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Low-carbon technology pathways for soot-free urban bus fleets in 20 megacities

Authors: Tim Dallmann, Li Du, and Ray Minjares

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Introduction

The year 2016 was the hottest on record. Although cumulative carbon dioxide emissions since the pre-industrial period are the most significant contributor to this warming, the short-lived climate pollutants emitted today—in particular, diesel black carbon—will also contribute to the warming we will experience in our own lifetimes. In fact, researchers estimate that up to 0.5 degrees of the warming that is expected over the next 25 years could be avoided by a 75% reduction in black carbon emissions alongside a 25% reduction in methane emissions and the elimination of hydrofluorocarbon emissions globally.[1] Achieving this will require investments in the transportation fleet to effectively eliminate diesel black carbon emissions.

Between 60% and 80% of uncontrolled diesel exhaust is black carbon, a harmful ultrafine particle that can operate as a universal carrier of toxins to the lungs and the bloodstream. As a short-lived climate pollutant, black carbon can cause over 3,000 times as much warming as an equivalent amount of carbon dioxide over a brief 20-year period. The Diesel Initiative of the Climate and Clean Air Coalition seeks to address these harmful impacts in cities by advising bus operators and city officials on the adoption and implementation of minimum "soot-free" emissions performance requirements for new bus purchases.

The definition of soot-free technology comes from the findings of a 2011 report by the UN Environment Programme, which found that installation of diesel particulate filters as part of a Euro 6/VI emission-control package for on-road diesel engines was among 16 win-win measures to control both the health and climate impacts of diesel black carbon.[2] Soot-free bus technology can include any bus engine that meets minimum Euro VI or US 2010 emission levels, including those powered by diesel, biodiesel, compressed natural gas, biogas, or even zero-emission battery electric engines. These technologies achieve up to a 99% reduction in black carbon emissions compared with pre-Euro VI diesel engine technology, effectively achieving soot-free emissions performance.

Approximately 20% of all new coach and transit buses sold today meet this definition of soot-free, according to 2014 data. They include buses sold in countries where national laws require soot-free emissions performance from new buses: Canada, the European Union, Iran, Japan, South Korea, Turkey, and the United States. India has adopted Euro VI emission norms to be implemented in 2020, and China has committed to implement these standards the same year. National proposals are also under development in Australia, Brazil, Mexico, and Thailand. If these proposals are adopted, then 55% of the global bus market will be soot-free by 2020.

This trend is promising, but more than 40% of the global population will not benefit. The problem will be particularly acute in the world's largest megacities, which will suffer from urban air pollution as population and economic growth rates increase. These include cities outside those countries named above, including Dhaka, Jakarta, Johannesburg, Lagos, Manila, and others. Some, like Mexico City, have announced diesel bans, a reaction to the delayed introduction by manufacturers of Euro VI engines that may have further contributed to negative perceptions of diesel technology. These and other megacities are looking for alternative

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[1] Drew Shindell et al. (2017). A climate policy pathway for near- and long-term benefits. *Science,* 356(6337), 493–494. doi:10.1126/science.aak9521

[2] United Nations Environment Programme and World Meteorological Organization. (2011). Integrated assessment of black carbon and tropospheric ozone. Retrieved from https://wedocs.unep.org/handle/20.500.11822/19899?show=full

technology pathways to deliver clean air and a sustainable transport system.

In most cities, an immediate shift to soot-free technology will require procurement of a Euro VI diesel engine. But alternative technology pathways over the long term can generate even greater climate benefits. For example, the rapid emergence of commercially available electric buses, which produce zero tailpipe emissions and can utilize near-zero carbon electricity, raises the question of whether all fleets should begin now to transition to electric. The adoption of the COP21 Paris climate accord and national commitments further emphasizes the importance of considering near-term steps like these.

But electric buses are not the only low-carbon technology pathway. And in some countries with high amounts of coal-based electric power, it is not clear at the start whether electric buses are the universally preferred option. There is a range of soot-free technology choices that present large differences in lifecycle greenhouse gas emissions, and this study aims to quantify these differences. This information is necessary to inform transitions that will be needed in 20 megacities to achieve soot-free emissions performance. Fleet operators can use this information to determine whether a shift away from diesel engines is justified and to understand where zero-emission electric drive technology is the preferred alternative.

Methodology

This analysis evaluates well-to-wheel (WTW) greenhouse gas (GHG) emissions from commercially available soot-free urban transit buses. The WTW framework applied here considers both direct emissions from fuel combustion, as well as upstream emissions from fuel production and transport. Bus types are shown in Table 1 and include diesel, diesel-electric hybrid, and compressed natural gas (CNG) buses powered by engines certified to Euro VI or EPA 2010 emission standards, as well as battery electric buses. For diesel and CNG buses, GHG emissions are calculated for conventional fossil fuels, as well as select biofuel alternatives. This is not a comprehensive list of soot-free transit bus technologies, but it focuses on the most common powertrain and fuel combinations in use today.

Table 1. Overview of powertrain and fuels considered in the GHG emissions assessment

Engine/Powertrain	Fuel	Fuel feedstock
Diesel	Ultra-low sulfur diesel (ULSD – 10ppm S)	Petroleum (U.S. average consumption mix)
	Biodiesel (B100)*	Animal fats
	Biodiesel (B100)*	Plant oils (e.g., soybean oil, canola oil)
	Biodiesel (B100)*	Palm oil
Diesel-electric hybrid	ULSD	Petroleum
Compressed natural gas (CNG)	Fossil CNG	
	Bio-CNG	Landfill or digester gas
	Bio-CNG	Maize silage
Battery electric	National grid electricity mix for year 2014	

**All results for biodiesel-fueled buses assume a 100% biodiesel blend ratio (B100).*

The main objectives of this analysis are to investigate:

1. How WTW GHG emissions vary across soot-free transit bus powertrain and fuel options,
2. The impact of driving cycle on WTW GHG emissions from transit buses, and
3. The influence of electricity generation source mix on WTW GHG emissions from battery electric buses.

To address these objectives, we evaluated WTW GHG emissions (E_{GHG}; gCO_2e/km) for each bus type using the following equation:

$$E_{GHG} = EC_{bus} \times CI_{fuel} \quad \textbf{(1)}$$

where EC_{bus} represents the energy consumption of a given bus type (kWh/km), and CI_{fuel} is the fuel carbon intensity (gCO_2e/kWh).

Energy consumption reflects the amount of energy required to move a bus a unit distance, as well as energy required to power auxiliary loads, such as air conditioning and lighting. For buses powered by internal combustion engines, energy consumption is directly proportional to fuel consumption. Energy consumption was evaluated for each bus type over a range of driving cycles/route types.

In the WTW framework used here, the fuel carbon intensity metric is a measure of the GHGs emitted directly through the combustion of fuels in bus engines, as well as upstream emissions resulting from fuel and feedstock production and transport. This framework allows for a more equal comparison among the different powertrain and fuel options than if only tailpipe emissions were considered.

For example, battery electric buses do not emit any tailpipe GHGs; however, emissions from the production, transmission, and distribution of electricity used to charge the batteries that provide power for the bus are important to account for in any assessment of the environmental impacts of a shift to this bus technology. For carbon intensity values used in this analysis, GHGs include carbon dioxide, nitrous oxide, and methane; 100-year global warming–potential (GWP) values are used for conversion to CO_2e units. Although 20-year GWP values were not applied to carbon intensity, their application would have emphasized the much larger near-term climate impacts of pollutants like methane.

A key focus of this analysis is to investigate how the electricity generation source mix in a given location influences WTW GHG emissions from battery electric buses. To this end, we have evaluated emissions for electric buses in 20 cities, with varying electricity grid source mixes. The cities included in this analysis are listed in Figure 1, along with estimates of the total transit bus fleet size for each city. The cities are predominately located in Africa, South America, and Southeast Asia, and nearly all (19 out of 20) are located in countries with national heavy-duty vehicle emission standards that today are less stringent than the Euro VI or EPA 2010 standards. Thus, transit bus fleets in these cities are a significant target for air pollutant emissions reductions through a shift to soot-free technologies. This analysis will provide fleet operators in each of these cities with information on how WTW GHG emissions from battery electric buses compare to those from other soot-free bus options.

A detailed description of data sources and analysis methods for the determination of energy consumption and carbon intensity values for each bus and fuel type, respectively, is included in the following sections.

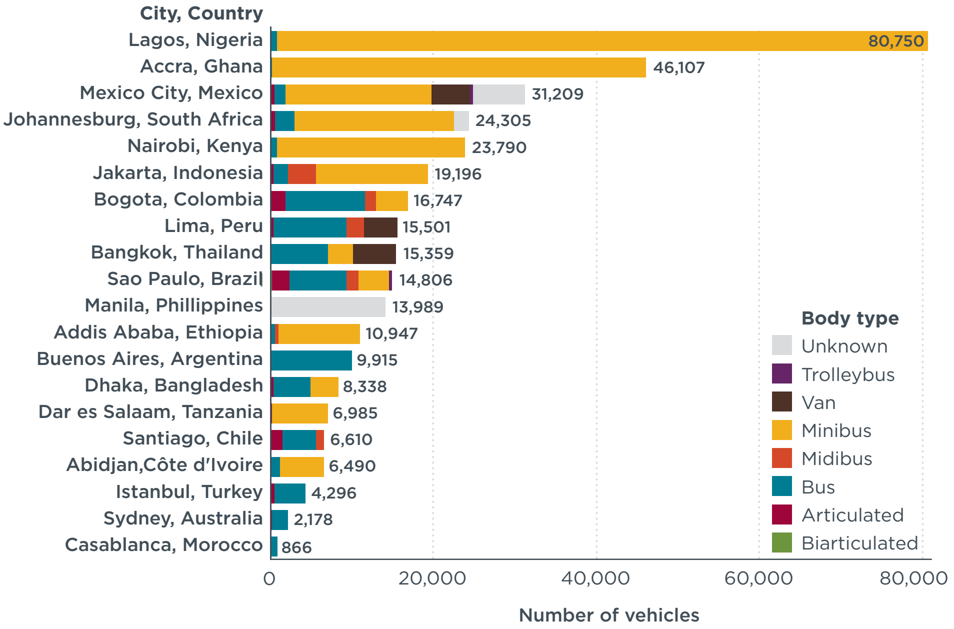

Figure 1. Target cities and transit fleet sizes.[3]

Energy Consumption of Soot-Free Buses

Energy consumption is one of the key parameters in determining GHG emissions from transit buses. Energy consumption depends on a number of factors, including bus type, driveline configuration, curb weight, powertrain technology, driving cycle, passenger loading, and auxiliary power demands.[4] In this analysis, we are primarily interested in investigating the influence of two of these parameters—bus powertrain technology and driving cycle—on energy consumption.

