WORKING PAPER

AUGUST 2024

Quantifying avoided greenhouse gas emissions by e-buses in Latin America: A simplified life-cycle assessment methodology

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INTRODUCTION

The E-BUS RADAR web platform tracks the deployment of battery electric buses (BEB) and trolleybuses in the public transport systems of Latin American cities and their associated reductions in greenhouse gas (GHG) emissions compared with conventional models (E-BUS RADAR, 2024). Built and maintained by members of the Zero Emission Bus Rapid-deployment Accelerator (ZEBRA) partnership, with support from Instituto Clima e Sociedade (ICS), the E-BUS RADAR platform had mapped 5,068 e-buses operating in the public transportation fleets of 41 cities in 12 Latin American countries as of the end of 2023.[1]

This work presents a methodology designed to upgrade the platform's capacity to calculate the GHG emissions avoided by the introduction of BEBs. The methodology applies a life-cycle assessment (LCA) to estimate the GHG emissions of electric and equivalent internal combustion engine (ICE) buses, accounting for tailpipe emissions and the emissions associated with vehicle and battery manufacturing, maintenance, and fuel and electricity production.

As an agile and frequently updated platform, E-BUS RADAR requires a robust and flexible methodology, which, in turn, calls for simplifying assumptions. Thus, we assign buses to five categories: 12–15 m trolleybuses, 18+ m trolleybuses, 8–11 m BEBs, 12–15 m BEBs, and 18+ m BEBs; the latter represents articulated and bi-articulated models. For each bus category and city, vehicle manufacturing, maintenance, and battery emissions are estimated based on technical and operational information, such as average energy efficiency, battery capacity, weight, and annual vehicle kilometers traveled. Country-

1 As of December 2023, the 12 countries mapped by the E-BUS RADAR platform are: Argentina, Barbados, Brazil, Chile, Colombia, Ecuador, Guatemala, Mexico, Paraguay, Peru, Uruguay, and Venezuela.

Acknowledgments: Funding for this work was generously provided by Instituto Clima e Sociedade.

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specific values are applied for biodiesel blends, the carbon intensities of different feedstocks, and the electrical grid.

The objective of this updated methodology is to ensure that E-BUS RADAR can provide up-to-date information on the implementation of BEBs in Latin America with reliable estimates of their life-cycle emissions reduction potential.

SCOPE OF THE STUDY

The avoided GHG emissions achieved with the electrification of bus fleets are calculated as the difference between the emissions of the ICE buses replaced and the deployed electric buses. Emissions include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), represented in grams of CO_2 equivalent (CO_2e) and based on the 100-year global warming potential factors provided by the Intergovernmental Panel on Climate Change (2021).

The LCA approach adopted in this study considers the GHG emissions produced during the operational life of a bus, which includes emissions from manufacturing and maintenance (vehicle cycle), and from fuel and electricity production and use (energy cycle).[2] Table 1 presents the GHG emissions considered in the scope of this study.

Table 1
GHG emissions scope considered in this study

Emissions cycle	Scope	Description
Vehicle cycle emissions	**Glider and powertrain**	Bus production, including raw material extraction and processing, components manufacturing, and bus assembly
	Battery	Battery pack production, including raw material extraction and processing, components manufacturing, and battery pack assembly
	Maintenance	In-service replacement of parts and accessories, including tires, oil, coolant, among others
Energy cycle emissions	**Fossil fuels**	• Oil extraction, transport, and processing • Fuel refining and distribution • Fuel combustion
	Biofuels	• Feedstock cultivation, transport, and processing • Fuel production and distribution • Indirect land-use change emissions of feedstock cultivation for crop-based biofuels
	Electricity	Electricity generation, including power plant infrastructure, transmission, distribution, and charging losses

Note: Glider refers to the body and chassis of the vehicle without its powertrain.

In the vehicle cycle, the calculation considers the emissions associated with battery production for electric buses, and the emissions of the rest of the vehicle—glider and powertrain—for both electric and ICE buses. This cycle also considers the emissions generated during bus maintenance.

The energy cycle, either for the fuel used by ICE buses or the electricity used to charge electric buses, includes well-to-tank (WTT) emissions from the energy production and tank-to-wheel (TTW) emissions from use. Well-to-tank emissions include emissions from energy source extraction, fuel production, and distribution. Tank-to-wheel emissions correspond to the emissions of the vehicle during the combustion of the fuel. The emissions from the complete energy cycle are referred to as well-to-wheel (WTW) emissions.

2 This study follows the same LCA approach adopted in Bieker (2021) and O'Connell et al. (2023).

For crop-based biofuels, the energy cycle also includes indirect land-use change (ILUC) emissions. Indirect land-use change occurs when an increase in feedstock demand for additional biofuel results in land conversion displacing existing activities, such as agricultural production. Emissions from ILUC are greatest when increased biofuel demand results in the conversion of lands with high carbon stock that were not previously used for agriculture.

Emissions associated with infrastructure for electric bus charging or fuel distribution and bus recycling are not included in the scope of this study. These are considered to either be similar across different technologies or have a low impact on total life-cycle emissions.

BUS DATA COLLECTION

One of the main challenges of the E-BUS RADAR platform is the collection of reliable data about bus operations across Latin America cities. Operational data and vehicle technical information are needed to calculate avoided emissions, as detailed in Table 2. The technical information needed includes the bus model and manufacturer, bus size, vehicle mass, and battery capacity. Bus operational characteristics comprise the number of buses in operation by bus size, bus lifetime, annual distance traveled, and energy consumption per kilometer.

