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THE FUTURE OF URBAN MOBILITY: THE CASE FOR ELECTRIC BUS DEPLOYMENT IN BOGOTÁ, COLOMBIA

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Abstract

Electrifying municipal bus fleets presents a unique opportunity to reduce local pollution, improve respiratory health and reduce greenhouse gas emissions in the transport sector. Despite the promises of electric buses (e-buses), their implementation faces many challenges, especially in Global South cities such as Bogotá, Colombia. To help overcome challenges and plan for e-bus infrastructure on a large scale, transit officials in Bogotá partnered with the World Resources Institute to use a new cost–benefit analysis tool, the Future Mobility Calculator. Siemens and the World Resources Institute, with support from the Coalition for Urban Transitions, developed this calculator to support decision-makers to assess the costs and benefits of shared, electric urban transport options. This paper highlights the preliminary outputs from the calculator in Bogotá and how these results guided efforts to plan for the integration of e-buses into the TransMilenio fleet. The calculator was used to provide analysis on a variety of transport electrification scenarios ranging from a large-scale electric fleet (1,661 e-buses) down to a smaller-scale transition (117 e-buses). The preliminary analysis estimated that, in all four examined scenarios, the selected benefits of bus electrification outweighed the selected costs. The cost–benefit analysis provided to the planning department at TransMilenio for the next phase of Bogotá's bus fleet helped them to assess the impact that different levels of electrification would have on the city. This preliminary analysis done for Bogotá helped inform the development of the city's bus tender for 2019, which led to the procurement of almost 500 e-buses.

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ABOUT THIS POLICY BRIEF

This policy brief was prepared by the World Resources Institute using the Future Mobility Calculator. The Future Mobility Calculator is an electric vehicle infrastructure planning tool, jointly developed by Siemens and the World Resources Institute. This is the first in a series of policy briefs setting out the findings and implications of the Future Mobility Calculator in different cities. The Future Mobility Calculator and accompanying policy briefs are published as part of the New Urban Mobility programme of the Coalition for Urban Transitions. The Coalition for Urban Transitions is a major international initiative to support decision makers to meet the objective of unlocking the power of cities for enhanced national economic, social, and environmental performance, including reducing the risk of climate change.

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Transmilenio bus passes through downtown Bogota. Credit: Jess Kraft / Shutterstock.

1. Highlights

- **Electric buses (e-buses) have the potential to provide many benefits**. E-buses can help to reduce CO_2 emissions (if the electricity is generated from a relatively clean grid, such as in most parts of South America) and curtail local pollutants. Furthermore, e-buses can also be a tool to improve energy efficiency, reduce noise pollution, enhance passenger comfort (by reducing vibration) and lower operating costs.
- **The adoption of e-buses has accelerated in recent years and is contributing to reaching long-term global climate targets, but this process is not occurring fast enough to curtail climate change**. The 2018 *Special Report on Global Warming of 1.5 °C* by the Intergovernmental Panel on Climate Change (IPCC) indicates that investment in low-carbon technologies, including e-buses, needs to increase by a factor of six by 2050 to maintain global warming well below a relatively safe threshold of 2 degrees Celsius (2°C).[1]
- **Bogotá faces clear challenges in adopting e-buses.** All of Bogotá's public transport is bus-based. The city's iconic bus rapid transit (BRT) system, TransMilenio, is one of the busiest in the world and relies on large, heavy-duty diesel buses which manage substantial loads for long periods of time. These operating challenges make it particularly difficult to electrify without integrated transport and electricity infrastructure planning. Despite the challenges for Bogotá, strong public support (among other factors) has allowed local government officials to demonstrate interest in progressing their bus electrification efforts.
- **TransMilenio staff used the Future Mobility Calculator to estimate the infrastructure requirements and some societal benefits of certain e-bus scenarios**. Developed by Siemens and the World Resources Institute (WRI) with support from the Coalition for Urban Transitions, the Future Mobility Calculator helped Bogotá officials answer important questions about the **costs** of vehicles and infrastructure and some of the **benefits** of energy savings and health and environmental improvements. The electrification scenarios were developed and the tool results were reviewed in a collaborative process with TransMilenio staff.
- **Using inputs specific to Bogotá, the Future Mobility Calculator provided preliminary results demonstrating the projected benefits of electrification.** In all four scenarios considered, the calculator estimated that the examined benefits of bus electrification outweighed the examined costs.
- **In late 2019, following this analysis, TransMilenio successfully tendered 483 e-buses.** While these e-buses will not be operational until they are successfully delivered and tested (which, as of publication, is expected to start in September 2020), this plan already represents a marked advancement in e-bus policy in Bogotá.

