electromobility-urban-fleets

South Africa Department of Environmental Affairs. (2014). South Africa's greenhouse gas (GHG) mitigation potential analysis. Retrieved from: https://www.environment.gov.za/sites/default/files/docs/mitigationreport.pdf

South Africa Department of Forestry, Fisheries and the Environment (DFFE). (2014). South Africa's greenhouse gas (GHG) mitigation potential analysis. Retrieved from https://www.environment.gov.za/sites/default/files/docs/mitigationreport.pdf

South Africa Department of Forestry, Fisheries and the Environment (DFFE). (n.d) National Climate Change Response Strategy. Retreived from: https://www.environment.gov.za/sites/default/files/legislations/national_climatechange_response_whitepaper.pdf

South Africa Department of Mineral Resources and Energy (DMRE). (2018). Integrated Resource Plan 2018. Retrieved from http://www.energy.gov.za/IRP/irp-update-draft-report2018/IRP-Update-2018-Draft-for-Comments.pdf

South Africa Department of Trade & Industry (DTI). (2011). Industrial Procurement 2011. Retrieved from http://www.dti.gov.za/industrial_development/ip.jsp

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