Table 2

Bus data required for each Latin American city with electric buses deployed to estimate the avoided emissions

Data category	Variables	Source
Vehicle characteristics	• Size of the bus (m), vehicle mass (kg) • Bus manufacturer and model • Battery capacity (kWh) for electric buses	• Official publications of the cities • Technical documents provided by bus manufacturers • Media articles
Operational characteristics	• Lifetime (years), annual distance traveled (km), energy consumption (L/km for ICE and kWh/km for electric), air-conditioning (yes or no) • Fleet size: number of buses by bus size	

Table 2 also describes the data sources used for these variables. We adopt official information whenever available and complement the data with bus technical characteristics provided by manufacturers. However, official information is not always available for electric buses deployed in all Latin American cities included in the platform. To increase the platform's regional representativeness, operational data collected from media articles is used. Only electric buses in operation in the public transportation systems are included in the database, and we do not consider those used in private fleets or used for testing or demonstration purposes.

Detailed electric bus technical and operational data is available from 11 cities: São Paulo (BRA), Curitiba (BRA), Mexico City (MEX), Guadalajara (MEX), Santiago (CHL), Las Condes (CHL), La Reina (CHL), Valparaiso (CHL), Bogota (COL), Medellin (COL), and Cali (COL). For the other cities, less detailed data is available; the minimum information collected is typically the number of electric buses purchased, bus size, and manufacturer; the model is also sometimes collected. Additional information is needed to calculate emissions, such as bus weight, energy consumption, and annual distance travelled. For cities with data gaps, missing information is filled using average values for similar-sized buses in different cities in the same country. If specific information is not available for a given country, a mean of the region is adopted.

VEHICLE AND OPERATIONAL CHARACTERISTICS

Table 3 summarizes the mean vehicle characteristics adopted for each bus category. We collected data for vehicle and operational characteristics of e-buses in 11 different cities from Brazil, Chile, Colombia, and Mexico in 2023, which are summarized in appendix Table A1. City specific data is aggregated by country and bus size; averages are used to fill missing information of other cities, as described in the previous section. Table 3 details the average values for battery capacity and bus weight by bus category considering the data collected. We adopted the passenger capacity information and the average passenger mass of 65.306 kg from the case of São Paulo (Prefeitura de São Paulo, 2018b).

Table 3
Mean vehicle specifications

Type	Size (m)	Passenger capacity	Battery capacity (kWh)	Glider and powertrain mass (kg)	
				Electric	ICE
BEB	8–11	61	248	8,987	6,016
BEB	12–15	87	335	14,880	11,429
BEB	18+	129	533	24,133	18,800
Trolleybus	18+	129	152	20,000	18,800
Trolleybus	12–15	87	30	10,318	10,318

Data on bus operational characteristics are summarized in Table 4, which presents Latin America averages. It lists the mean values for BEB lengths of operation (years), annual distances traveled (km/year), BEB energy consumption (kWh/km and MJ/km), and diesel equivalent energy consumption (MJ/km) for the five bus types and sizes considered in this analysis. The country-specific values used to obtain these means are presented in Table A1 in the appendix. Although we observe variations, in most cases, they are limited for the four countries for which we have collected data. For annual distances traveled in all countries by buses of all types and sizes, the maximum variation is about 33%, from 60,000–80,000 km/year, with a mean of 67,029 km and a standard deviation of 7,464 km. Energy consumption varies between 1.24 and 1.5 kWh/km among 12–15 m BEBs, and between 0.77 and 0.98 kWh/km for smaller 8–11 m BEBs. More meaningful variations are observed between different models. For instance, the trolleybuses with large Lithium-ion batteries deployed in Mexico consume about 44% less energy than older models in Brazil, Colombia, and Chile.

Table 4
Mean standard vehicle operational characteristics

Type	Size	Time in operation (years)	Annual distances (km/year)	Energy consumption kWh/km (MJ/km)	Diesel equivalent energy consumption (MJ/km)
BEB	8–11	15	62,554	0.92 (3.31)	12.4
BEB	12–15	15	67,296	1.36 (4.90)	18.5
BEB	18+	15	71,384	1.76 (6.34)	25.8
Trolleybus[a]	18+	15	80,000	1.74 (6.26)	27.4
Trolleybus	12–15	15	66,384	3.28 (11.81)	19.5

[a] We only collected data from 18+ m trolleybuses from Mexico City. These are newer models with large batteries and, thus, are more energy efficient than the average, older 12–15 m trolleybuses identified in other countries in the region.

VEHICLE AND BATTERY MANUFACTURING, MAINTENANCE, AND RECYCLING EMISSIONS

The bus weight and battery capacity values are used to calculate emissions from vehicle and battery manufacturing and recycling. Maintenance emissions are a function of annual km traveled and years in operation. For battery electric and ICE gliders and powertrains, we apply a fixed emission factor of 6.6 kg CO_2e/kg (O'Connell et al., 2023). We assume all vehicles are equipped with LFP-Graphite (Lithium-ion iron phosphate) batteries with emissions equivalent to 58 kg CO_2e/kWh (Bieker, 2021) and battery density of 0.14 kWh/kg (Basma, et al., 2021). The methodology assumes a fixed project length of 15 years for BEBs with a battery replacement after year 7 or 8 of operation. Thus, the calculation considers emissions equivalent to the manufacturing of one BEB and two batteries. To maintain the same period of analysis for ICE buses, which are usually operated for 10 years, the tool considers emissions equivalent to the manufacturing of 1.5 ICE buses.

Maintenance emissions are based on the maintenance emission factors for 12 m urban buses from Hill et al. (2020), which is 52.4 gCO_2e per vehicle kilometers traveled (vkm) for diesel buses and 67.5 gCO_2e/vkm for electric buses.

FUEL AND ELECTRICITY EMISSIONS

The emissions from the fuel and electricity cycle include the GHG generated by the production and consumption of the energy used by the vehicle, whether it is a fossil fuel, biofuel, or electricity. The energy cycle emissions include the WTT emissions, which correspond to the emissions generated during fuel and electricity production, and TTW emissions, which are the tailpipe emissions generated during fuel combustion.