2. The challenge: adopting electric buses

THE GLOBAL CHALLENGE

Globally, the transport sector is responsible for a significant and growing proportion of greenhouse gas (GHG) emissions, accounting for approximately 8 billion tonnes of annual GHG emissions in 2016 and constituting roughly one-quarter of all GHG emissions.[2] Furthermore, transport is the fastest-growing source of CO_2 emissions and fossil fuel demand worldwide.[3] In the near-term future, concrete action must be taken to mitigate transport-related GHG emissions and address the imminent threat of climate change.

Within the field of transport, public transport fleets are of special interest because of the significant emissions they generate. Although buses produce lower emissions on a per-passenger basis (assuming average occupancy of 30% or higher), they account for a disproportionate amount of emissions on a per-vehicle basis compared with passenger cars, especially in the Global South where older and less efficient transit vehicles are more common.[4] Public transport in cities can be responsible for over a quarter of carbon emissions, hazardous particulate matter and nitrogen oxide emissions. In Shenzhen China, for example, before the launch of the city's remarkable 16,000-strong fully electric bus fleet, conventional buses were responsible for 25% of the city's transport-associated energy consumption and 20% of the CO_2 emissions associated with vehicles, despite accounting for just 0.5% of total vehicles.[5] Similar figures are seen in cities around the world.[6] Although buses typically have lower emissions than private vehicles on a per-passenger basis, measures taken to increase the sustainability of municipal bus fleets can noticeably reduce emission levels and provide environmental and health benefits to urban residents.

Within the suite of sustainable bus technologies, electric vehicles, with zero tailpipe emissions, are emerging as an option with serious potential for reducing local and global emissions.[7] E-buses have propulsion systems which do not require the burning of fuel, so no exhaust is emitted from the vehicle. Thus, e-buses can help to reduce local pollutants while also reducing CO_2 emissions globally (if the electricity is generated from a relatively clean grid, such as in most parts of South America). Reductions to local pollutant levels in a city can also provide health benefits to the population, including low-income residents who are often hit hardest by poor air quality.[8]

On top of these environmental benefits, e-buses can also improve energy efficiency, reduce noise pollution, help to stabilise the grid (through vehicle-to-grid applications), enhance passenger comfort (by reducing vibration) and lower operating costs (through lower fuel and maintenance costs).[9] In the case of Shenzhen, the public transport sector was able to cut fossil fuel consumption by 95%.[10] Even when taking into account emissions from electricity generation on China's National Grid, e-buses in Shenzhen still demonstrated a 15–20% CO_2 emissions reduction.[11]

Electrifying municipal bus fleets presents a unique opportunity to reduce GHG emissions in the transport sector while also bringing co-benefits to those cities and countries making the transition.

Despite the promises of e-buses, their implementation faces many challenges. According to a recent WRI report based on case studies from 16 cities,[12] the major barriers facing the adoption of e-buses include the following:

- **Technological barriers,** created by the lack of relevant information necessary for informed decision-making regarding:
  - Proper inputs required for initial cost–benefit analysis (including an analysis of charging infrastructure technology options, or the total emissions impact of manufacturing e-buses and their batteries);
  - Strategies to optimise successful e-bus project design and implementation, including comprehensive infrastructure planning development prior to adoption; and
  - The current operational characteristics, limitations and maintenance requirements of e-buses and charging infrastructure.
- **Financial barriers,** emerging from:
  - The difficulties agencies face in making the necessary changes to rigid procurement structures, which are not designed to accommodate the high upfront costs of vehicles, infrastructure and longer-term pay-out through lower operational expenses; and
  - The lack of long-term, sustainable financing, because financial institutions are often unwilling to provide investment beyond lower-risk small-scale pilot projects.
- **Institutional barriers,** stemming from:
  - The lack of political momentum and enabling policies and/or a specific implementation plan to promote public transport electrification (this is often related to opposition from operators);
  - The lack of institutional capacity, technical resources or jurisdictional authority for successful project execution;
  - Insufficient funding; and
  - A lack of physical real estate for charging and grid infrastructure.

Compared with personal vehicles, buses provide emission reductions on a passenger-mile basis but produce a large amount of emissions in aggregate.

As a result of these barriers, e-bus adoption in most cities has occurred at a relatively slow and uneven pace. Only about 17% of the world's current municipal buses are electrified (almost all are in China, as described below), and even the most bullish projections for e-bus growth forecast that less than 70% of buses will be electric by 2040.[13] More generally, several studies estimate the rate of investment in low-carbon technologies, including e-buses, needs to increase by a factor of six through to 2050 to maintain global warming well below a relatively safe threshold of 2°C.[14] The growth of e-buses thus far has been concentrated mainly in China, which possesses over 99% of all e-buses in operation.[15] A unique set of government incentives and mandates have allowed China to foster an ecosystem of government, industry, utility and research institutions aligned with the common purpose of advancing electrification of municipal bus fleets.[16] For e-buses to be an effective tool against pollution, respiratory diseases and climate change elsewhere, the pace of adoption must accelerate, with more attention focused on cities located in a wider range of geographies.