Our primary source of energy consumption data is the Altoona Bus Research and Testing Center (ABRTC) bus testing database.[5] In the United States, federal funding for new bus purchases is available to transit operators through the Federal Transit Administration (FTA). The use of these FTA funds is restricted to bus models that have undergone standardized safety and performance testing at the ABRTC. As a result, more than 400 buses have been tested at the ABRTC since the program's inception in 1987. Detailed test results for each bus are made available to the public through the ABRTC website, providing transit agencies with an important source of information to compare bus models and support procurement decisions.

For the purpose of this analysis, relevant tests conducted during the Altoona test program include an on-road fuel economy evaluation, as well as chassis dynamometer–based testing of tailpipe emissions over

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[3] Lingzhi Jin, Ray Minjares, Josh Miller. (2017). Urban bus database. Washington, D.C.: The International Council on Clean Transportation.

[4] Antonius Kies et al. (2013). Options to consider future advanced fuel-saving technologies in the CO_2 test procedure for HDV (FTV: Graz AUT). Retrieved from http://www.theicct.org/sites/default/files/publications/2013-12-19_ICCT-HDV-FuelSaving_FINAL.pdf

[5] The Altoona Bus Research and Testing Center. (2017). http://altoonabustest.psu.edu/

three standardized driving cycles. Each of these tests provide data on the energy consumption of transit buses. Advantages of the Altoona test database include (1) the use of a consistent test methodology for all bus types, (2) availability of test results for each of the four powertrain types considered for this analysis, and (3) energy consumption data for a broad range of operating conditions. Although there are many other sources of information on transit bus energy consumption, we are not aware of a similarly robust, publically available dataset where each of the technologies considered here are evaluated using a common test protocol.

To investigate energy consumption for soot-free transit buses, we retrieved and analyzed test reports for all model year 2010 and newer 12-m transit buses tested at the ABRTC.[6] These buses are all compliant with EPA 2010 emission standards and, as such, are expected to be representative of soot-free buses available today. In total, this dataset includes test results for 5 diesel buses, 7 CNG buses, 3 diesel-electric hybrid buses, and 5 battery electric buses. Reported fuel consumption values for CNG, diesel, and diesel-electric hybrid buses were converted to energy consumption using the lower heating value of CNG and diesel fuels.[7] Energy consumption is reported directly for battery electric buses in Altoona reports.

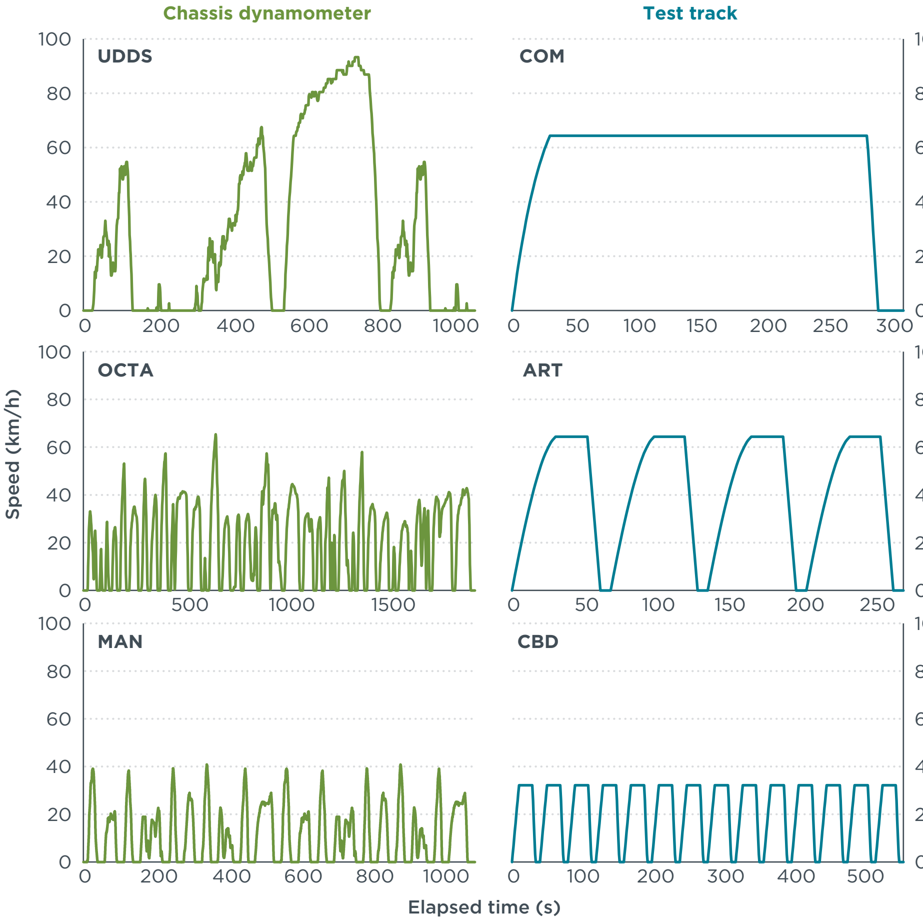

Figure 2. Speed-time traces for Altoona test program driving cycles.[9]

Two separate tests performed during the Altoona program provide information on the energy consumption of transit buses. The first is an on-road fuel consumption test, which follows a procedure based on the Fuel Economy Measurement Test (Engineering Type) for Trucks and Buses developed by the Society of Automotive Engineers.[8] This test is performed on a test track, where buses are operated over three distinct phases, representative of different transit bus operating cycles or routes types: commuter (COM), arterial (ART), and central business district (CBD). Average fuel consumption values are reported for each phase. Speed-time traces for each of these phases are shown in the right-hand panel of Figure 2.

Energy consumption data are also obtained from chassis dynamometer emissions testing conducted during the Altoona program. In this case, tailpipe emissions and fuel economy are measured as buses are operated on a chassis dynamometer over three separate driving cycles: the Manhattan cycle (MAN) representing low-speed transit bus operation, the

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[6] Information on each bus model included in this analysis can be found in the Appendix. A similar analysis of Altoona test results was previously conducted by M.J. Bradley & Associates [M.J. Bradley & Associates. (2013). Comparison of modern CNG, diesel, and diesel hybrid-electric transit buses: Efficiency and environmental performance. Retrieved from http://www.mjbradley.com/node/241]. Our work builds on this analysis through the inclusion of battery electric buses and additional test data for other powertrains.

[7] Lower heating values of 923 BTU/scf and 128,488 BTU/gal for CNG and diesel fuel, respectively, were assumed (www.afdc.energy.gov/fuels/fuel_properties.php).

[8] Society of Automotive Engineers. (1997). Fuel economy measurement test (engineering type) for trucks and buses. Standard J1376_199712.

[9] Dieselnet. (2017). https://www.dieselnet.com/standards/cycles/

Orange County Transit Authority cycle (OCTA) representing intermediate-speed bus operation, and the Urban Dynamometer Driving Schedule (UDDS) representing high-speed operation for buses. Speed-time traces for each of these driving cycles are shown in the left-hand panel of Figure 2.[10] It should be noted that, to date, battery electric buses have not been subject to dynamometer testing during the Altoona test program.

Table 2. Characteristics of urban bus driving cycles affecting energy consumption.

Cycle type	Cycle	Average speed (km/h)	Stops per km	Percentage idle (%)	Kinetic intensity (km^{-1})
Low kinetic intensity (Commuter/suburban)	COM	57	0.2	12	0.1
	UDDS	30	1.8	33	0.4
	ART	40	1.2	16	0.8
Medium kinetic intensity (Medium-speed urban)	OCTA	19	2.9	22	2.2
	CBD	20	4.3	21	2.5
High kinetic intensity (Low-speed urban)	MAN	11	6.0	37	5.7

The range of driving cycles used in the Altoona test program allows for investigation of how energy consumption varies as a function of bus driving conditions or route type. Key characteristics for each of the driving cycles used during test track and chassis dynamometer testing are shown in Table 2. These cycle characteristics have been found to have a strong effect on fuel consumption and include average speed, stops per kilometer, percentage idle, and kinetic intensity.[11] Whereas the other parameters are straightforward, kinetic intensity may be less familiar. Kinetic intensity is a metric that was developed to compare different driving cycles on an energy basis and specifically to identify those duty cycles where hybridization would offer the greatest fuel savings benefits for heavy-duty vehicles.[12] Kinetic intensity is calculated as the ratio of the driving cycle's characteristic acceleration to the square of the cycle's aerodynamic speed—parameters that characterize the inertial work required to accelerate and/or raise the vehicle and the impacts of aerodynamics on vehicle fuel usage, respectively. 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.

Altoona driving cycles are grouped according to kinetic intensity in Table 2. In general, the cycles align into three distinct kinetic intensity classes. Low kinetic cycles (<1 km^{-1}) include the COM, UDDS, and ART cycles and are characterized by higher average speeds and a limited number of stops per kilometer. These cycles are most representative of commuter or suburban bus routes. Medium kinetic intensity cycles (2–3 km^{-1}) include the OCTA and CBD cycles and tend to have lower average speeds than the low kinetic intensity cycles and more stops per kilometer. These conditions are more typical of medium-speed urban routes, such as segregated bus rapid transit (BRT) corridors. Finally, high kinetic intensity cycles (>5 km^{-1}), represented in this dataset by the MAN cycle, are characterized by low speeds and frequent stops—conditions representative of congested urban driving.