Table 5 shows the GHG intensity data adopted for the main fuels used by ICE buses in Latin America. We use CO_2e emissions data from the GREET model (ANL, 2022),[3] considering the values reported for a 100-year global warming potential horizon. For biofuels, non-biogenic GHG emissions are considered in the TTW emissions.

Table 5
Well-to-tank, tank-to-wheel, and well-to-wheel emissions in gCO_2e/MJ from the GREET model

Feedstock	Well-to-tank	Tank-to-wheel	Well-to-wheel
Soybean biodiesel	17.31	4.63	21.94
Palm biodiesel	29.87	4.63	34.50
Tallow biodiesel	15.51	4.63	20.14
Used cooking oil (UCO) biodiesel	14.89	4.63	19.52
Fossil diesel	15.75	75.66	91.41

The GREET model uses the carbon intensity of the electricity grid as an input to define WTT emissions. These values are based on the U.S. electricity grid, which has a carbon intensity of 466.5 gCO_2e/kWh. The U.S. electricity grid has a similar carbon intensity factor to Chile (416.9 gCO_2e/kWh). We performed a sensitivity analysis and calculated the WTT emissions from GREET assuming a 100% decarbonized grid. The differences across WTT emissions for the biofuels considered in this study range between 2 and 4

3 Argonne National Laboratory. (2022). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) (Version 2022), https://greet.es.anl.gov/ index.php

gCO_2e/MJ, depending on the feedstock. This difference would not provide a significant change in the results, and we used the same WTT emissions factors for all countries.

The biodiesel blend share by country is sourced from the ICCT Roadmap model (ICCT, 2022). Of the 12 countries in Latin America with e-buses in their fleet, four have a mandatory blend of biodiesel in diesel in place, as presented in Table 6.[4] Biodiesel feedstock shares are retrieved from the U.S. Department of Agriculture 2022 Biofuels Annual reports for Brazil, Argentina, Peru, and Colombia (USDA, 2022a, 2022b, 2022c, 2022d). We calculate feedstock shares using 2021 data.

Table 6
Biodiesel blends in diesel, feedstock shares, and share of imported biodiesel by country

	Biodiesel share	Feedstock				Import percentage	Origin of imports
		Soybean oil	Animal fat (tallow)	Used cooking oil	Palm oil		
Brazil	12%	82.2%	12.8%	2.1%	2.9%	0.0%	–
Argentina	9.60%	100.0%	0.0%	0.0%	0.0%	0.0%	–
Peru	3.84%	0.0%	0.0%	0.0%	100.0%	51.0%	Spain (41%), Indonesia (30%), Malaysia (21%), Netherlands (8%)
Colombia	0.40%	0.0%	0.0%	5.2%	94.8%	0.0%	

We also add ILUC emissions for crop-based biofuels. These emissions are estimated with economic models that measure the net change in land use globally and are paired with an emission factor to estimate the associated GHG emission impacts. ILUC emissions are site-specific, as they depend upon the economic characteristics and trade patterns of the region. Table 6 shows that the biodiesel in the four countries considered is mainly produced domestically, except for Peru, where 51% of it is imported.

For biodiesel produced from soybean oil in Brazil and Argentina, we adopt the ILUC factors for soy-derived fuels in Brazil developed as part of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (International Civil Aviation Organization, 2020). Although CORSIA is a carbon accounting program for international aviation, we consider the ILUC factors applicable to our analysis because they correspond to the supply chain of biofuel feedstocks; In this context, there is almost no difference between the supply chains for soy used to produce biodiesel or sustainable aviation fuel. For the share of palm biodiesel in Peru imported from Indonesia and Malaysia, we also adopt CORSIA's ILUC values. CORSIA does not include ILUC factors for palm cultivated in Brazil, Peru, and Colombia, and, to our knowledge, similar modeling has not been conducted for these feedstocks. Due to this limitation, we adopt zero for their ILUC emissions, which can be considered a conservative approach as it underestimates the avoided emissions achieved with the introduction of BEBs and trolleybuses.

Table 7 shows the ILUC carbon intensities considered for this analysis. The two economic models applied for estimating ILUC emissions in CORSIA are GTAP-BIO and GLOBIOM. In our study, we apply both values to estimate a variation range for the emissions.

4 Besides these other four countries, Uruguay also had a biodiesel blend mandate, which was 5% by 2021. However, we excluded the country from this list as this mandate was canceled in November of 2021 after the publication of Law n.º 19.996 (https://www.gub.uy/ministerio-industria-energia-mineria/politicas-y-gestion/programas/agrocombustibles).

Table 7
CORSIA's ILUC emission values for soy and palm-derived fuels in Brazil, Malaysia, and Indonesia

Region	Feedstock	gCO_2e/MJ	
		GTAP-BIO	GLOBIOM
Brazil	Soy oil	22.5	117.9
Malaysia and Indonesia	Palm oil (open/close pond)	34.6	60.2

Source: International Civil Aviation Organization (2020)

The TTW emissions are zero for trolleybuses and BEBs, as they do not produce tailpipe emissions, but their WTT emissions depend on the energy sources used to generate electricity. We use the 2021 GHG intensity values for electricity production from Ember Climate (2021), retrieved from the Our World in Data platform.[5]

Table 8 presents the 2021 carbon intensity of electricity production for the current countries mapped in E-BUS RADAR. These are static and ignore future deployment of renewable energy sources, which can reduce the carbon intensity of e-buses WTT emissions during their lifetime. Thus, we multiply the 2021 carbon intensities by the percentage reductions projected in International Energy Agency's Stated Policies scenario (International Energy Agency, 2022). Individual carbon intensity projections are provided for Brazil and Mexico, and a unique growth projection is provided for the other Latin American countries. Figure 1 presents the carbon intensity variation projections adopted for Brazil, Mexico, and other countries in this analysis, and provides an example of the projected carbon intensities for Brazil, Mexico, Chile, and Colombia.