THE CHALLENGE IN BOGOTÁ

Buses in Bogotá – as with many cities in the Global South – present a clear opportunity for curbing urban emissions and improving air quality. Compared with personal vehicles, buses provide emission reductions on a passenger-mile basis but produce a large amount of emissions in aggregate. Even five years after the introduction of the city's environmentally improved TransMilenio system in 2000, Bogotá's bus fleet was still responsible for 23% of CO_2, 55% of PM_{10} and 40% of NO_x vehicle emissions in the city, while representing less than 5% of the total vehicles in the city.[17] In recent years, more than 50% of the articulated buses procured during the earlier stages of TransMilenio (and still in operation) failed to meet government emission standards, but faced few punitive measures.[18] Bogotá remains one of Latin America's most polluted cities, and, although current buses are cleaner than private cars on a per-passenger-mile basis, a clean bus fleet would provide substantial environmental benefits in a country where the transport sector was responsible for over 30% of energy-related emissions in 2013.[19]

Recognising the important health and emissions benefits of a zero-emission bus fleet, Bogotá first explored e-buses as part of the Hybrid and Electric Bus Test Program. Conceived around 2012, this programme measured the emissions from, and evaluated the technological and economic performance of, hybrid e-buses, considering specific driving conditions and duty cycles.[20] The programme involved several bus manufacturers and various local transport operators. In 2016, manufacturer BYD provided Transmasivo (a TransMilenio operating company) with the world's first articulated e-bus, along with charging infrastructure, for free to enable a one-year pilot project. These projects provided proof-of-concept for future e-buses in Bogotá, but they did not proceed past their pilot stages.

Early e-bus efforts failed to scale beyond the pilot stage because TransMilenio faced many of the common challenges to adopting e-buses. **Technologically,** e-buses typically have not offered the same range as conventional buses. The initial pilot with a TransMilenio bus indicated that, due to battery constraints, e-buses averaged 235 kilometres per day, while diesel buses could average 440 kilometres.[21] E-buses also faced challenges dealing with Bogotá's hilly topography and rough roads, which were especially apparent for articulated e-bus models. **Financially,** e-buses have required TransMilenio to alter rigid, conventional business models not designed to accommodate the elevated financial risk that comes with e-buses' high upfront costs. Conventional procurement models were unable to adequately evaluate the return on investment that e-buses offer in operational costs, compared with conventional buses. **Institutionally,** despite recent support, e-buses have historically faced a lack of the political momentum, incentives and/or institutional know-how that is needed to effectively support adoption.

Despite these early barriers, as e-bus technology improved, environmental concerns galvanised TransMilenio to eventually procure e-buses en masse in 2019. In March 2018, the city of Bogotá issued a draft tender to replace 1,441 articulated and biarticulated buses corresponding to the oldest in the TransMilenio fleet of 2,884 BRT buses. Initially, the tender did not include any incentives for adopting e-buses (the first draft even required new buses must have internal combustion engines). After a large group of stakeholders voiced concerns on social media, TransMilenio amended the tender to include some incentives for clean buses (but no distinction was made between electric, compressed natural gas (CNG) and "clean" diesel technologies).[22] In December 2018, TransMilenio decided that the selected bidder would be providing 741 CNG buses, 700 Euro V diesel buses and zero e-buses.

Although TransMilenio's 2018 tender did not result in the procurement of any e-buses, it sparked a public dialogue which forced e-buses into the political spotlight.[23] Cognisant of e-buses' newfound support, TransMilenio decided that it wanted to strongly promote e-buses in their 2019 tender, which was the first stage of a large fleet overhaul, dubbed "Phase V". This tender also included TransMilenio's smaller, non-articulated fleet, which better aligned with the commercially competitive and available e-bus sizes and provided a greater opportunity to go electric.

3. The policy context

Bogotá's push for e-buses has been framed by several relevant policies. While the below policies rarely provided legally binding requirements, they have fostered dialogue and political will for addressing environmental issues. This section highlights a few of the agreements and plans which have provided declarations of support for adopting e-buses.

