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AN ENERGY TRANSITION ANALYSIS FOR A PUBLIC TRANSIT BUS SYSTEM

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Abstract

Worldwide, Brazil is the seventh largest contributor to greenhouse gases emissions. Public transport, which is highly dependent on fossil fuels, accounts for 17% of all emissions from the Brazilian energy sector. This paper aims to identify the carbon dioxide emissions reduction potential by switching Curitiba's public transport bus fleet from diesel fueled buses to electric buses. The calculation, which was based on data collected from the system management company and from the literature, was applied into three scenarios. In the first, we estimate the system's CO2 emission for the current fuel choice, diesel; in the second, we consider the adoption of electric buses, by meeting the energy demand with the national energy matrix; and in the third, the demand would be fed by photovoltaic systems. The results indicated a CO2 emission reduction potential of about 81%, 90% and 93%, considering three different analysis: (1) buses energy demand supplied by the national electric matrix in a context of a rainfall worst-case; (2) buses energy demand supplied by the national electric matrix in a context of a rainfall best-case; and (3) energy demand supplied by solar energy. It would represent a reduction of, respectively, 68, 75 or 78 thousand tons of carbon dioxide emitted into the atmosphere per year. The results suggest that a switch from fossil fuel run buses to electric buses has a great potential to contribute to decarbonising transport, especially in cities with a large bus fleet and distance traveled.

Keywords: Electric Buses; CO2 emission reduction; photovoltaic solar energy; renewable energy; urban mobility

1. INTRODUCTION

The relationship between climate change and human activities has been discussed since the 70's. Since then, the debate has been consolidated through a series of conferences and conventions, which promoted interactions between several social actors. More recently, in 2015, Paris received the 21st UN Climate Change Conference (COP-21). In the event, 195 countries agreed on goals to reduce greenhouse gases emissions (GGE) by 2030, including preliminary targets for 2020. Among the targets, it could be highlighted the effort to limit the temperature increase to 1.5ºC in relation to the pre-Industrial Revolution levels (Woischnik, 2016). According to the Brazilian Ministry of Science, Technology and Innovation, Brazil is committed to reducing greenhouse gases emissions to 37% less than 2005 concentration levels by 2025 and 43% less than 2005 levels by 2030 (Brasil, 2017b).

Worldwide, Brazil is the seventh largest contributor to greenhouse gases emissions (Angelo & Rittl, 2019). In the country, changes in land use are the largest source of greenhouse gases due to high levels of deforestation and farming activities. Moreover, the energy segment accounts for 19% of emissions, thus the third largest contributor. Weber et al. (2019) argues that there is a high potential for reducing emissions from the energy sector through implementing a series of mitigation measures, including energy efficiency techniques, use of renewable sources, and changes in the transportation sector, which is highly dependent on fossil fuels.

The Brazilian transportation sector is characterized by the predominance of road transport, corresponding to 93% of all energy consumption in 2015, and by a heavy dependency on fossil fuels, which accounted for 77% of all fuel consumption in 2015 (Angelo & Rittl, 2019). Within this category, 51% of greenhouse gas emissions are related to cargo transport from which 65% is carried through the road system. On the other hand, countries, such as, Russia, the United States, and Canada rely 8%, 32%, and 43% on the road system to carry their production, respectively (Brasil, 2012).

Moreover, in 2016, the passenger transportation segment was responsible for 19.7% of all energy emissions. Out of this, public transport by buses accounts for 17%. In this context, as an alternative to decarbonize the fleet, electric vehicles have gained space in scientific discussions (Chunark & Limmeechokchai, 2018; Miles & Potter, 2014; Nilsson, 2011). Nonetheless, according to the "Plano Decenal de Expansão de Energia" – PDE 2026 (Ten-year Energy Infrastructure Expansion Plan) from the Ministry of Mines and Energy (Brasil, 2017a), the automobile industry energetic transition in Brazil might be a slow and late process due to high costs, energy infrastructure not being enough to supply demand, lack of battery discharge policies, and, mainly, the need for governmental incentives. Lack of robust data to assess the effects of different policies may also hamper the design and implementation of effective solutions to reduce traffic emissions and low-carbon development (Cui et al., 2011; Kim Oanh et al., 2018; Kurbatova & Khlyap, 2015).