Table 8
Carbon intensity of electricity by country in 2021

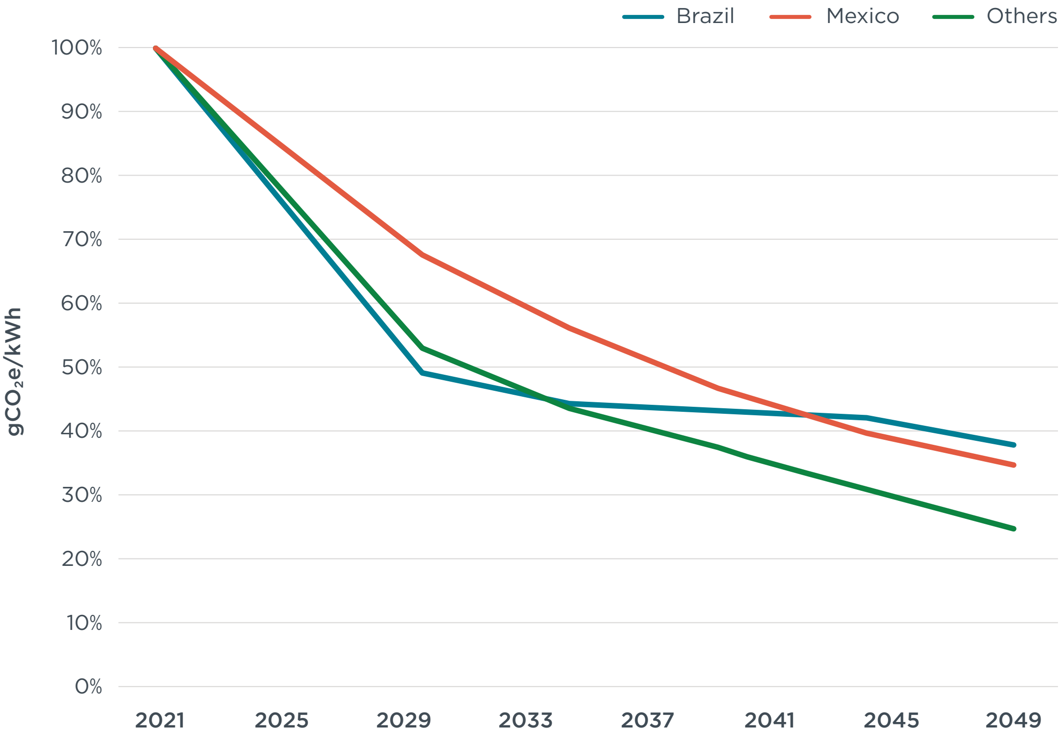
Country	Carbon intensity of electricity (gCO_2e/kWh)
Argentina	357.8
Barbados	644.9
Brazil	158.6
Chile	416.9
Colombia	181.7
Ecuador	136.1
Guatemala	313.0
Mexico	399.9
Paraguay	25.5
Peru	228.6
Uruguay	147.3
Venezuela	189.4

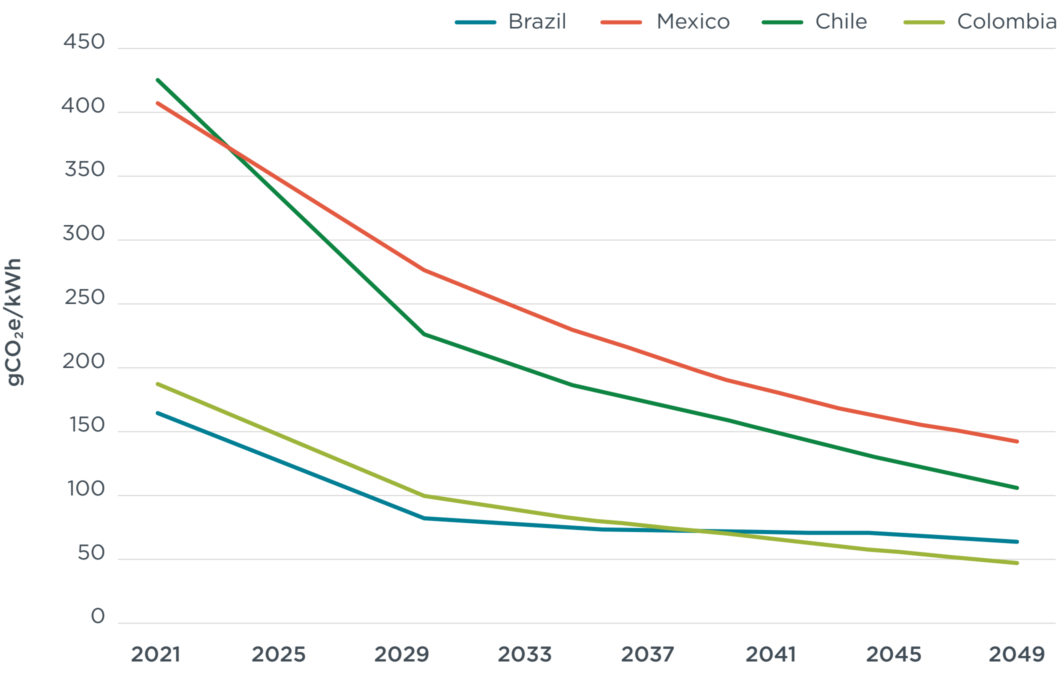
Source: Ember Climate (2021)

5 Carbon intensity of electricity from Our World in Data platform available at https://ourworldindata.org/grapher/carbon-intensity-electricity.

Figure 1

Projections for grid carbon intensity as a percentage (top) and in gCO_2e/kWh for selected countries (bottom)





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CALCULATING AVOIDED GHG EMISSIONS

This section describes how the data presented above is applied to calculate life-cycle emissions avoided with the introduction of BEBs. The following equations detail the calculations for the emission avoided by one BEB.