COLOMBIA'S NATIONALLY DETERMINED CONTRIBUTION

Perhaps the most well-known climate action taken by Colombia in recent years is their Nationally Determined Contribution (NDC), which the country produced as part of the 2016 Paris Agreement. Colombia has pledged through their NDC to reduce CO_2 equivalent (CO_2eq) emissions by 20% below their business-as-usual projections by 2030.[24] Since the transport sector accounts for 32% of all energy-related emissions in Colombia,[25] transport is identified in Colombia's NDC plan as one of the "6 priority sectors of the economy" for climate change action. Thus, reforming the transport sector is an integral part of Colombia's countrywide CO_2 emissions reduction goal for 2030. While Colombia's NDC is not directly relevant to e-bus implementation in Bogotá, these measures indicate the country's commitment to reducing carbon emissions in all sectors.

THE CONPES ACT 3943

Colombia's Council on Economic and Social Policy (CONPES in Spanish) is an entity within the National Development Agency which establishes various goals and objectives at the national level.

In 2018, CONPES Act 3943 outlined an action plan to achieve a reduction of the concentration of pollutants in the air that affect health and the environment.[26] Among other objectives, this document states that, by 2028, 100% of vehicles operating within Colombia's mass transport systems will be natural gas or electric vehicles. CONPES also established goals to reduce energy intensity by 22% and introduce 600,000 electric vehicles by 2030.

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In 2018, the Bogotá City Council set a draft agreement to promote the mass introduction of electric mobility. The overarching objective of the draft agreement is to reduce pollutant emissions and address the public health issues associated with poor air quality. The agreement is specifically designed to achieve electrification of official vehicles, emergency service vehicles and public transport vehicles between 2030 and 2050, with the ultimate goal of creating complete zero-emission fleets.[27]

4. Methodology

Information for this paper is principally based on the preliminary findings from the Future Mobility Calculator. This calculator is an electric vehicle infrastructure planning tool, originally developed by Siemens and enhanced by WRI for the Coalition for Urban Transitions.[28] The preliminary findings from the calculator were discussed at an in-person workshop, which was held with officials from TransMilenio and other city departments in Bogotá in March 2019. Based on the input received during the workshop in Bogotá, WRI staff refined the Future Mobility Calculator. After improvements were made, the scenarios discussed during the workshop were rerun to provide the most up-to-date and accurate results from the tool (although the tool remains in beta as of the publication of this paper). The Future Mobility Calculator and the workshop are described in greater detail below.

In addition to the two primary methodological components (the Future Mobility Calculator and the in-person workshop), supplementary research provided context for this paper. The authors conducted a literature review, which included a scanning of scholarly articles written on Bogotá, TransMilenio and e-buses. This review also included research into public documents from the Colombian government and news articles on recent releases and events. In 2018, the authors also conducted a deep-dive study of e-bus efforts in Bogotá, to document the policy context and key stakeholders surrounding early e-bus efforts in the city. This study included interviews with city representatives, transit officials, utility and charging stakeholders, and researchers.

THE FUTURE MOBILITY CALCULATOR

To determine which e-bus adoption scenarios might work best for TransMilenio, given the nature of their system and the extent of their resources, TransMilenio staff consulted with WRI and explored the preliminary findings provided by the Future Mobility Calculator. The Future Mobility Calculator is a tool that, for a given range of city-specific inputs (general city data, mobility data, electric infrastructure data and cost data) and a projected electric transport adoption scenario, estimates the **costs** of vehicles and infrastructure, and the **benefits** of health and environmental improvements that would result. The Future Mobility Calculator is not intended primarily to provide a comparative cost–benefit analysis against other propulsion technologies such as diesel or CNG. These types of comparisons are addressed in other literature and tools, including recent work produced by WRI.[29] Instead, the main purpose of the tool is to forecast the costs, requirements and benefits of electrification scenarios, which are needed to effectively plan for future electric vehicle use.

The tool is designed to accommodate inputs for four modes of motorised transit: private car, private two-wheeler, public bus and shared fleet vehicle. The user designates a desired future transport electrification scenario for the city for the years 2035 and 2050. In the analysis performed for TransMilenio, the tool was used to specifically look at public buses through to 2035.

In addition to user-specified inputs, the tool is programmed with over 500 default data points, which help to fill gaps in the user's data. Based on the city's density and economy, these default inputs are sourced from four pre-loaded city typologies:

(1) emerging economy – high density; (2) high-income economy – low density; (3) high-income economy – high density; and (4) emerging economy – low density. While no planning tool can provide forecasts with absolute certainty, the Future Mobility Calculator uses these different city typographies to source specific default inputs that are most applicable to the city in question.

The Future Mobility Calculator is specifically designed to conduct city-level analysis, but the geographic extent of the analysis can be modified depending on how the user defines limits in the inputs.