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Another concerning issue in the adoption of electric vehicles in large scale is the increase in energy demand. The energy sector expansion, both in terms of generation as well as transmission, is a sensitive topic. Increasing generation and transmission capacity implies in comprehensive studies of national resources availability as well as measuring the social, economic, and environmental costs and benefits of each individual project. Likewise, the development of new projects also requires considerable time and resource spending (Baran & Legey, 2013; Galindo Noguera et al., 2018; Teoh et al., 2018).

In 2012, to supply the need of diversifying the Brazilian energy matrix, to reduce both the impacts and the resources required to increase production capacity, as well as to reduce customer spending on energy, the generation and distribution of energy was regulated by ANEEL's Resolution 482. Since then, the number of connections to the photovoltaic panel networks has been increasing. The number of photovoltaic generating units in Brazil grew from 2012 to 2017 by almost 147,000% and the photovoltaic installed capacity grew by approximately 27,000% from 2012 to 2018. In 2016, the country's matrix had an installed capacity of 150,338 MW. In the same year, the photovoltaic installed capacity of generation and distribution was 59.58 MWp, which represents only 0.0396% of all installed capacity in the country (Nascimento, 2017).

Even though there was an expressive increase in the number of connections since the regimentation in 2012, there is still a huge potential to explore this energy source, which is heightened by Brazil's favorable climate conditions. For example, the average solar irradiation in the country is 1,986 kWh/m². year, while Germany, a worldwide leader in photovoltaic installed capacity, is 1,251 kWh/m². year, about 63% (Tiepolo et al., 2013). Nonetheless, in 2016, Germany had 40.85 GWp of photovoltaic installed capacity, which is about 685 times the Brazilian current capacity.

In addition, this energy source has the benefit of not emitting greenhouse gases in its generation process. Due to its modular nature, photovoltaic networks can be applied within urban environments, which is a another positive aspect of this energy source (Seme et al., 2017). As the distance between energy generation and consumption is shorter, the losses due to transmission are also reduced (Dreier et al., 2018; Xuan et al., 2019). Finally, photovoltaic systems can, when compared to other sources, such as, hydroelectric power plants, be implemented in a shorter period (Xuan et al., 2019). Consequently, photovoltaic solar energy can be a viable alternative to supply electric fleet demand, contributing both for diversifying the energy matrix and for reducing greenhouse gases emissions.

Recently, Curitiba joined the C40 group, which aggregates cities in the world engaged in reduced greenhouse gases emissions through sustainable actions. The city has also signed the "C40 Cities Clean Bus Declaration of Intent", which aims to reduce emissions in the transportation sector and increase air quality through implementing bus fleets with zero or low emission rates.

As to reduce CO_2 emissions within the Brazilian context, and to reach the targets agreed by the Brazilian government, this paper aims to analyze the potential of reducing carbon dioxide emissions through a shift to electric buses in Curitiba's public transportation system. Moreover, the paper also apply a simplified methodology which could be employed without the aid of a software and with a limited dataset. For this, three different scenarios have been considered: in the first, we estimate the system's CO_2 emission for the current fuel choice, diesel; in the second, we consider the adoption of electric buses, by meeting the energy demand with the national energy matrix; and in the third, the demand would be met by photovoltaic systems.

2. LITERATURE REVIEW

Cities are accountable for a large share of GHG emissions. Even though, the share of emissions produced by cities is disputed and it can change based on whether production-based or consumption-based GHG attribution methods are applied, it remains that cities will have to adjust to tackle climate change (Hernández-Moreno et al., 2016; Hoornweg et al., 2011). In this context, initiatives like the C40 appear. The C40 is a network of cities that share tools and best practices for combating climate change (C40, 2019). For instance, they work towards achieving carbon neutrality or net zero emissions at a city-wide level (C40 Cities, 2019). In this sense, reducing transportation emissions is an important part of the process.