Energy consumption results for soot-free transit bus types tested at the ABRTC are shown in Figure 3. Results are averaged by powertrain and driving cycle and are presented from left to right in order of increasing test-cycle kinetic intensity. For conventional diesel and CNG buses, energy consumption is lowest for low kinetic intensity cycles and tends to increase considerably with increasing cycle kinetic intensity. For these bus types, energy consumption over the MAN cycle is more than a factor of two greater than over the COM cycle. This result means a diesel or CNG bus operating in low-speed, stop-and-go conditions would use more than twice as much fuel per kilometer driven as the same bus would if operated in the higher speed, cruise conditions represented by the COM cycle. At low kinetic energy cycles, energy consumption for diesel and CNG buses is, on average, similar, although these data indicate that CNG buses tend to perform relatively worse over test cycles with higher kinetic intensities. The average energy consumption for CNG buses is about 10% and 20% greater than for diesel buses over medium and high kinetic intensity cycles, respectively.

For the diesel-electric hybrid buses included in the Altoona dataset, there is no significant difference in energy

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[10] Test track and chassis dynamometer testing is conducted with the following conditions: air conditioning off, evaporator fan or ventilation fan on, exterior and interior lights on, heater pump motor off, defroster off, and windows and doors closed. Test track testing is conducted at seated load weight, while chassis dynamometer testing is conducted at one half seated load weight.

[11] Tu, J., Wayne, S. W., Perhinschi, M. G. (2013). Correlation analysis of duty cycle effects on exhaust emissions and fuel economy. *Journal of the Transportation Research Forum,* 52, 1.

[12] O'Keefe, M. P., Simpson, A., Kelly, K., Pedersen, D. (2007). Duty cycle characterization and evaluation towards heavy hybrid applications. SAE Technical Paper 2007-01-0302. doi:10.4271/2007-01-0302

consumption relative to diesel and CNG buses for low kinetic intensity cycles. In fact, average energy consumption for hybrid buses is slightly higher than for diesel buses over the COM and UDDS cycles. These data suggest there are little to no fuel savings benefits for hybrid buses under high-speed suburban operating conditions. The efficiency benefits of hybridization, however, are clear for driving cycles with higher kinetic intensities. On average, energy consumption for hybrid buses is about 20% lower than for conventional diesel buses over medium and high kinetic intensity driving cycles. This dynamic reflects, in part, efficiency benefits of regenerative braking systems employed in hybrid buses, which recover energy that would otherwise be dissipated during braking events. The benefits of these systems are maximized over routes with many starts and stops. Compared to diesel and CNG buses, hybrid bus energy consumption is less sensitive to the cycle kinetic intensity, with only a 60% difference between the highest (MAN) and lowest (COM) cycle-average energy consumption values.

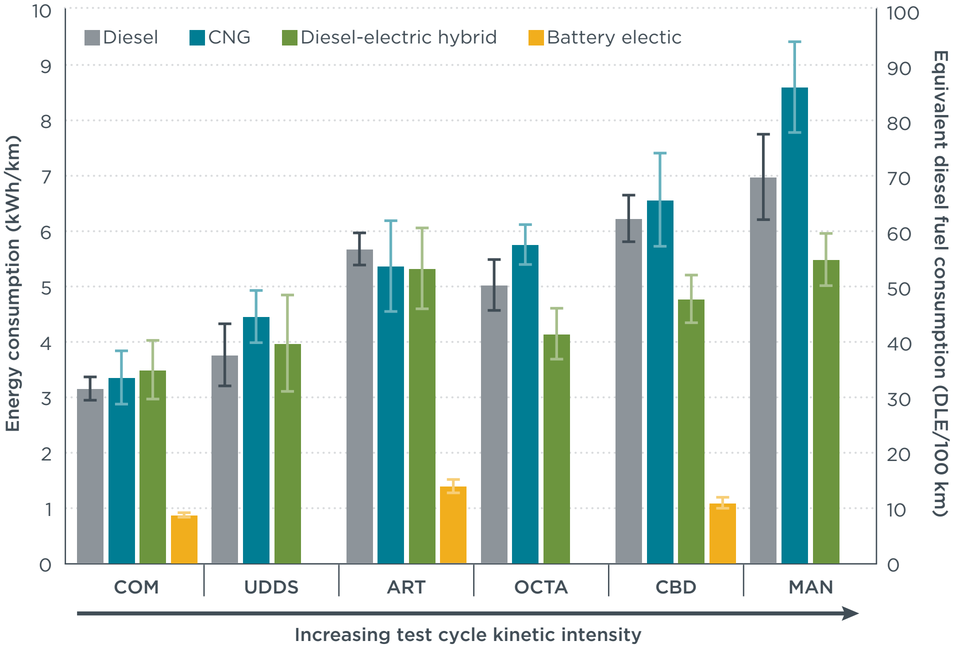

Figure 3. Average energy consumption by powertrain type and test driving cycle for 2010 and newer model year buses tested at the Altoona Bus Research and Testing Center. The right axis shows fuel consumption in terms of the energy equivalent of a liter of diesel fuel, referred to as diesel liter equivalent (DLE). Uncertainty bars show the standard deviation of average energy consumption values.

Battery electric buses tested at the ABRTC show significant efficiency advantages relative to diesel, CNG, and hybrid counterparts. In the Altoona program, battery electric buses are only subject to test track evaluations, and data are available for the COM, ART, and CBD cycles. For these test cycles, battery electric buses use between 70% and 80% less energy per kilometer than do conventional diesel buses. Reasons for the improved efficiency of battery electric buses include the use of regenerative braking systems, significantly less waste heat generation, more efficient motors, and more efficient transmissions.[13] The Altoona test results for battery electric bus energy consumption are in general agreement with recent data published from real-world assessments of electric bus performance. For example, the National Renewable Energy Laboratory has performed evaluations of initial deployments of battery electric buses in the United States. They report an average energy consumption of 1.34 kWh/km for a fleet of 12 electric buses operated by Foothill Transit[14] and of 1.40 kWh/km for a fleet of 3 buses operated by King County Metro.[15] Together, these data represent over 1.5 million kilometers of accumulated mileage for the battery electric buses. A similar evaluation of battery electric bus performance was performed by Grütter Consulting for a fleet of 10 buses operating in Zhengzhou, China.[16] An average energy consumption of 1.00 kWh/km was reported for the 3-year evaluation period. These results are in line with the range of energy consumption values derived from the Altoona dataset and lend support to the selection of Altoona data as the foundation for this assessment of battery electric bus energy consumption.

Energy consumption results for each soot-free bus type are summarized in Figure 4. While not exhaustive, these data give a good indication of the range of energy consumption that can be expected of different transit bus powertrain types. The sensitivity of bus energy consumption to

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[13] California Air Resources Board. (2015). Draft technology assessment: Medium- and heavy-duty battery electric trucks and buses. Retrieved from https://www.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf

[14] Eudy, L., Jeffers, M. (2017). Foothill transit battery electric bus demonstration results: Second reports. National Renewable Energy Laboratory Technical Report NREL/TP-5400-67698. Retrieved from http://www.nrel.gov/docs/fy17osti/67698.pdf

[15] National Renewable Energy Laboratory. (2017). King County Metro battery electric bus demonstration – preliminary project results. Report No. NREL/BR-5400-68412. Retrieved from https://www.afdc.energy.gov/uploads/publication/king_county_be_bus_preliminary.pdf

[16] Grütter, J. (2015). Real world performance of hybrid and electric buses. Grütter Consulting. Retrieved from http://www.repic.ch/files/7114/4126/7442/Grutter_FinalReport_e_web.pdf

operating conditions highlights the importance of evaluating a range of expected conditions in any comparative assessment of bus technologies. This is particularly true in the case of diesel and CNG buses, whose energy consumption shows the most sensitivity to driving cycle.

For the assessment of GHG emissions from soot-free transit buses, we have aggregated Altoona energy consumption data into three separate groups for each bus type, representative of typical transit bus operating conditions or route types: commuter/suburban, medium-speed urban, and low-speed urban. WTW GHG emissions are evaluated separately for each route type. Energy consumption values applied for each representative operating condition/route type are shown in Table 3. These values were estimated by averaging energy consumption values over low kinetic intensity cycles for commuter/suburban operations (COM, UDDS, ART),[17] medium kinetic intensity cycles for medium-speed urban operations (OCTA, CBD), and the high kinetic intensity MAN cycle for low-speed urban operations. For battery electric buses, which are not tested over a high kinetic intensity cycle in the Altoona program, the low-speed urban energy consumption value is derived from recent modeling assessments of battery electric bus performance.[18,19]

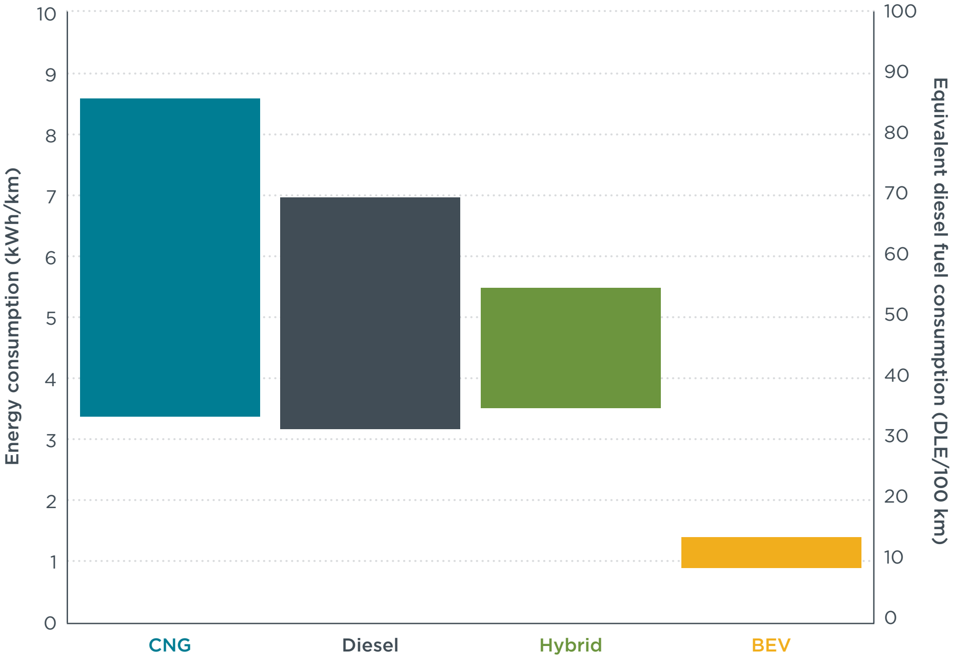

Figure 4. Range of average energy consumption values measured in the Altoona test program by powertrain type.