The Future Mobility Calculator is specifically designed to conduct city-level analysis, but the geographic extent of the analysis can be modified depending on how the user defines limits in the inputs. As an example, the tool was used previously in an electric vehicle charging infrastructure forecast report which examined data at the country level.[30] Using the inputs manually entered by the user in conjunction with default inputs, the tool estimates the GHG emissions, air quality improvements, land-use changes, electricity consumption, and required number and type of electric vehicle charging stations.

TransMilenio staff used the preliminary results for Bogotá produced by the tool to help them explore the advantages and needed infrastructure for e-bus adoption, for a 2019 tender and beyond. Bogotá is the first of three city-level interactive workshops held to apply the tool in real-world scenarios and gather feedback for improvement. The other two workshops were held in Beijing and Delhi. The Future Mobility Calculator is slated to be launched for public use online in 2020 and will be released alongside a detailed technical note.

THE POLICY-MAKER AND PRACTITIONER WORKSHOP

WRI introduced the Future Mobility Calculator to TransMilenio staff through a workshop in March 2019. The workshop served two main purposes: (1) to provide TransMilenio information on the infrastructure requirements and potential costs and benefits of the electrification process; and (2) to collect technical and usage feedback on the tool from TransMilenio.

To maximise the utility of the workshop, WRI staff primed the Future Mobility Calculator with data specific to the City of Bogotá. To the largest extent possible, pre-collected information for the City of Bogotá was entered into the tool to amend the default assumptions. The city-specific data were taken from desktop research from a variety of primary and secondary sources. Table 1 provides a sample of some of the major Bogotá-specific information that was collected and entered into the tool.

Table 1: Select input data used in the Future Mobility Calculator at the workshop in Bogotá (2019)

CATEGORY		
Population		7,877,830
Average annual population growth rate		1.2%
City population density (residents/km^2)		17,501
Per capita annual income (2010 US$)		US$8,275
Total average electricity consumption in city per day (TWh)		139.46
Composition of electricity generation mix	2019	2035
Coal	0%	0%
Natural gas	35%	0%
Oil	0%	0%
Renewables*	65%	100%

* Renewables includes hydro, wind and solar power.

The one-day workshop consisted of two sessions. In the first session, the WRI research team presented the tool to TransMilenio technical staff, who then used the tool to develop and analyse four different electrification scenarios. In the second session, members of TransMilenio's managerial and advisory team discussed and reflected on the scenarios developed in the first session. One representative of each team who devised a scenario in the first session presented their scenario to the managerial team. The results and discussion from the workshop are summarised below.

5. Key findings

TransMilenio staff developed four electric bus scenarios examining different levels of electrification in the upcoming Phase V tender, which they expected to include 1,661 buses. During the workshop in March 2019, staff explored these four different scenarios, listed below:

- **Scenario 1: All Phase V buses electrified.** TransMilenio Staff estimated that this would result in 1,661 new e-buses during the tender.
- **Scenario 2: Half of Phase V buses electrified.** Staff estimated that this would result in 831 new e-buses during the tender.
- **Scenario 3: Only Phase V feeder (local access) route buses electrified.** Based on the current fleet make-up, Scenario 3 was estimated to result in 478 buses electrified during the tender.
- **Scenario 4: Only routes in the Suba neighbourhood electrified.** This was the least ambitious scenario, which targeted a single neighbourhood for a limited e-bus expansion. Staff estimated that this would result in 117 buses electrified during the tender.

All of the buses included in the tender are of roughly the same size and technical specifications. In Scenarios 2–4, it is assumed that the remainder of the buses in the tender would meet Euro 6 emission standards.

For each of the four scenarios, the Future Mobility Calculator provided estimates related to future electricity consumption, emission reductions, health benefits and required infrastructure investments. Some of the provisional results are provided in the tables below. To be conservative, the results assume Phase V will be completed in 2035 with an annual deployment rate of 6.25% of the total tender, safely past the proposed time horizons discussed with TransMilenio staff. Using this timeline, the calculator does not take into consideration future rounds of investment beyond the Phase V tender or how buses will be replaced once they reach end of life. Each scenario was based on an electricity mix based on 65% renewable sources today and 100% in 2035.

To ensure the most accurate results possible, the figures below represent numbers recalculated after the conclusion of the workshop, which use the most up-to-date version of the tool (see below for more information on the improvements made to the tool after the workshop). Nevertheless, these results are still **preliminary**, as the tool is still in beta and has not yet been through a formal review process.