In 2016, the transportation sector was responsible for 24.3% of global carbon dioxide emissions from fuel combustion. In Brazil, this share was even higher reaching 47.6% (International Energy Agency, 2018). In the Global South, a strong correlation between motorization rates, income inequality, and income growth can usually be found (Kutzbach, 2009). As to curb the negative impacts of car dependency on both the climate and on the quality of life of its citizens, cities need an urban mobility paradigm shift (Litman, 1999). Thus, focusing its efforts on promoting more sustainable travel modes, such as public transport (Batur et al., 2019; Lin et al., 2018).

In cities in the Global South, the bus is key to public transport networks due to lower infrastructure costs when compared to other options (Vuchih, 2007). For instance, about 60% of cities adopting bus rapid transit (BRT) systems are in South America, Africa, and Asia (BRT Data, 2021). Nonetheless, the global bus fleet is mostly fueled by diesel and natural gas. Therefore, as to achieve zero-emission conditions an effort should be made for fleet electrification (Bloomberg New Energy Finance, 2018; Popescu & Luca, 2017). It is important to highlight that an electric fleet has potential for GHG emission reduction only if renewable sources are used (Bauer et al., 2015; Wolfram & Wiedmann, 2017). If fossil fueled-based, emissions are likely to remain the same or even to increase (Bauer et al., 2015).

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In the literature, there are several papers developing scenario-based analyses targeting emission reduction by shifting the vehicle fleet towards fuels originated from renewable sources (*e.g.* Alshammari, 2019; Batur et al., 2019; Chollacoop et al., 2013; Dorotić et al., 2019; Dranka and Ferreira, 2020; Grahn et al., 2009, 2003; Lunz et al., 2016; Oldenbroek et al., 2020; Xiao et al., 2019). A scenario analysis is a tool to predict possible future developments according to proposed hypotheses (Lorenzi & Baptista, 2018). In the analysed studies, the scenarios are mostly composed of a business as usual (BAU) perspective combined with different energy and fuel sources, modal splits, target emission levels, or levels of electric fleet adoption. In most cases, solar energy is combined to other sources, such as wind and hydrogen. For instance, (Oldenbroek et al., 2020) showed that an energy grid based on solar, wind, and hydrogen power sources could be a reliable and self-sufficient option for supplying power, heat, and transportation needs across different climates in Europe. Overall, most analyzes are performed using software such as energyPLAN, LEAP, and MESSAGE. Finally, these studies mostly focus on private passenger vehicles. The research on evaluating public transit bus systems emissions is scarce.

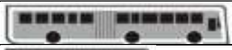
Given the importance of bus networks for Global South cities, this paper analyses the potential of reducing CO_2 emissions from shifting Curitiba's public transport bus fleet from diesel-based to electric-based. Our aim was to apply a simplified methodology, so that it is made more accessible for cities to perform such analyzes. In this sense, we proposed a multiple scenario analysis of (1) a business-as-usual scenario, where the fleet is fueled by diesel; (2) a within reach scenario, where the fleet is fueled by the current energy grid; and (3) a target scenario, which is an optimistic hypothetical situation where the fleet is fueled by photovoltaic panels.

3. MATERIALS AND METHODS

Curitiba's public transport system is operated exclusively by buses. The bus lines are grouped into different categories, as shown in Table 1.

Blue Express is a BRT service with fewer stops and traffic signal priority, providing a faster travel option in comparison to the Red Express. Direct Lines, like Red Express and Blue Express, make stops at stations with on-level boarding and off-board fare payment, but it does not use a segregated lane. Inter-Neighborhoods, Feeder Lines and Trunk Lines have similar characteristics: conventional stop points, in-board fare payment and use of the shared network system. Inter-Neighborhoods and Trunk lines are also operated by hybrid vehicles, fueled on diesel and electricity, according to the demand for engine traction. Conventional, Circular and Tourism lines do not have fare integration with the rest of the system. Tourism lines also have a different fare system, the passenger pays for a day, and not for just one trip. Figure 1 presents a summary of the methodological steps of this study.