Table 3. Energy consumption values used for GHG emissions modeling (kWh/km / DLE/100km)

	Commuter/ suburban operation	Medium-speed urban operation	Low-speed urban operation
Diesel	4.2 / 42	5.6 / 56	7.0 / 70
Diesel-electric hybrid	4.3 / 43	4.5 / 45	5.5 / 55
CNG	4.4 / 44	6.2 / 62	8.6 / 86
Battery electric*	1.4 / 14	1.4 / 14	1.9 / 19

**Battery electric bus energy consumption values reported here reflect an assumed 90% charger efficiency and 90% battery charge/discharge efficiency.*[20]

Carbon Intensity of Enabling Fuels

In the framework used here, fuel carbon intensity, along with bus energy consumption, is needed to evaluate WTW GHG emissions for soot-free transit buses. As noted above, carbon intensity is a metric that characterizes lifecycle GHG emissions from the use of a unit energy quantity of fuel, including both direct emissions from fuel combustion, as well as upstream emissions that are associated with the production of the fuel and feedstock.[21] For the liquid and gaseous fuels considered in this analysis, carbon intensity values are derived from lifecycle assessment modeling studies. Our primary focus in this paper is diesel and CNG derived from fossil sources, as these remain the most prevalent sources for these fuels today. A secondary focus is to investigate the potential for GHG emissions reductions from transitions to biofuel alternatives.

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[17] Although the kinetic intensity of the COM cycle is significantly lower than those of the UDDS and ART cycles, energy consumption trends are similar across powertrain types for these three cycles. Thus, we have decided to group the cycles into a single category representative of commuter/suburban operations.

[18] Xu, Y. et al. (2015). Assessment of alternative fuel and powertrain transit bus options using real-world operations data: Life-cycle fuel and emissions modeling. *Applied Energy, 154,* 143–159. doi:10.1016/j.apenergy.2015.04.112

[19] 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

[20] Bi, Z., Song, L., De Kleine, R., Mi, C. C., Keoleian, G. A. (2015). Plug-in vs. wireless charging: Life cycle energy and greenhouse gas emissions for an electric bus system. *Applied Energy, 146,* 11–19, doi:10.1016/j.apenergy.2015.02.031

[21] Emissions from the combustion of fuel in a bus engine are typically referred to as tank-to-wheel (TTW) emissions, whereas upstream emissions are referred to as well-to-tank (WTT) emissions. The sum of these two yields well-to-wheel (WTW) emissions, which are the focus of this analysis.

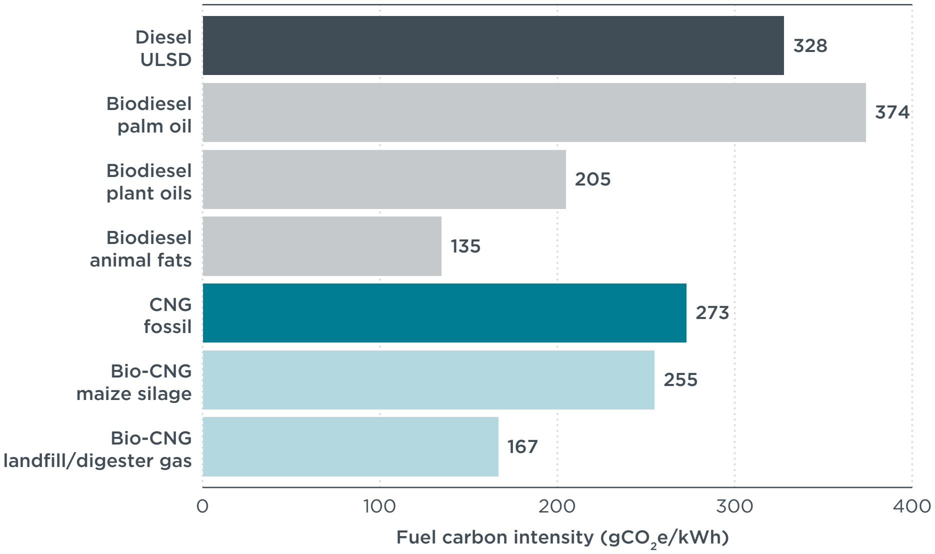

Figure 5. Carbon intensities for fuels used in diesel and CNG engines.

For petroleum-derived ultra-low sulfur diesel and fossil CNG fuels, carbon intensity values are taken from the Argonne National Laboratory AFLEET tool, which incorporates data outputs from the Argonne GREET 1 2015 model and represent average values for the U.S. consumption mix.[22] Carbon intensities for these fuels, shown in Figure 5, indicate that lifecycle GHG emissions for fossil CNG are 17% lower than for diesel when expressed on a per-fuel energy basis.[23] For both fuels, combustion accounts for the majority of lifecycle GHG emissions—83% for ULSD and 75% for fossil CNG. Applying carbon intensity values for fuels consumed in the U.S. to other regions introduces some uncertainty to this analysis. Crude oil sources, production methods, refining, and transport will all vary somewhat by region and will influence upstream GHG emissions. As an example, Nigerian petroleum production is associated with very high flaring emissions; consequently, diesel fuel derived from this source may have a WTW carbon intensity on the order of 10% greater than the default value used in this study.[24] A detailed assessment of the carbon intensity of specific diesel and CNG fuels used in each region considered here is outside of the scope of this analysis. Because most of the GHG emissions from these fuels are due to combustion, variability in upstream emissions across regions is not expected to have a significant impact on the WTW GHG emissions estimates presented below.

Relative to fossil diesel and CNG, biofuel alternatives have much greater variability in carbon intensity values. The carbon intensity of a given biofuel is a function of many factors, including the fuel feedstock, region of production, production pathways, land-use changes, and transportation methods. Lifecycle assessments of GHG emissions from biofuel production and use are also sensitive to decisions and assumptions made by analysts. This study does not aim to provide a comprehensive assessment of biofuels and their role in reducing GHG emissions from transit buses. Rather, the priority is to provide a general estimate of the range of GHG emissions that can be reasonably expected from transitions to biofuel alternatives. To this end, the analysis includes carbon intensity estimates for a selection of biodiesel and bio-CNG fuel types. These values are primarily taken from the State of California Low Carbon Fuel Standard (LCFS) Temporary Pathway table, and include carbon intensity estimates for biodiesel derived from plant oil (e.g., soybean oil, canola oil) or animal fat feedstocks and bio-CNG produced from landfill or digester gas.[25] This study also considers two additional biofuels, which are relevant to the international scope of this analysis—palm oil biodiesel and bio-CNG derived from maize silage. The carbon intensity for palm oil biodiesel is calculated by adjusting the LCFS Temporary Pathway value for plant oil upward to reflect the higher indirect land-use-change factor for palm biodiesel.[26] For silage maize bio-CNG, carbon intensity is derived from a recent Joint Research Centre assessment.[27]

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[22] Argonne National Laboratory. (2016). Alternative fuel life-cycle environmental and economic transportation (AFLEET) tool version 2016 rev1. Retrieved from https://greet.es.anl.gov/afleet

[23] The carbon intensity for fossil CNG is sensitive to assumptions made regarding the amount of methane leakage that occurs throughout the natural gas supply chain. The carbon intensity value used in this analysis assumes a leakage rate of 1.26%. For more discussion of the impacts of methane leakage assumptions on fossil CNG carbon intensity, refer to: Delgado, O., Muncrief, R. (2015). Assessment of heavy-duty natural gas vehicle emissions: Implications and policy recommendations. Washington, D.C.: The International Council on Clean Transportation. Retrieved from http://www.theicct.org/assessment-heavy-duty-natural-gas-vehicle-emissions-implications-and-policy-recommendations

[24] Chris Malins et al. (2014). Upstream emissions of fossil fuel feedstocks for transport fuels consumed in the European Union. Washington, D.C.: The International Council on Clean Transportation. Retrieved from http://www.theicct.org/upstream-emissions-fossil-fuel-feedstocks-consumed-european-union

[25] California Air Resources Board, Low Carbon Fuel Standard, Final Regulation Order, Title 17, California Code of Regulations. (2015). https://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

[26] California Air Resources Board. (2016). LCFS land use change assessment. Retrieved from https://www.arb.ca.gov/fuels/lcfs/iluc_assessment/iluc_assessment.htm

[27] Joint Research Centre. (2014). Solid and gaseous bioenergy pathways: Input values and GHG emissions, Report EUR 26696. Retrieved from https://ec.europa.eu/energy/sites/ener/files/2014_jrc_biomass_report.pdf

Carbon intensity values for all biofuels considered here are shown in Figure 5.

For electric buses, the fuel carbon intensity reflects lifecycle GHG emissions associated with the generation, transmission, and distribution of electricity used to charge bus batteries. This is also referred to as the carbon intensity of the electricity grid and can vary considerably depending on the relative mix of generation sources used to produce electricity in a given region. Grid carbon intensities tend to be highest for regions heavily dependent on carbon intensive fossil fuels, like coal or oil, and lowest for regions that have a higher percentage of electricity generated from renewable sources.