Table 2: Implications of different e-bus deployment scenarios in Bogotá, Colombia up to 2035 (preliminary results)

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Number of e-buses in bus fleet	1,661	831	487	117
Slow chargers needed for bus fleet	471	236	136	33
Fast chargers needed for bus fleet	157	79	45	11
Electricity needed for bus fleet (kWh/day)	339,250	169,727	97,629	23,897
Depot average electric power demand (MW)	14.14	7.07	4.07	1.00
Avoided GHG (kg/year)	106,096,375	53,080,125	30,532,250	7,473,375
Avoided PM_{10} (kg/year)	6,790	3,397	1,945	478
Avoided NO_x (kg/year)	509,263	254,785	146,555	35,872

Notes: Slow charger is defined as 80–149 kW; fast charger is defined as >150 kW.

As seen in Table 2, the four scenarios would require a wide range of charging and electricity needs and would provide a broad spectrum of environmental benefits. More aggressive scenarios provide substantially higher environmental benefits through avoided emissions, but they also require a larger deployment of charging infrastructure. Emissions values listed here are the estimated emissions that would have occurred if diesel buses had been implemented in the scenarios rather than e-buses (with emission factors as noted in the Appendix).

For Scenario 1, the annual estimated GHG emissions reduction of over 100,000 metric tonnes is equivalent to taking over 21,000 cars off the road.[31] The benefits of avoided PM_{10} and NO_x emissions would primarily be experienced locally, whereas the avoided GHG emissions would have a more global impact. From an energy perspective, the ambitious Scenario 1 is estimated to require roughly 340 MW of electricity per day to fuel the buses, which is equivalent to the daily electricity consumption of about 60,000 Colombian households.[32] While 340 MW is a significant amount of electricity, e-buses are at least 1.5 times as fuel efficient as the cleanest diesel buses (and often much more efficient).[33] Generally, the preliminary data in Table 2 provided TransMilenio staff with an idea of the level of commitment required and the anicipated environmental impacts that would be associated with different e-bus plans.[34]

The tool also provided direct monetary estimates for some of the costs and benefits for each scenario and allowed TransMilenio staff to examine these findings in a cost–benefit analysis. Table 3 provides a summary of this cost–benefit analysis. To provide a conservative estimate of the lifetime of the Phase V project, this analysis covers the entire time period from now until 2035, which is beyond the timeline discussed with TransMilenio regarding e-bus implementation.

Table 3: Analysis of selected costs and benefits (2010 million USD) (preliminary results)

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Selected costs				
Capital cost for the e-bus fleet	$290.680	$145.430	$83.650	$20.480
Total maintenance cost of the e-bus fleet	$15.160	$7.590	$4.360	$1.060
Capital cost for slow chargers	$5.652	$2.832	$1.632	$0.396
Capital cost for fast chargers	$4.663	$2.333	$1.342	$0.328
Total cost to install charging infrastructure	$90.472	$45.315	$26.102	$6.347
Total energy consumption for the buses	$0.223	$0.111	$0.064	$0.015
Selected costs total	$406.850	$203.611	$117.150	$28.626
Selected benefits				
Social cost avoided from GHG	$279.600	$148.889	$85.642	$20.962
Social cost avoided from PM_{10}	$167.651	$83.876	$48.246	$11.809
Social cost avoided from NO_x	$62.472	$31.254	$17.978	$4.400
Selected benefits total	$509.723	$264.019	$151.886	$37.171

Notes: All amounts are in millions of 2010 USD. This analysis examines the time period between now and 2035. Slow charger is defined as 80-149 kW, fast charger is defined as >150 kW.

Sources: See the appendix for more details on how the benefit figures are calculated.

As seen in Table 3, there are several components which contribute to the cost of implementing e-buses. For each scenario, the major cost is estimated to be the upfront capital expenditure needed to procure the e-buses, accounting for roughly 70% of the total estimated costs. Costs to install charging infrastructure and maintain the e-bus fleet are also substantial, jointly contributing to around 25% of the estimated total costs. For comparison, the upfront costs of procuring an e-bus is often around double the upfront capital cost of a diesel bus;[35] however, the total cost of ownership of an e-bus is typically lower than that of a diesel bus (since e-buses are cheaper to fuel and maintain).[36] Prices for e-buses vary dramatically based on the manufacturer, the specifications of the e-bus and the location of the transit agency.[37] For example, e-bus prices quoted (but not authenticated) through previous case studies ranged from roughly US$300,000 in Santiago, Belo Horizonte and Shenzhen, to US$475,000 in Izmir, US$600,000 in Cape Town and US$900,000 in Philadelphia. Due to this price variability, most global e-bus price-trend analyses use estimates and assumptions (based on the prices for different bus components). Fuel savings alone can recover about half the cost of an e-bus throughout its lifetime (roughly 10 years).[38]

To provide a cautious estimate of the benefits of adopting e-buses, only a few of the health and social benefits are examined in the cost–benefit analysis. These benefits include the social costs avoided for reductions of different emissions (i.e. GHG, PM_{10} and NO_x) but do not include specific considerations for other pollutants (such as hydrocarbon, CO and SO_2). Unlike costs, benefits for an e-bus project are hard to enumerate, let alone monetise. Monetary values were determined based on an extensive variety of factors, some of which were specified towards Bogotá as part of the prep work prior to the workshop.[39] Some of the key assumption values are displayed in the Appendix.