TABLE 1 - LINE CATEGORIES OF THE CURITIBA'S PUBLIC TRANSPORT BUS SYSTEM

Category	Fleet		Characteristics
	Type	Design	
Blue Express	Biarticulated		BRT (Bus Rapid Transit)
Red Express	Biarticulated		BRT (Bus Rapid Transit)
	Articulated		
Direct Lines	Articulated		Serve punctual demands with stops every 3 km on average
	Padron		
Inter-Neighborhoods	Articulated		Connect different neighborhoods without going through downtown
	Padron		
	Hybrid		
Feeder Lines	Articulated		Connect neighborhoods to the nearest bus terminals
	Common		
	Micro especial		
Trunk Lines	Articulated		Connect bus terminals to the downtown area
	Common		
	Hybrid		
	Micro Special		
Conventional Lines	Common		Connect neighborhoods to the downtown area
	Micro Special		
	Micro		
Circular	Micro		Circular itinerary within downtown
Tourism	Double-deck		Connect the main tourist attractions

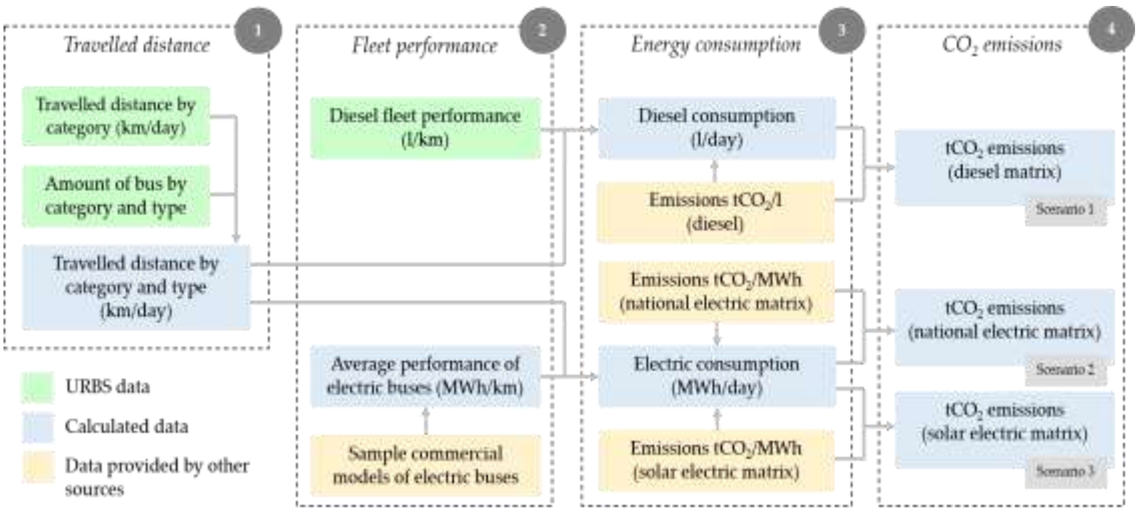


FIGURE 1 - METHODOLOGY STEPS FLOW CHART

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3.1 Scenarios

Three different scenarios for estimating CO_2 emissions in Curitiba's public transport were evaluated. Table 2 presents the three scenarios considered.