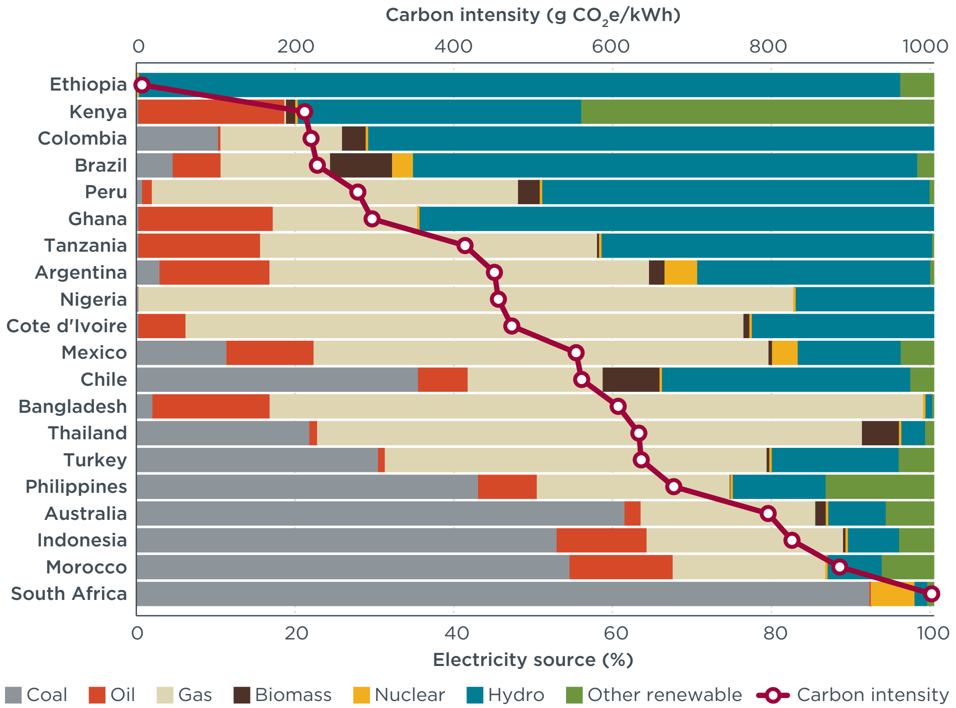

Figure 6. Source generation mix and carbon intensity of electricity production for target countries. Carbon intensity estimates account for transmission and distribution losses.

For each city considered in this study, this analysis estimates grid carbon intensity using three data inputs: (1) national-level annual electricity production by generation source type, (2) carbon intensities of individual electricity production source types, and (3) country-specific transmission and distribution losses. Electricity production data is sourced from the International Energy Agency (IEA) and reflects national-level production for the year 2014.[28] Carbon intensities of individual electricity production source types follow median values reported in a review of lifecycle assessment studies conducted by the Intergovernmental Panel on Climate Change (IPCC)[29] and are shown in Table 4. The bioenergy carbon intensity reported by the IPCC has been adjusted to account for land-use-change emissions excluded from the original lifecycle assessments on which the IPCC estimates are based.[30]

Table 4. Carbon intensities of electricity generation technologies

Generation technology	Carbon intensity (gCO_2e/kWh)
Coal	1001
Oil	840
Natural gas	469
Bioenergy	309–1,050*
Nuclear	16
Hydropower	4
Other renewable	27

**Bioenergy carbon intensity varies by region and depends on biomass feedstock.*

The carbon intensity of grid electricity is calculated as the fraction of electricity produced from a given source multiplied by its carbon intensity, summed over all source types. The result gives carbon intensity in units of grams CO_2e emitted per kWh of electricity generated. This value must be further adjusted to account for transmission and distribution losses that occur as the electricity is transmitted from the generating station to the electric bus charging station. This analysis applies transmission and distribution losses estimated by the IEA for this purpose (see Appendix). Country-level electricity generation source mix and grid carbon intensity values are presented in Figure 6.

Electricity grid carbon intensity results vary widely across the countries included in this analysis, ranging from about 10 gCO_2e/kWh in Ethiopia, where most electricity is produced from hydropower, to 1,000 gCO_2e/kWh in South Africa, where coal-fired power plants are predominant. Along with South Africa, other countries with

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[28] International Energy Agency. (2017). Statistics. http://www.iea.org/statistics/

[29] William Moomaw et al. (2011). Annex II: Methodology," in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[30] Baral, A., Malins, C. (2014). Comprehensive carbon accounting for identification of sustainable biomass feedstocks. Washington, D.C.: The International Council on Clean Transportation. Retrieved from http://www.theicct.org/comprehensive-carbon-accounting-identification-sustainable-biomass-feedstocks

significant fractions of coal and oil-fired power in their generation mix (e.g., Australia, Indonesia, Morocco) have among the highest carbon intensity grids. The grid carbon intensity is reduced for countries that rely more heavily on natural gas derived power, such as Cote d'Ivoire, Mexico, and Nigeria. In the IPCC dataset used here, hydropower has the lowest carbon intensity of any of the generation sources. Consequently, countries with high fractions of hydropower tend to have the lowest carbon intensity grids. With the exception of Kenya, the countries considered here have yet to incorporate significant fractions of other renewable technologies into their generation source mixes. However, it is important to note that projected decarbonization pathways for electricity production will have a significant effect on the long-term potential for GHG emissions savings from transitions to zero-emission electric transit bus fleets. This dynamic will be discussed in more detail below.

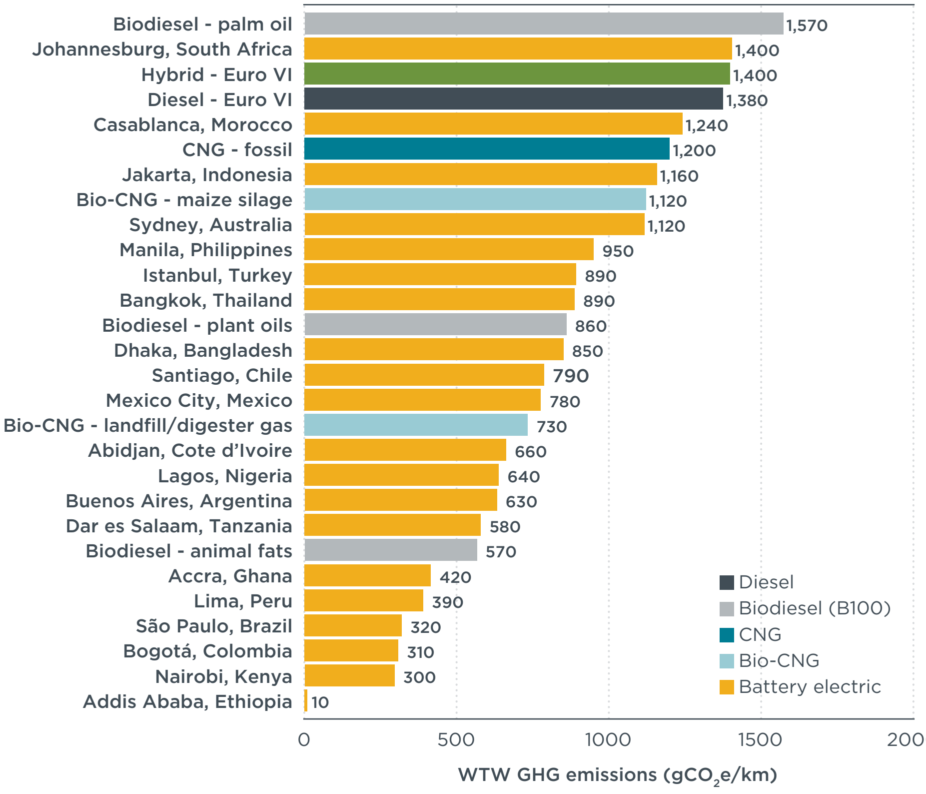

Figure 7. WTW greenhouse gas emissions of soot-free buses operating in commuter/suburban driving conditions in 20 megacities, ranked by climate impact

Lifecycle Greenhouse Gas Emissions of Soot-Free Buses

Energy consumption and carbon intensity values were combined to estimate WTW GHG emissions from each powertrain and fuel combination for three representative transit bus route types. As described above, transit bus energy consumption varies considerably according to driving cycle; therefore, operational conditions can have a significant impact on GHG emissions. Thus, it is important to consider a range of route types to fully assess the relative performance of alternative powertrain and fuel types. This consideration will aid transit operators in efficiently targeting specific technologies to those route types where they can provide the largest emissions benefits.

Well-to-wheel GHG emissions results for commuter/suburban routes are shown in Figure 7. For diesel, CNG, and hybrid buses, energy consumption is similar for the higher speed operating conditions typical of commuter/suburban route types, and relative differences in WTW GHG emissions largely reflect differences in fuel carbon intensity. Diesel and diesel-electric hybrid buses using ULSD fuel have similar GHG emissions—about 1,400 gCO$_2$e/km. CNG buses fueled with fossil gas, which has a lower carbon intensity than ULSD, perform relatively better. In this case, GHG emissions for CNG buses are estimated to be 13% lower than for diesel or hybrid buses.

For battery electric buses, WTW GHG emissions for commuter/suburban route types span a wide range, reflecting the variability in grid carbon intensity in the countries considered in this analysis. For countries with the highest carbon intensity grids, GHG emissions from battery electric buses are comparable to those estimated for diesel and CNG buses using fuels derived from fossil sources. Under these operating conditions, results for South Africa represent what can be considered a worst-case scenario for battery electric buses when compared to conventional diesel buses. The efficiency benefits of battery electric buses relative to diesel buses are lowest over these commuter/suburban route types, and the grid carbon intensity for South Africa, with its heavy reliance on coal power, is among the highest globally. Even with these conditions, WTW GHG emissions from battery electric buses are about the same as those from conventional diesel and diesel-electric hybrid counterparts.