Even with a conservative estimate of the benefits, the selected benefits outweigh the selected costs in every scenario. In general, the selected benefits were determined to be roughly 1.25 times larger than the costs. The examination indicated that implementing e-buses would provide a strong net benefit to the city of Bogotá.

In addition to the insights provided by the tool to TransMilenio staff, workshop participants also provided insights to WRI on how the tool could be improved. Based on feedback from TransMilenio technicians, the tool was updated to correct various errors identified in the electric infrastructure calculation sheet and electric data entry cells. The tool was also adapted to allow users to manually enter a specific number of electric vehicles into the calculations. These improvements were incorporated into the tool after the conclusion of the workshop.

6. Limitations

Although the Future Mobility Calculator provides a robust calculation framework, it faces some limitations. The tool is not yet published, and it is still in the beta development stage with improvements ongoing and planned. As a part of this process, the Bogotá workshop provided the opportunity to test the calculator and collect feedback from local experts, and then improve the tool to better serve local policy-makers. Prior to publishing the Future Mobility Calculator, several aspects of the tool will be updated to improve overall functionality and provide the most accurate and updated results. For example, the dollar amounts in the tool are currently calculated in 2010 US dollars; when the calculator was first conceived this conversion was appropriate, but it is now outdated and will be updated accordingly. Similarly, the tool currently provides results for 2035 and 2050; to better facilitate both short-term and long-term forecasting, WRI plans to improve the tool to allow for a more flexible and detailed planning timeline, which can include more than two forecast periods and provide year-by-year results.

Another important aspect to note about the Future Mobility Calculator is that the tool's cost–benefit analysis does not provide a comparison between different bus technologies (like electric, CNG or diesel). The tool is not intended to help cities decide which propulsion systems would be best for their bus fleets. These types of comparison are addressed in other literature and tools, including recent work produced by WRI.[40] Instead, the Future Mobility Calculator is designed to provide estimates of the electricity, land and infrastructure needs for a given electrification scenario and an analysis of the associated costs and benefits.

With regard to the social and health impacts associated with electric vehicle adoption and emissions reductions, these values are often controversial and can be difficult to accurately quantify. Conscious of this reality, the tool provides estimates of these values that may not necessarily reflect the real costs. Assumptions including the social costs specifically associated with kilograms of certain emissions are highly debated and there is little consensus on their values. The provided estimates of social and health benefits are therefore imprecise and are intended as benchmarks rather than exact monetary values.

7. Scaling up

The experience in Bogotá can help to inform the adoption of e-buses in multiple ways. For TransMilenio officials, the outcomes from the Future Mobility Calculator can be directly applied to scaling up the procurement and business models for future tenders. As TransMilenio staff continue to tailor their use of modelling tools, such as the Future Mobility Calculator, they will be better prepared to anticipate the costs and requirements of future e-bus rollouts, including the additional 2,000-plus buses that are expected to be put out to tender soon, for subsequent stages of TransMilenio's procurement plan. Based on the estimates described in the tables above, there are clear social and environmental benefits to adopting e-buses in Bogotá; these benefits can be leveraged to gain political and economic support to advance e-buses in Bogotá.

In November 2019, following the outcomes of the workshop, TransMilenio completed a new bus tender (Stage One of their Phase V tender). Through this tender, TransMilenio purchased 379 buses.[41] Unlike the tender from the previous year, which procured zero e-buses, **all** of the buses in this new tender will be electric. The following month, TransMilenio procured another 104 e-buses, bringing the total number of procured e-buses to 483. While these e-buses will not be operational until they are successfully delivered and tested (which is expected to start in September 2020), this plan already represents a marked advancement in e-bus policy in Bogotá.

Despite the focus of this case study on Bogotá, many beneficiaries from Bogotá's experience are likely to be located in other cities. The input and feedback from technicians in Bogotá will be used to improve the accuracy and applicability of the Future Mobility Calculator. In turn, the pending e-bus delivery to Bogotá will allow the tool to be checked and calibrated against actual cost and benefit data collected by TransMilenio in the future. The lessons learned from Bogotá will directly help improve the Future Mobility Calculator and allow it to benefit more cities and countries worldwide.