TABLE 2 - SCENARIOS CONSIDERING DIFFERENT ENERGY SUPPLY AND THEIR SOURCE

	Scenario	Energy supply	Source
1	Business as usual	Diesel	-
2	Within reach	Electric energy	National electric matrix
3	Target	Electric energy	Solar electric matrix

In these scenarios, we considered bus running either on diesel (the current form of supply) or on electricity. This last form was also analyzed considering two different sources of electrical energy: from the national electric matrix and from photovoltaic systems. Each scenario was set in order to represent the steps to achieve decarbonized transport: the first presents the current GHG emission rate (Business as usual); in the second is shown an intermediate and realistic scenario (Within reach); and in the third an optimistic hypothetical condition is considered (Target). The analysis of different scenarios is essential for planning transportation systems, as it allows the identification of different strategies and their outcomes without subjecting the system to unnecessary spending and operation risks. That is, scenario-based analysis plays the role of determining the most desired outcomes (Zhou et al., 2016), in this case, the best option for reducing CO_2 emissions whilst substituting the fleet energy source.

3.2. Travelled distance

At this step, it was necessary to collect data on the distance travelled by the bus fleet. The data was provided by the system management company, Curitiba Urbanization (URBS, 2016), and grouped by line category. The average fleet performance (l/km), also provided by URBS, was grouped by bus type (URBS, 2013). Consequently, distance traveled and average fleet performance were also regrouped by category and vehicle type. Each line category uses one or more types of vehicles. Thus, the distance travelled by each type of vehicle was considered proportional to the quantity of that particular type within the category. Table 3 presents the line categories, the fleet of each category, the types of vehicles in each category, the fleet of each type of vehicle, the percentage of each type of vehicle in the total fleet size of each category, and the distance travelled daily by category and type of vehicle (km/day).

For the following analysis, hybrid-fueled buses were excluded, as the aim was to establish diesel-fueled vehicles as the base line. Buses for the tourism lines were also excluded from the analysis, since they provide a differentiated service in addition to not operating on Mondays. In this way, the analysis comprises 97% of the fleet.

TABLE 3 - CALCULATION OF THE DISTANCE TRAVELLED BY THE BUS FLEET

					Travelled Distance (km/day)	
Category	Fleet	Type	Fleet	% Fleet	By Category	By Type
Blue Express	44	Biarticulated	44	100.00	5990	5990
Red Express	128	Biarticulated	97	75.78	26570	20100
		Articulated	31	24.22		6430
Direct Lines	219	Articulated	38	17.35	40010	6960
		Padron	181	82.65		33100
Inter-Neighborhoods	92	Articulated	91	98.91	18822	18610
		Padron	1	1.09		207
Feeder Lines	425	Articulated	71	16.71	86910	14510
		Common	325	76.47		66500
		Micro Special	29	6.82		5910
Trunk Lines	67	Articulated	5	7.46	11245	843
		Common	59	88.06		9910
		Micro Special	3	4.48		506
Conventional Lines	207	Common	102	49.28	37603	18540
		Micro Special	102	49.28		18540
		Micro	3	1.45		564
Circular	5	Micro	5	100.00	608	608

Source: URBS (2019) (URBS, 2016) adapted by Authors (2019)

3.3. Fleet performance

For scenario 1 (diesel-fueled fleet) the average bus performance data was provided by URBS (URBS, 2013). Table 4 shows the average performance for each type of bus.

TABLE 4 - CURITIBA'S FLEET PERFORMANCE

Type	Performance (l/km)
Biarticulated	0.909
Articulated	0.762
Padron	0.541
Common	0.360
Micro Special	0.312
Micro	0.231

For scenarios 2 and 3 (fleet supplied with an electric matrix), an average performance of commercial models of electric buses was calculated. This calculation was based on data provided by vehicle manufacturers. For the application of this average performance value for Curitiba´s city buses, it was necessary to establish a common variable for all electric bus models we found available. Initially, the capacity of the vehicles was chosen. The average performance was then calculated in kWh/km*passenger. The passenger capacity for commercial electric bus models was also provided by the respective manufacturers. Possibly due to differences in the criteria for quantifying the maximum

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number of passengers transported by each vehicle, the statistical treatment carried out revealed that this parameter would not be the most suitable for plotting vehicle consumption. Through the analysis of the data of the commercial models supplied by the manufacturers, it was noticed that the length of the vehicles had a stronger dependent correlation to energy consumption. Thus, the average performance of electric vehicles was calculated for each model based on the length of the bus (kWh/km*m). Table 5 shows all the commercial models considered in this stage of the research.