Subscript k indicates the size and type of the BEB and its correspondent ICE bus, listed in Table 3. Countries and cities are specified by subscripts i and j, respectively. For diesel buses, the analysis considers the environmental impacts of biodiesel produced from different crops (c). Given the level of uncertainty and variation to calculate the carbon intensity of ILUC emissions, we present the lowest and highest emissions values from the two different models considered: GTAP and GLOBIOM (International Civil Aviation Organization, 2019). These two options for ILUC emissions are denoted by subscript l.

ICE BUSES

Equation 1 is used to calculate the life-cycle emissions for ICE buses, split between vehicle manufacturing and maintenance, fuel production, and fuel consumption or tailpipe emissions. We calculate the glider and powertrain mass (Mass) as the gross vehicle's weight (GVW) net of its passenger capacity *(CAP)* (data available in Table 3) multiplied by the average passenger mass $\kappa = 65.306\ kg$ (Prefeitura de São Paulo, 2018b) (Equation 2). Vehicle cycle emissions ($E\_vehicle^{ICE}$)account for the vehicle manufacturing emissions and the maintenance emissions throughout its lifetime. We multiply the vehicle's mass by the fixed manufacturing emissions parameter of 6.6 kg CO_2e/kg (O'Connell et al., 2023) (α) and by 1.5, since we consider 15 years of operation, and we assume that ICE buses are typically used for 10 years. Maintenance emissions are estimated by multiplying its emission factor of 52.4 gCO_2e/km (Hill et al., 2020) (τ^{ICE}) by years of operation and annual kilometers traveled.

$$E\_vehicle^{ICE}_{ijk} = \underbrace{\alpha.1.5.Mass^{ICE}_{k}}_{\text{Vehicle production}} + \underbrace{\tau^{ICE}.Y.VKT_{ij}}_{\text{Vehicle maintenance}} \quad \text{(Equation 1)}$$

$$Mass^{ICE}_{k} = GVW^{ICE}_{k} - k.Cap_{k} \quad \text{(Equation 2)}$$

Well-to-tank emissions from fuel production depend on whether and which ILUC factors are included (Equation 3) and the carbon intensity (ψ) of fuel production (Equation 4). The ILUC factors considered in this study are presented in Table 7. The carbon intensity of fuel production (ψ) is a function of the percentage of biodiesel blended in diesel (ρ_bd), the percentage of each biomass (ρ_{crop}) used to produce the biodiesel, and the carbon intensities of fuel production for fossil diesel (ψ^{diesel}) and biodiesel ($\psi^{biodiesel}$) which assess the emissions related to feedstock extraction, transportation, distribution, and industrial processes. The biodiesel blend information in each country, including biodiesel share and feedstock share, is detailed in Table 6. The carbon intensities of fuel production are presented in Table 5. Equation 5 calculates the fuel production emissions (E_fuel_{WTT}) by multiplying the carbon intensity of its production (ψ) by the total fuel demand, which is a function of annual vehicle kilometers traveled *(VKT)*, years of operation (*Y*), and vehicle energy consumption (ε^{ICE}, in MJ/km). The average operational data (annual vehicle kilometers traveled, years of operation, and vehicle energy consumption) is presented in Table 4, and the country-specific values are detailed in Table A1 in the appendix.

$$ILUC_{cl} = \begin{cases} min\ (ILUC_C^{GTAP}, ILUC_C^{GLOBIOM})^{0} \\ max\ (ILUC_C^{GTAP}, ILUC_C^{GLOBIOM}) \end{cases} \quad \text{(Equation 3)}$$

$$\Psi il = \left(p\_bd_i \sum_C \rho_{crop_{cit}} . (\Psi_C^{biodiesel} + ILUC_{cl}) \right) + (1 - p\_bd_i) . \Psi^{diesel} \quad \text{(Equation 4)}$$

$$E\_fuel\_WTT_{ijkl}^{ICE} = \Psi il . \varepsilon_{jk}^{ICE} . Y_t . VKT_{ij} \quad \text{(Equation 5)}$$

The final step is to calculate tailpipe emissions, also known as tank-to-wheel emissions *(TTW)*. Its carbon intensity (Equation 6) also depends on biodiesel blends *(ρ_bd)*, its biomass composition (ρ_{crop}), and the carbon intensity of fossil (ω^{diesel}) and biodiesel ($\omega^{biodiesel}$) tailpipe emissions. Multiplying this carbon intensity (ω) by vehicle energy efficiency (ε^{ICE}), years of operation (*Y*), and annual kilometers traveled *(VKT)* results in total combustion or tank-to-wheel emissions *(E_fuel_TTW)* (Equation 7). Biodiesel blend information is shown in Table 6, and the carbon intensity of tailpipe emissions is presented in Table 5. Operational data is detailed in Table 4, and in Table A1 in the appendix.

$$\omega_{it} = \left(p\_bd_{it} \sum_c p_{crop_{cit}} \cdot \omega_c^{biodiesel} \right) + \left(1 - p\_bd_{it}\right) . \omega^{diesel} \quad \text{(Equation 6)}$$

$$E\_fuel\_TTW_{ijk}^{ICE} = \omega_{it} \cdot \varepsilon_{jk}^{ICE} . Y . VKT_{ij} \quad \text{(Equation 7)}$$

Total life-cycle emissions for one typical ICE bus (Equation 8) are the sum of the three components explained above.

$$E_{ijkl}^{ICE} = E\_vehicle_k^{ICE} + E\_fuel\_TTW_{ijk}^{ICE} + E\_fuel\_WTT_{ijkl}^{ICE} \quad \text{(Equation 8)}$$

ELECTRIC BUSES

For BEBs and trolleybuses, we sum the vehicle cycle emissions, including glider and powertrain production, battery manufacturing, and maintenance emissions, to those generated in electricity production, transmission, and distribution.