8. Conclusions

An examination of Bogotá's e-bus endeavours reveals the trials and tribulations that are universally inherent in electrifying bus fleets. E-buses provide great potential to reduce local pollution in Bogotá while bringing a slew of co-benefits to TransMilenio and Bogotanos. Policy-makers in Bogotá, however, have struggled to overcome a lack of political momentum and the technological challenge of electrifying their articulated buses, which are the workhorses of their fleet. Nevertheless, Bogotá has demonstrated the institutional support to adopt e-buses, going beyond the steps taken in most other cities, especially those outside of China. Bogotá provides a bold and ongoing story of how a transit agency can use tools such as the Future Mobility Calculator to provide an idea of what lies ahead before they enter the unchartered territory of large-scale bus electrification. It also offers valuable insights for national governments looking to deploy electric buses at greater scale to achieve their health and environmental objectives.

The outcomes from Bogotá provide a foundation for much work yet to be done. Bogotá has set ambitious goals for electrifying their bus fleet, as have cities and countries around the world. These electrification objectives will only be achieved, however, through prudent planning. Planning, in turn, requires solid forecasts of the expected costs and benefits associated with the project. As national and local governments are able to understand how the numbers pencil out on electrification efforts, they will be able to intelligently navigate their own planning processes, as Bogotá is doing with the release of their Phase V tender.

Appendix: Benefit calculation methodology

The process for calculating the value of social benefits is inherently subjective (more so than many of the other calculator results which are more intuitive to quantify). Given the ambiguity in monetising the value of social benefits, this appendix is included to describe the methodological approach taken in the Future Mobility Calculator to determine the cost of the selected benefits listed in Table 3. Below are descriptions of the calculation methodology, followed by tables with the key assumptions used in the analyses.

- For each of the selected emissions (GHG, PM_{10} and NO_x), the social cost avoided was determined by multiplying the emission reduction amount in each scenario by the value of the social costs associated with a kilogram of each emission.
- The amount of reduced emissions was determined by multiplying the annual bus kilometres travelled by their diesel emission factor.
- The factors determining the "value of social cost" are complex and vary by emission type and source. In general, these values were calculated based on the following considerations (see the cited sources for more information on these assumptions):
  - **Market damages,** loss of tradable goods from pollution (especially agricultural yield loss)
  - **Non-market damages,** including the loss value to health or ecosystems (including hospital visits for respiratory issues, days of restricted outdoor activities), and the cost of increased regional poverty and conflict.
- As mentioned in the report, these values are subjective in nature and are only intended to provide a general estimate for initial planning purposes.

Table A.1: Key diesel bus emission factors assumed for Bogotá in the Future Mobility Calculator

EMISSION TYPE	DIESEL EMISSION FACTOR (KG/KM)	SOURCE	VALUE OF SOCIAL COST ($/KG) (USD 2010)	SOURCE
CO_2eq	1.25	Cooper et al (2019)	$0.33[1]	UK Department for Environment, Food and Rural Affairs - AEA Technology Environment (2005); Victoria Transport Policy Institute, (2018)
PM_{10}	0.000478	US EPA (2008)	$478.18[2]	Rowan Williams Davies and Irwin Inc (RWDI). (2006); Victoria Transport Policy Institute, (2018)
NO_x	0.008	Cooper et al (2019)	$10.82[3]	AEA Technology Environment (2005); Victoria Transport Policy Institute, (2018)

Table notes

1. The value of social cost for CO_2eq is originally sourced by UK Department for Environment, Food and Rural Affairs - AEA Technology Environment (2005) and included in table 5.10.4-14 in Victoria Transport Policy Institute (2018). This number represents the upper bound estimate of the abovementioned sources, since this figure was on par with other estimates in other major sources (such as Downing et al. (2005) who indicate this figure is well within one standard deviation of the average estimates). This number was converted from dollars per ton to dollars per kilogram and then adjusted for inflation to 2010 USD.

2. The value of social cost for PM_{10} is originally sourced by Rowan Williams Davies and Irwin Inc (2006) and included in table 5.10.4-1 in Victoria Transport Policy Institute (2018). Since it is difficult to find reliable and robust sources for information on the value of the social cost associated with PM_{10}, this figure represents a number provided for $PM_{2.5}$, which was converted to PM_{10} by dividing by a conversion factor of 0.6, based on WHO (2014). This number was converted from dollars per ton to dollars per kilogram and then adjusted for inflation to 2010 USD.

3. The value of social cost for NO_x is originally sourced by AEA Technology Environment (2005) and included in table 5.10.4-1 in Victoria Transport Policy Institute (2018). This number was converted from dollars per ton to dollars per kilogram and then adjusted for inflation to 2010 USD.

All inflation adjustments are based on the US Inflation Calculator, available at: https://www.usinflationcalculator.com/.

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