In countries with lower electricity grid carbon intensities, the GHG emissions benefits of battery electric buses are significant. Take, for example, the case of a battery electric bus operating in Mexico, which has the median grid carbon intensity of the countries considered in this analysis. Relative to conventional diesel Euro VI or diesel-hybrid Euro VI buses, the electric bus would have WTW GHG emissions that are lower by a factor of approximately 2 (780 vs. 1,380–1,400 gCO_2e/km). Emissions reductions are even greater for the countries with lower grid carbon intensities than Mexico. Ethiopia, which relies almost exclusively on hydropower, provides the best-case scenario for electric bus GHG emissions. The extremely low carbon intensity of the grid there means electric buses would have near-zero WTW GHG emissions.

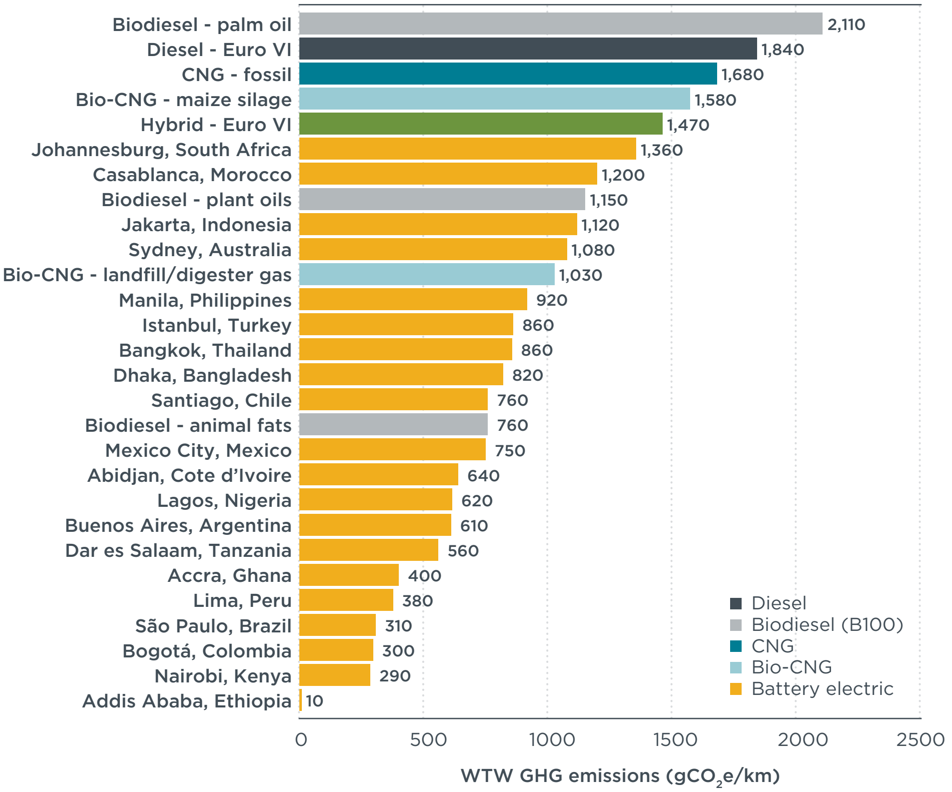

Figure 8. WTW greenhouse gas emissions of soot-free buses operating in medium-speed urban driving conditions in 20 megacities, ranked by climate impact.

As mentioned above, results for biodiesel and bio-CNG presented in Figure 7 are not intended to represent a comprehensive analysis of GHG emissions for buses fueled with these alternative fuel types. Rather, these values give an approximate range of the GHG emissions that can be expected of various example biodiesel and bio-CNG fuels. With this in mind, these results do allow for a number of general conclusions regarding the emissions performance of buses fueled with biofuels. First, substituting biofuels for fossil-derived diesel or CNG does not necessarily provide a GHG emissions benefit: GHG emissions for a diesel bus fueled with palm oil biodiesel are estimated to be 14% greater than the base ULSD case; maize silage biogas GHG emissions are similar to those for fossil-CNG. In these cases, the carbon intensities of biofuel alternatives are similar to or greater than for fossil diesel or CNG. For some other biofuels considered here, carbon intensities are substantially lower, and, consequently, GHG emissions reductions relative to fossil-derived diesel or CNG are large, on the order of 40%–60%. For these biofuels, WTW GHG emissions are comparable to those of an electric bus operating in a country with a medium carbon intensity grid. These results demonstrate the need for careful assessment of biofuel carbon intensities when considering transitions to these alternative fuels. Further consideration of low-carbon biofuels as feedstocks for electric power generation is also warranted, particularly in countries with high electricity grid carbon intensity.

Well-to-wheel GHG emissions for medium-speed urban operating conditions, presented in Figure 8, show the impact of operating conditions on the ranking of low-carbon technology pathways. These results illustrate significant advantages for Euro VI diesel-hybrid and battery electric buses relative to fossil-fueled Euro VI diesel and CNG buses. For both hybrid and battery electric buses, there is little difference in energy consumption for medium-speed urban and commuter/suburban operating conditions. Because fuel carbon intensity does not vary by operating cycle, this means that WTW GHG emissions are also similar for these route types. In contrast, Euro VI dedicated diesel and CNG buses consume approximately 30%–40% more fuel per kilometer while operating in medium-speed urban conditions compared to commuter/suburban conditions. WTW GHG emissions increase proportionally.

For all regions considered in this analysis, battery electric buses have lower GHG emissions than do conventional diesel, CNG, or hybrid buses when operating on medium-speed urban route types. Emissions reductions relative to diesel range from 25%–35%, for regions with the highest carbon intensity electricity grids, to 50%–85%, for areas with medium and low carbon intensity grids.[31] To put these results into perspective, consider a scenario in which an electric bus replaces a conventional diesel bus in Mexico. If used on a medium-speed urban route, the electric bus would yield GHG emissions reductions of 1,090 gCO$_2$e for every kilometer traveled. Assuming the bus is driven, on average, 70,000 km per year and is used for 12 years, the single electric bus would yield GHG emissions savings of approximately 915 tonnes over its lifetime. Even in the case of South Africa, with its high carbon intensity grid, a similar scenario would result in GHG emissions reductions of 400 tonnes. These results, extrapolated over a larger fleet of vehicles, demonstrate the considerable opportunity electric buses offer cities and transit operators for lowering the climate and air quality impacts of their public transportation systems.

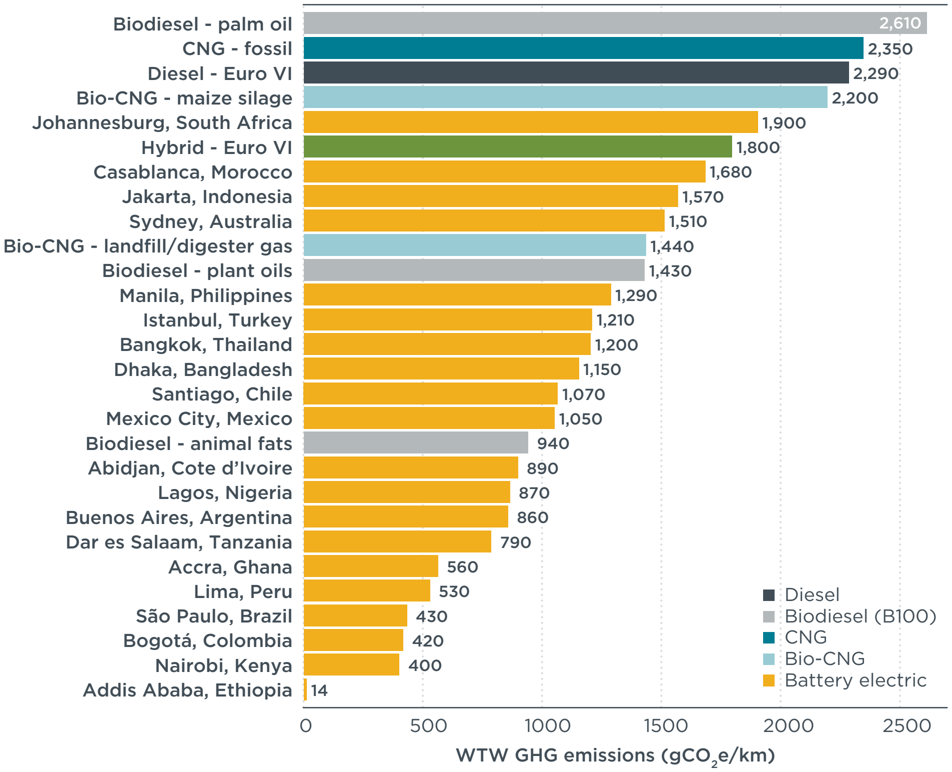

Figure 9. WTW greenhouse gas emissions of soot-free buses operating in low-speed urban driving conditions in 20 megacities, ranked by climate impact.

Greenhouse gas emission results for the final set of driving conditions considered in this analysis—low-speed urban operations—are shown in Figure 9. Relative to other route types, energy consumption and, consequently, WTW GHG emissions are highest under these conditions. Efficiency penalties are greatest for Euro VI diesel and CNG powertrains, for which GHG emissions are 66% and 96% greater, respectively, for these driving conditions compared to commuter/suburban operations. The low-speed, stop-and-go conditions are well suited for hybrid or electric powertrains, and GHG emissions are only 30%–35% higher than the commuter/suburban driving scenario for these technologies.

As was the case with medium-speed urban route types, battery electric buses offer significant potential for GHG emissions reductions relative to fossil-fueled diesel or CNG buses on low-speed urban routes. These data indicate that a battery electric bus operating in South Africa would have slightly higher emissions than a diesel-electric hybrid bus, although for all other regions considered here, battery electric buses have lower emissions. Battery electric bus WTW GHG emissions reductions relative to a diesel bus fueled with ULSD range from about 400 gCO$_2$e/km to 1,900 gCO$_2$e/km depending on the grid carbon intensity of the respective region of interest.