For the vehicle cycle emissions *($E\_vehicle^{BEB}$)*, we first subtract the mass of the maximum passenger capacity and battery from the gross vehicle weight to obtain glider and powertrain mass (Equation 9). The mass of maximum passengers is again calculated by multiplying the bus passenger capacity *(CAP)* (detailed in Table 3) and the average passenger mass (κ) of 65.306 kg (Prefeitura de São Paulo, 2018b). The battery mass is the product of battery capacity (*Batt,* in kWh) and the inverse of the battery density (δ, in kWh|kg*)*. Battery capacity and vehicle and powertrain mass by bus type are presented in Table 3. In addition, the battery density adopted is 0.14 kWh/kg (Basma et al., 2021). Manufacturing and maintenance emissions for a typical BEB *($E\_vehicle^{BEB}$)* (Equation 10) are computed as the sum of the vehicle production, battery, and maintenance emissions, considering 15 years of project length. The vehicle production emissions are calculated by multiplying the powertrain and glider mass *($Mass^{BEB}$)* and the same fixed parameter of 6.6 kg CO_2e/kg (O'Connell et al., 2023) considered for ICE buses (α), multiplying the lifetime kilometers traveled *(VKT)* (presented in Table 4 and Table A1 in the appendix) by the BEB specific maintenance carbon intensity of 67.5 gCO_2e/vkm (τ^{BEB}) (Hill et al., 2020) and the emissions equivalent to two battery packs, considering a mid-operation battery swap. The emissions of a battery pack are the product of the battery capacity *(Batt,* in kWh*)* and the battery carbon intensity of 58 kg CO_2e/kWh (η) (Bieker, 2021).

$$Mass_k^{BEB} = GVW_k^{BEB} - \frac{1}{\delta} \cdot Batt_k^{BEB} - \kappa.Cap_k \quad \text{(Equation 9)}$$

$$E\_vehicle_{ijk}^{BEB} = \underbrace{\alpha.Mass_k^{BEB}}_{\text{Vehicle production}} + \underbrace{\eta.2.Batt_k^{BEB}}_{\text{Battery}} + \underbrace{\tau^{BEB}\Upsilon.VKT_{ij}}_{\text{Vehicle maintenance}} \quad \text{(Equation 10)}$$

The WTT emissions of BEBs and trolleybuses *(E_energy_WTT)* (Equation 11) are a function of the electrical grid emissions intensity in 2021 (ρ), its projected reductions in carbon intensity for each year (Φ_{it}), years of operation *(Y)*, energy consumption (ε^{BEB}), which includes charging losses, and lifetime kilometers traveled *(VGT)*. Electrical grid emissions and projections are detailed in Table 8 and Figure 1. Energy consumption and lifetime kilometers traveled are reported in Table 4, and in Table A1 in the appendix.

$$E\_energy\_WTT_{ijk}^{BEB} = \sum_{t=t_0}^{t_0+Y} \mathrm{P}_i \cdot \Phi_{it}\varepsilon_{jk}^{BEB} \cdot VKT_{ij} \quad \text{(Equation 11)}$$

The total life-cycle emissions for a typical BEB are presented in Equation 12.

$$E_{ijk}^{BEB} = E\_vehicle_{ijk}^{BEB} + E\_energy\_WTT_{ijk}^{BEB} \quad \text{(Equation 12)}$$

AVOIDED EMISSIONS

Life-cycle emissions avoided by a typical BEB or trolleybus are calculated as the difference between ICE and BEB emissions for similar buses (k) in the same country (i) and city (j) (Equation 13).

$$\Delta E_{ijk} = E_{ijkl}^{ICE} - E_{ijk}^{BEB} \quad \text{(Equation 13)}$$

Multiplying avoided emissions by the number of electric buses deployed and summing by bus type/size and city results in country-level emissions avoided (Equation 14).

$$\Delta E_i^{Country} = \sum_j \sum_k N_{ijk} \cdot \Delta E_{ijk} \quad \text{(Equation 14)}$$

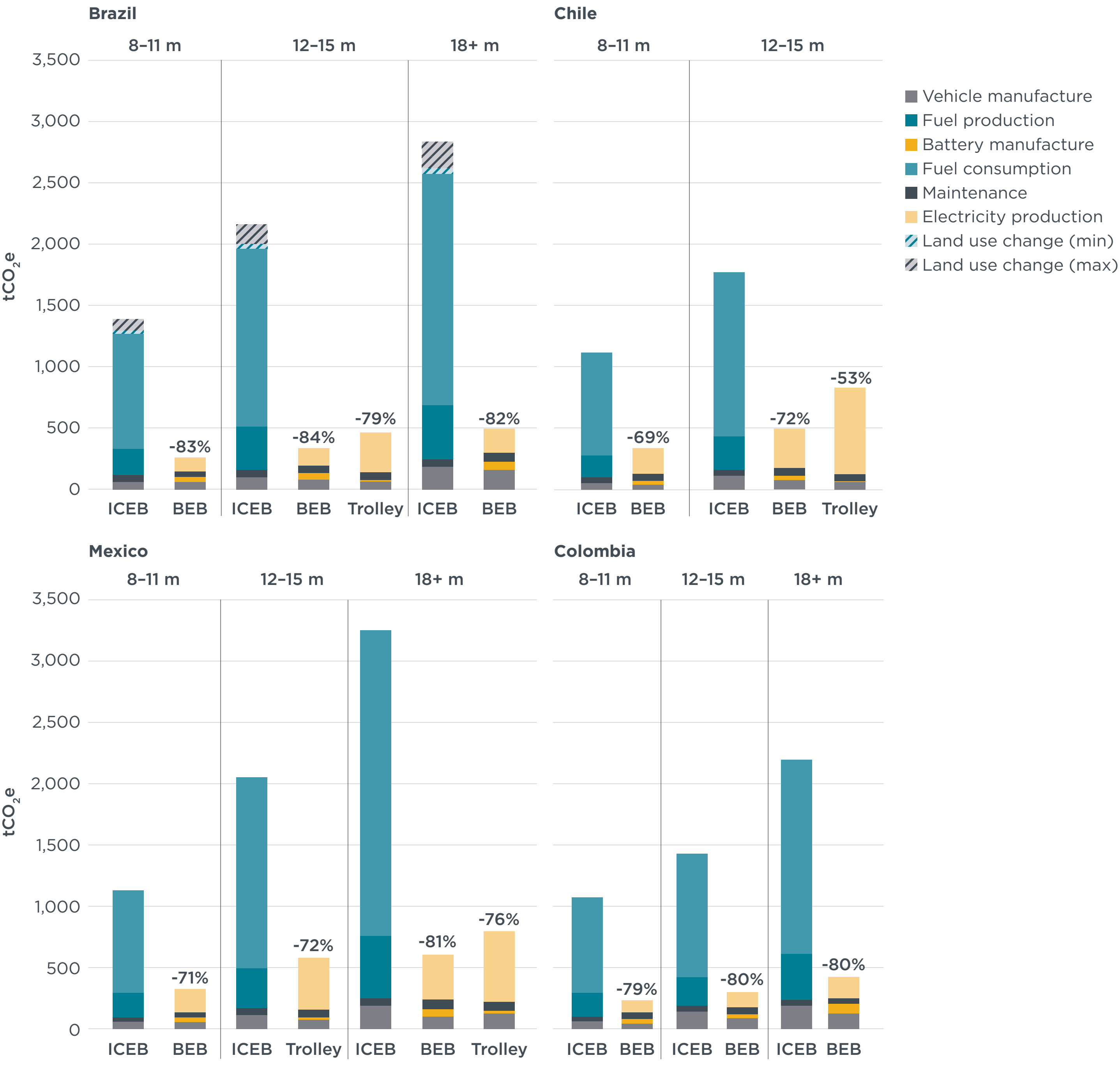
Finally, by summing all avoided emissions by bus type and size, city, and country, we can calculate emissions avoided per year. Manufacturing emissions equivalent to one vehicle are allocated to the first year of operation for BEBs and ICE buses, while manufacturing emissions for half of a vehicle are included at tenth year for ICE buses. Battery emissions, exclusive to e-buses, for the two battery packs are assigned to the first and eighth years, halfway through the e-bus projected lifetime. WTT emissions of e-buses vary over time according to the grid carbon intensity projections plotted in Figure 1. Emissions from all other sources—WTT for ICE buses, TTW, maintenance, and ILUC—are spread uniformly during all years of operation since energy intensity and VKT are also assumed uniform over time.

RESULTS

This section presents an example of the results that can be obtained with the methodology developed above. Figure 2 shows the life-cycle GHG emissions of ICE and electric buses in the four Latin American countries with the largest electric bus fleets in the region: Brazil, Chile, Mexico, and Colombia. The emissions plotted correspond to the lifetime of single buses of different sizes: 8–11 m, 12–15 m, and 18+ m. The models shown in each country are those we had access to detailed information, as presented in Table 3 and Table A1. This sample does not necessarily represent all the e-bus models operating in these countries. The graph also shows the composition of total GHG emissions by source: manufacturing of the glider and powertrain, battery manufacturing, maintenance, fuel production, fuel consumption, electricity production, and the minimum and maximum ILUC. The numbers on the top of the bars for electric buses' emissions show the percentage decrease in GHG emissions with respect to a comparable ICE bus.

Figure 2

Comparison of life-cycle GHG emissions for internal combustion engine buses, battery electric buses, and trolleybuses in Brazil, Chile, Mexico, and Colombia



Note: ICEB = Internal combusions engine bus; BEB = battery electric bus; trolley = trolleybus

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The results show that the life-cycle GHG emissions from battery electric buses are 71%–84% lower than emissions from ICE buses. Although there are variations among countries, the greater energy efficiency of electric motors results in notable GHG reductions in countries with electricity grids with low carbon intensities like Brazil and Colombia, and in those with relatively more fossil fuels in electricity generation like Mexico and Chile. Differences in emissions between countries for similar bus models are a function of operational characteristics, such as annual distances traveled and energy efficiency.

For the most common bus size deployed, 12–15m, BEBs have life-cycle emissions 72%–84% lower than ICE buses. Total life-cycle emissions over a 15-year period from BEBs are estimated to be 305 tCO_2e in Brazil, 558 tCO_2e in Chile, 323 tCO_2e in Colombia. Emissions of similar sized ICE buses in the same countries are estimated to be 1,970, 1,964, and 1,587 tCO_2e, respectively. The analysis also shows that life-cycle emissions of articulated 18+ m BEBs are 80%–82% below those of comparable ICE buses. Currently available in Brazil, Columbia, and Mexico, their estimated total life-cycle GHG emissions are 451 tCO_2e, 486 tCO_2e, and 505 tCO_2e, respectively.

The analysis also shows that air conditioning systems have significant impact on energy consumption and, thus, emissions. The articulated 18+ m BEBs that circulate in Mexico City do not have air conditioning, resulting in an average energy consumption of 1.10 kWh/km (Miaja et al., 2022), whereas similar sized BEBs in Brazil and Colombia consume 2.0 kWh/km and 1.90 kWh/km, respectively. However, the lower energy consumption is offset by the higher carbon intensity of Mexico's electricity grid, resulting in similar percentage GHG reductions.

Smaller models measuring between 8 and 11 m, with and without air conditioning, are available in all four countries and emit 69%–83% less GHG over their life-cycles compared with ICE buses.