Low-Carbon Technology Pathways for Fleet Operators

This study shows that in almost all cases, a switch away from dedicated CNG and diesel buses can be justified not only to achieve soot-free emissions but also to generate the greatest climate benefits from a future technology transition. Certain non-fossil fuels should be avoided entirely, such as palm oil biodiesel. And in at least two megacities—Johannesburg and Morocco—dedicated CNG or Euro VI diesel hybrid engines may provide a narrow climate benefit over some of the non-fossil alternatives. The

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[31] Ethiopia is not included in these ranges as its ultra-low carbon intensity grid is an outlier in the data set. For this case, WTW GHG emissions from electric buses are 99% lower than from conventional diesel buses.

introduction of some low-carbon fuels can take advantage of existing refueling infrastructure and deliver meaningful climate benefits, such as bio-CNG from landfill or digester gas and biodiesel from plant oils or animal fats. But, on the whole, zero-emission electric drive buses appear to provide the greatest magnitude of climate benefits for the greatest number of routes in the largest number of cities.

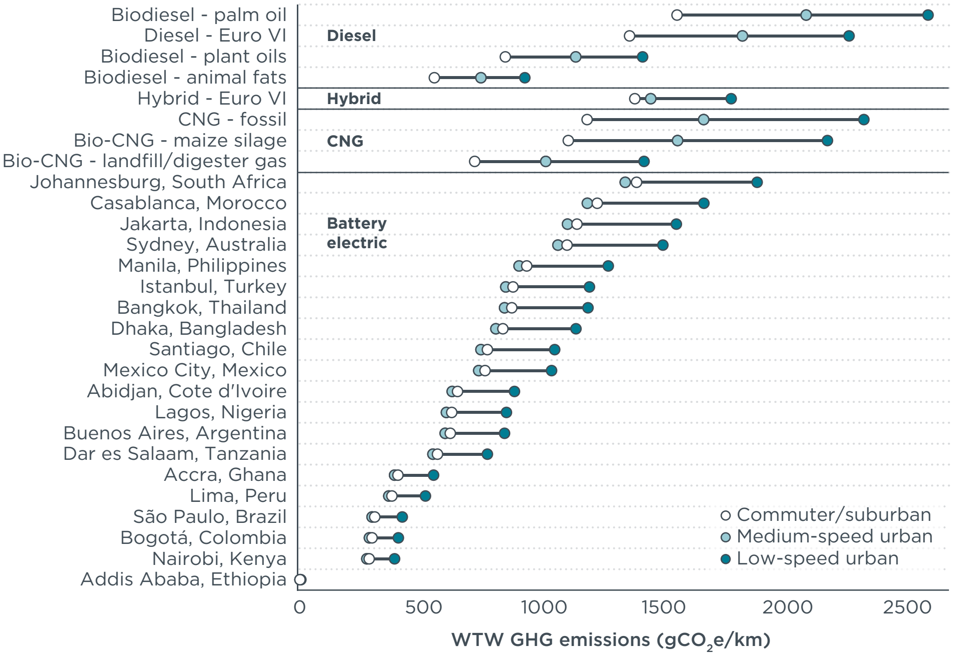

Figure 10. Summary of WTW GHG emissions from transit bus powertrain and fuel combinations.

Well-to-wheel GHG emissions for all bus types and operating conditions are summarized in Figure 10. These results provide the general range of emissions that can be expected for different transit bus powertrain and fuel combinations. A key insight of this analysis relates to the important role that driving cycle has in determining GHG emissions from transit buses. Outside of any switch in engine technology, efficiency improves as buses are operated in free-flowing traffic conditions with higher average speeds. Although many routes are constrained because of the number and frequency of scheduled stops, traffic management practices, such as reducing congestion or bus-dedicated lanes, would serve to reduce GHG emissions from transit buses. This impact is most important for diesel Euro VI and CNG powertrains, whose efficiency is most sensitive to driving cycle. Hybrid and battery electric buses have less variance in GHG emissions by operating cycle. Transitioning from a low-speed urban driving cycle to a medium-speed cycle would potentially reduce GHG emissions by 20%–30% depending on the powertrain used. These GHG emissions reductions would be accompanied by reductions in fuel consumption, leading to cost savings for fleet operators as well.

Of the soot-free bus types considered here, battery electric buses appear to offer the best low carbon option for most cities. In the majority of cases, battery electric buses have significantly lower WTW GHG emissions than do diesel Euro VI, CNG, or Euro VI diesel-hybrid alternatives. At worst, GHG emissions are comparable to those from dedicated CNG or diesel Euro VI buses with fossil-derived fuel. In general, GHG emissions savings are maximized over driving cycles where battery electric buses have the highest efficiency advantages—low- and medium-speed urban operations—and for regions with low carbon intensity electricity grids. As shown in Figure 11, this analysis indicates that an electric bus replacing a conventional diesel bus on a low- or medium-speed urban route would result in lifetime GHG emissions savings of approximately 500 tonnes in regions with high carbon intensity electricity grids, 1,000 tonnes in regions with medium carbon intensity grids, and 1,500 tonnes in regions with low carbon intensity grids.

Further reductions in battery electric bus GHG emissions will rely on long-term decarbonization pathways for the electricity grids in the respective regions of study. As countries move to incorporate more low carbon electricity generation technologies into their grid mix, the GHG emissions performance of battery electric buses will improve. As an example, Figure 12 shows how decarbonization of the South African electricity grid would influence WTW GHG emissions from battery electric buses operating in the country. The bottom panel of the figure shows the baseline electricity generation mix for 2014 and the projected 2040 grid mix for two decarbonization scenarios.[32] Both decarbonization scenarios project replacement of coal-fired power generation with nuclear and renewable generation technologies. In the most optimistic case, WTW GHG

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[32] International Energy Agency. (2015). World energy outlook 2015. The New Policies scenario reflects policies that have been adopted or announced as of mid-2015. The 450 scenario assumes the adoption of a set of energy policies that would be needed to meet a climate goal of less than 2°C increase in global temperature.

emissions from battery electric buses could be reduced by 60%, from 1,390 gCO_2e/km to 560 gCO_2e/km.

Biofuels may be an option to accelerate GHG emissions reductions in areas with higher electricity grid carbon intensities. However, transit operators considering transitioning to these alternative fuels need to carefully assess the carbon intensity of potential biofuel alternatives to ensure that GHG emission reduction goals are realized. For high carbon intensity biofuels, such as palm oil biodiesel, WTW GHG emissions can be higher than for fossil-derived conventional fuels. Lower carbon intensity biofuels considered here indicate relative GHG emissions reductions on the order of ~50%. In this case, biofuels may offer a better low-carbon alternative to battery electric buses in regions with higher electricity grid carbon intensities. For any transition to biofuels, it is important that transit operators have systems and procedures in place to guarantee the supply of biofuels from known feedstocks and production pathways.

This analysis finds that WTW GHG emissions for CNG and diesel Euro VI buses fueled by fossil-derived fuels are generally similar; CNG buses have slightly lower emissions over commuter/suburban and medium-speed urban route types, whereas diesel buses perform slightly better under low-speed urban operating conditions. For engines certified to Euro VI or EPA 2010 emission standards, emissions of conventional air pollutant emissions from these two technology types are expected to be similar. As such, there is no significant difference in the climate impact of Euro VI diesel and CNG buses.

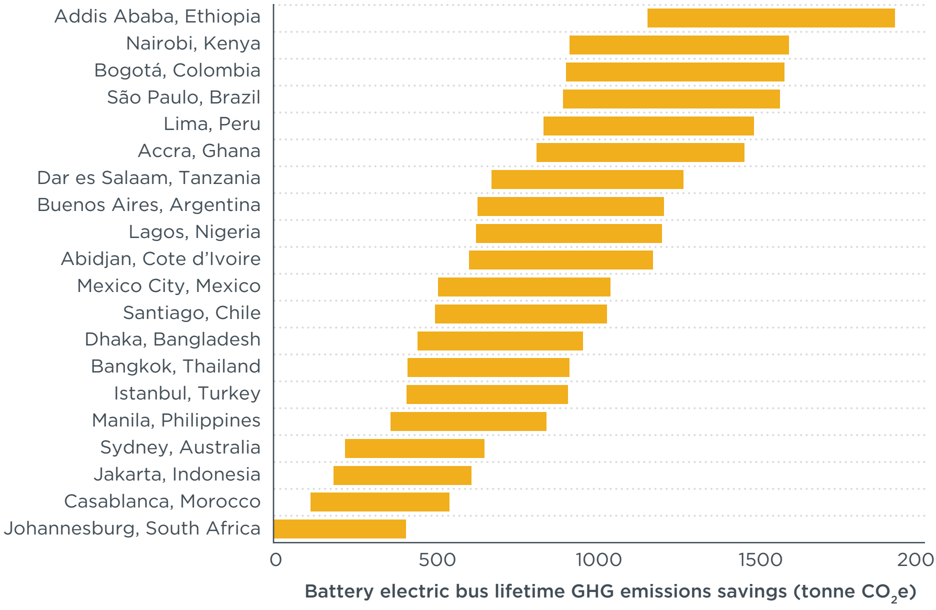

Figure 11. Range of lifetime GHG emissions savings for an electric bus relative to a conventional diesel bus. Annual bus activity and bus lifetime are assumed to be 70,000 km/yr and 12 years, respectively. For each country, the lower end of the range corresponds to commuter/suburban operations, while the upper end reflects savings for medium- and low-speed urban operations.