Other model characteristics are also shown in our analysis to affect total life-cycle emissions. For instance, the modern trolleybuses deployed in Mexico have larger batteries and greater energy consumption compared with BEBs. The 12–15 m trolleybuses from Mexico City have 128 kWh batteries and consume 1.46 kWh/km, comparable to the average similar sized BEBs in Brazil (1.39 kWh/km), Chile (1.50 kWh/km) and Colombia (1.24 kWh/km). Older trolleybus models present in Brazil and Chile are estimated to consume around 3.3 kWh/km. The life-cycle GHG emissions from trolley buses are 79% lower in Brazil, 53% lower in Chile, and 72% lower in Mexico than those of comparable ICE buses.

CONCLUSION AND DISCUSSION

The methodology developed in this work estimates the avoided GHG emissions from e-bus deployments in Latin American cities. To assess life-cycle GHG emissions from electric and ICE buses, we apply country-specific values for the carbon intensity of electricity production, biofuel usage and crops. We have also collected country-specific vehicle and operational data from Brazil, Chile, Colombia, and México, including battery size, vehicle mass, energy consumption, and annual kilometers traveled.

For the application of this methodology on the E-BUS RADAR platform, the data used can be extended to include more precise estimates for other countries and models, and whenever country-specific data is not available, the Latin American mean values can be applied. For similar bus models, we observe comparable energy consumption values across countries, thus Latin American means should yield good approximations. However, whenever significant differences in model specification are present—such as the modern trolleybuses with larger lithium-ion batteries or the articulated BEBs without air conditioning observed in Mexico City—using Latin American means may result in over or underestimation of electric bus life-cycle emissions.

Currently, the E-BUS RADAR tracks BEB deployment in 12 Latin American countries. We presented in more detail the avoided GHG emissions in the four countries with the largest BEB fleets in Latin America: Brazil, Chile, Colombia, and Mexico. The results show a notable mitigation potential from e-bus deployment. Life-cycle GHG emissions from electric buses in these four countries are 71%–84% below ICE buses' emissions. A higher potential to mitigate emissions is observed in countries with low-emission electricity grids like Brazil and Colombia. Significant mitigation potential is also observed in countries with relatively more fossil fuels used in electricity generation, like Mexico and Chile, mostly due to the greater energy efficiency of electric vehicles.

The life-cycle emissions of 12–15 m BEB models are 72%–84% lower than comparable ICE buses. Articulated 18+ m BEBs reduce total emissions by 80%–82%, while smaller 8–11 m BEBs have GHG emissions 69%–83% lower than those of ICE buses. Finally, trolleybuses in Brazil, Chile and Mexico reduce emissions by 79%, 53%, and 72%, respectively.

The methodology presented in this work was developed to represent e-bus deployment in any Latin American country and to be capable to estimate life-cycle emissions even with limited information on operational characteristics, although at the cost of precise estimates when country specific data is lacking. Future improvements of the methodology would benefit from increased granularity in the e-bus models considered, as well as country-specific data on mean annual distances traveled.

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APPENDIX

Table A1 provides the average vehicle and operational characteristics for e-buses and trolleybuses in four Latin American countries in 2023 and their diesel-equivalent buses. This data was sourced from public information provided by the cities' transit authorities and bus manufacturers (Dina, n.d.; Gobierno de la Ciudad de México, 2019; Prefeitura de São Paulo, 2018a; São Paulo Transportes S.A., 2021; Urbanização de Curitiba S.A., 2023; Yutong, 2024), from previous studies developed as part of the ZEBRA initiative (Acevedo et al., 2023; Batista & Bastos, 2023; Becerra & Galarza, 2022; Bueno & Delgado, 2022; Castillo et al., 2021; Eufrasio et al., 2022; Eufrasio et al., 2023; Miaja et al., 2022; Miaja et al., 2023; Muñoz et al., 2023; Pettigrew et al., 2023; Pineda et al., 2022), and direct communication of local ICCT staff with transit authorities and bus operators.

Table A1
Country specific vehicle and operational characteristics

Country	E-bus type	Bus size	Battery	Empty weight - Electric	Glider mass electric	Empty weight - Diesel equivalent	Annual distance	Energy consumption - Electric	Fuel consumption - Diesel equivalent	Fuel consumption - Diesel equivalent
		m	kWh	kg	kg	kg	km/y	kWh/km	L/km	MJ/km
BRA	BEB	8–11	270	8,987	7,058	6,016	72,768	0.92	0.4	12.4
BRA	BEB	12–15	364	15,145	12,544	10,318	72,768	1.39	0.6	19.4
BRA	BEB	18+	531	28,465	24,676	18,800	72,768	2.01	0.7	25.1
BRA	Trolleybus	12–15	30	10,318	10,104	10,318	72,768	3.28	0.6	19.4
MEX	BEB	8–11	243	8,987	7,251	6,016	60,000	0.77	0.4	12.4
MEX	BEB	18+	507	19,800	16,179	18,800	80,000	1.10	0.8	27.4
MEX	Trolleybus	12–15	128	12,600	11,686	12,000	70,000	1.46	0.6	19.5
MEX	Trolleybus	18+	152	20,000	18,914	18,800	80,000	1.74	0.8	27.4
COL	BEB	8–11	243	8,987	7,251	6,016	60,000	0.98	0.4	12.4
COL	BEB	12–15	284	14,350	12,325	13,650	60,000	1.24	0.5	15.9
COL	BEB	18+	564	24,133	20,104	18,800	60,000	1.91	0.7	25.1
COL	Trolleybus	12–15	30	10,318	10,104	10,318	60,000	3.28	0.6	19.4
CHL	BEB	8–11	243	8,987	7,251	6,016	60,000	0.98	0.3	12.4
CHL	BEB	12–15	324	14,880	12,566	11,429	60,000	1.50	0.6	19.5
CHL	BEB	18+	533	24,133	20,326	18,800	71,384	1.96	0.7	25.8
CHL	Trolleybus	12–15	30	10,318	10,104	10,318	60,000	3.28	0.6	19.5

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