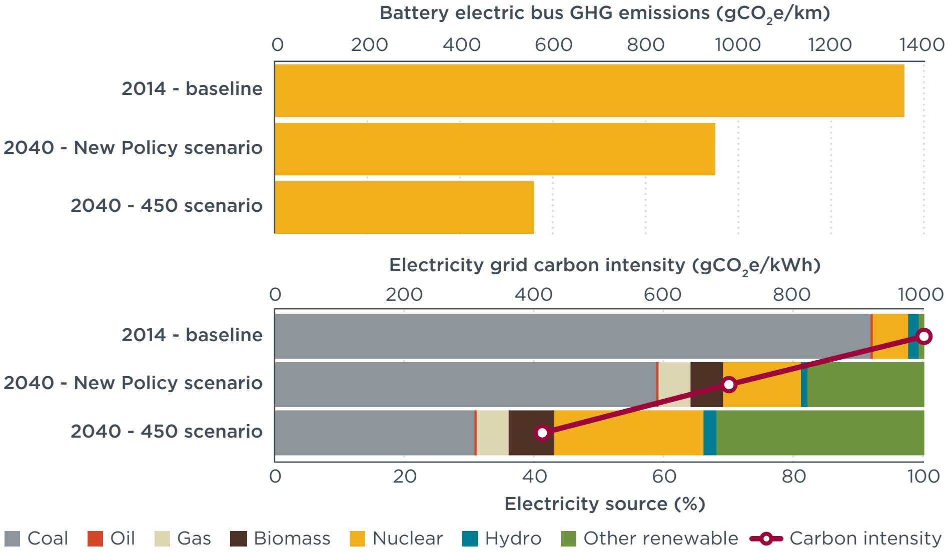

Figure 12. South Africa electricity generation projections and impacts on WTW GHG emissions from battery electric buses. Results are shown for medium-speed urban operating conditions.

Natural gas engines provide a near-term soot-free option for areas without access to low-sulfur diesel fuel. A number of the cities considered in this analysis, including Bangkok, Jakarta, and Sydney, have already turned to CNG buses to reduce the environmental impacts of their transit fleets. Such transitions require these cities to invest in natural gas distribution and fueling infrastructure, and, to a certain degree, to commit to natural gas bus fleets. For cities on this technology pathway, decarbonization can be achieved through the incorporation of low carbon intensity bio-CNG into their fuel mix.

From purely an emissions perspective, these results indicate that zero-emission battery electric buses are currently the best option for transit operators seeking to improve the environmental performance of their fleets. Of course, emissions are not the only consideration, and factors such as cost, route suitability, and technology availability must be considered when making technology transitions such as this. However, this analysis would seem to dispel the notion that transitioning to electric bus fleets would have a negative climate pollution impact.

Technology transitions involve commitments from fleet operators as well as the public and other stakeholders. Switching from diesel to either battery electric or natural gas bus fleets involves investments in charging or fueling infrastructure as well as retraining of maintenance staff to operate on these new technologies. Similarly, battery electric buses introduce novel challenges related to, for example, recharging strategies. Initial costs of purchasing alternative technology buses may be higher, but in the case of battery electric buses, long-term reductions in operating costs may lead to a lower total cost of ownership over the lifetime of the bus. In all cases, the primary mission of fleet operators—providing dependable, low-cost public transport—must be kept in mind.

Uncertainties and Future Research Directions

In this analysis, we attempted to present a high-level assessment of the relative WTW GHG emissions from soot-free bus types. We relied on publicly available energy consumption and carbon intensity data to provide a transparent and consistent framework for comparisons among technology types. Some uncertainty is inherent in this type of assessment, and it is worthwhile to identify a number of the key areas where the analysis could be refined.

Of the two parameters used to assess WTW GHG emissions—energy consumption and fuel carbon intensity—a lesser degree of uncertainty is associated with energy consumption. Uncertainties in energy consumption were addressed, in part, by including estimates across a range of operating conditions. However, energy consumption will vary according to other factors, such as auxiliary power demands, which were not fully captured in this assessment. At the individual city level, this analysis could be refined by incorporating route-specific driving cycle data to better assess the suitability and emissions benefits of alternative technologies. Finally, it is worthwhile to point out that battery electric buses are still a relatively new technology, and the extent of real-world energy consumption data is limited. As these buses gain broader usage, data on real-world performance will become more widely available; this, in turn, will promote a more robust comparison with conventional engine technologies.

We described uncertainties in our assessment of biofuel carbon intensities earlier, but will reiterate here that results presented in this paper are meant to be illustrative and do not cover all of the biofuel types that may be used in public transit applications. Additional analysis for individual cities considering biofuels, with carbon intensities reflective of the specific biofuel being considered, could provide a more detailed assessment of the degree to which this pathway delivers GHG emissions savings.

For fossil-derived diesel and CNG fuels, uncertainties in the carbon intensity estimates used here are primarily associated with uncertainties in upstream GHG emissions. Crude oil and natural gas sources, production and processing pathways, and transport will all vary somewhat by region. These factors will influence total upstream emissions for these fuel types. Upstream GHG emissions estimates for CNG are also highly sensitive to the amount of methane leakage assumed to occur throughout the natural gas supply chan. This analysis assumed a relatively low leakage rate of 1.26%. Higher leakage rates would result in a relatively worse emissions performance for CNG buses than what has been presented here. In all cases, the analysis could be refined by conducting lifecycle assessment studies for the specific fuels being used in each region of study.

In our assessment of electricity grid carbon intensities, we relied on IPCC estimates of the carbon intensity of individual electricity production source types. The IPCC dataset assigns a relatively low value to electricity produced at hydropower plants; therefore, in our analysis, battery electric buses tend to perform best in regions with large percentages of power produced by this source type. There is a great deal of uncertainty in assessments of the carbon intensity of hydropower, and researchers have found that GHG emissions from hydroelectric reservoirs may be higher than what is reflected in IPCC estimates, in particular for plants located in tropical forested regions.[33] A higher carbon intensity for hydropower would increase the WTW GHG emissions of battery electric buses somewhat for many of the countries considered here. However, it is unlikely to change the general conclusion that battery electric buses can provide significant GHG emissions savings relative to conventional diesel and CNG buses.

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[33] de Faria, F. A. M., Jaramillo, P., Sawakuchi, H. O., Richey, J. E., Barros, N. (2015). Estimating greenhouse gas emissions from future Amazonian hydroelectric reservoirs. *Environmental Research Letters, 10,* 124019. doi:10.1088/1748-9326/10/12/124019

Appendix

Table A1. Description of transit buses included in energy consumption assessment. Test cycles for which energy consumption data is reported are commuter (COM), heavy-duty urban dynamometer driving schedule (UDDS), arterial (ART), Orange County Transit Authority bus cycle (OCTA), central business district (CBD), and Manhattan bus cycle (MAN).[34]

Engine type	Manufacturer	Model	Passenger capacity	GVW(kg)	Energy consumption (kWh/km)					
					COM	**UDDS**	**ART**	**OCTA**	**CBD**	**MAN**
Diesel	NABI	416.15	72	18,090	3.31	4.37	5.71	5.74	6.26	8.12
	Daimler	Orion VII	80	18,470	3.30	3.93	5.71	4.79	6.06	6.48
	New Flyer	XD40	81	18,130	2.85	2.89	5.22	4.48	5.94	6.52
	NABI	40 LFW	72	19,530	3.31	4.03	6.03	5.03	5.95	6.34
	Eldorado	Arrivo	60	15,360	3.01	3.61	5.74	5.09	6.94	7.43
Diesel-electric hybrid	Daimler	Orion VII	80	18,860	3.44	4.91	5.35	4.35	5.04	5.86
	New Flyer	XDE 40	76	17,660	3.00	3.17	4.58	3.63	4.29	4.96
	Gillig	Low Floor BAE	72	18,690	4.06	3.85	6.05	4.48	5.02	5.64
CNG	Gillig	Low Floor	73	17,890	2.56	4.20	3.96	5.63	5.13	8.10
	Daimler	Orion VII	77	19,560	3.95	4.41	6.40	5.75	6.83	8.49
	New Flyer	C40LF	85	20,000	3.56	4.36	6.25	5.85	6.21	8.79
	Gillig	Low Floor	73	18,250	3.23	4.04	5.50	5.23	6.21	7.21
	NOVA	CNG LFS 40	65	18,060	3.27	4.19	5.28	5.80	6.91	8.71
	Eldorado	Axess HD	61	18,590	3.11	5.46	5.23	6.44	6.88	9.89
	New Flyer	XN40	71	19,530	3.86	4.54	4.93	5.60	7.83	8.98
Battery electric	Proterra	BE-35	65	16,930	0.86		1.29		1.06	
	Proterra	BE35	61	17,020	0.83		1.39		1.14	
	BYD	K9	49	17,780	0.89		1.58		1.24	
	Proterra	BE40	79	17,870	0.88		1.31		0.97	
	New Flyer	XE40	76	19,750	0.93		1.42		1.09	

Note: Reported fuel consumption values (scf/mi or gal/mi) converted to energy consumption using lower heating values of 923 BTU/scf and 128,488 BTU/gal for CNG and diesel fuels, respectively (www.afdc.energy.gov/fuels/fuel_properties.php)

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[34] The Altoona Bus Research and Testing Center. (2017). http://altoonabustest.psu.edu/

Table A2. Country-specific electricity production by source for year 2014 (%).[35]

Country	Coal	Oil	Gas	Biomass	Nuclear	Hydo	Other renewable	Transmission and distribution losses (%)
Argentina	3	14	48	2	4	29	1	16
Australia	61	2	22	1	0	7	6	6
Bangladesh	2	15	82	0	0	1	0	13
Brazil	5	6	14	8	3	63	2	16
Chile	35	6	17	7	0	31	3	7
Colombia	10	0	15	3	0	71	0	12
Cote d'Ivoire	0	6	70	1	0	23	0	19
Ethiopia	0	0	0	0	0	96	4	19
Ghana	0	17	18	0	0	65	0	22
Indonesia	53	11	25	0	0	7	4	10
Kenya	0	19	0	1	0	36	44	18
Mexico	11	11	57	0	3	13	4	14
Morocco	54	13	19	0	0	7	7	16
Nigeria	0	0	82	0	0	18	0	15
Peru	1	1	46	3	0	49	1	11
Philippines	43	7	24	0	0	12	14	10
South Africa	92	0	0	0	5	2	1	8
Tanzania	0	15	42	0	0	42	0	20
Thailand	22	1	68	5	0	3	1	6
Turkey	30	1	48	0	0	16	4	15

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[35] International Energy Agency. (2017). Statistics. http://www.iea.org/statistics/