TABLE 5 - ELECTRIC BUS COMMERCIAL MODELS

Model/ Manufacturer	Type	Battery	Length (m)	Consumption (kWh/km)	Consumption/ length (kWh/km*m)
XY030/BYD	Padron	Iron phosphate	12	1.2	0.100
K9/BYD	Padron	Lithium iron phosphate	12.25	1.24	0.101
I2E/Irizar	Padron	Sodium nickel + superc	12	1.5	0.125
XE40/New Flyer	Padron	Lithium ions	12.5	1.56	0.125
Optare Versa	Padron	Iron-lithium-magnesium phosphate	11.7	0.61	0.052
XR40/Proterra	Padron	Nickel Manganese Cobalt	12.2	0.99	0.081
Akita E-bus/Isuzu	Padron	Lithium ions	9	0.73	0.081
E-bus/Eletra	Articulated	Lithium ions	23	2.45	0.107
Exqui.City/Van Hool	Articulated	Lithium	18.61	1.79	0.096
				Mean	0.0965

Source: (Baldissera, 2016; BYD, 2015; Eletra, 2020).

The data was statistically treated through observing the standard deviation, spurious data analysis, and related standard uncertainty (error). The standard uncertainty (error) associated with the data, considering a Student correlation, was of 8%. Thus, the value of 0.0965 kWh/km*m was considered for the average performance of buses for scenarios 2 and 3. After that, the calculations of energy consumption of the fleet were carried out.

3.4. Energy consumption

In this step, the total energy consumption was calculated for each of the considered scenarios. That is, for scenario 1, the total diesel consumption was calculated, and for scenarios 2 and 3, the total electricity consumption was calculated. For scenario 1, the total daily consumption of diesel in liters for each bus line was based on Equation 1.

$$C_i = D_i \cdot P \tag{1}$$

where: C_i – daily consumption (l/day); Di – average distance travelled by the line i (km/day); P – average performance of the bus models (l/km).

For scenarios 2 and 3 the daily electrical consumption for each bus line was calculated using Equation 2.

$$C_i = \frac{C_a\ D_i \cdot L_i}{1000} \tag{2}$$

where: C_i – daily consumption (MWh/day); C_a – average performance per vehicle lenght (kWh/km*m); *Di* – average distance travelled by the line *i* (km/day); L_i – lenght of bus models (m).

3.5. CO_2 emissions

For scenario 1, two forms of CO_2 emissions were considered: the first, from the burning of the diesel, and the second, from the production of the diesel consumed. The CO_2 emissions estimate for scenario 1 was based on Equation 3.

$$\text{Emissions}_{\text{diesel}} = \frac{\sum C_i . (CE_{\text{diesel}} + PE_{\text{diesel}}) \cdot T}{1000} \tag{3}$$

where: *Ci* – daily consumption of the line *i* (l/day); CE_{diesel} – CO_2 emission rate in diesel consumption: 2.671 $kgCO_2/l$ (Brasil, 2011); PE_{diesel} – CO_2 emission rate in diesel production in Brazil: 0.23 $kgCO_2/l$ (Vianna, 2006); *T* – analysis time interval: 240 days.

A time interval of 240 days was considered for all 3 scenarios, as only the average daily distance travelled data for business days was provided.

For scenario 2, emissions estimations were calculated considering the emissions factor from the Brazilian National Electric Matrix for 2016. This data was calculated based on the individual factor for each identified source (Miranda, 2012), and according to the Life Cycle Analysis taking into account renewable source emissions as well. Once the main energy source in the country is hydroelectric, this emissions factor is dependent on rainfall patterns. If rain volumes are low there is a tendency to produce more energy in thermoelectric plants, which would increase emissions. In order to consider a best and a worst-case in terms of rainfall patterns we adopted the higher and the lowest matrix emissions factor in the last twenty years. The factors adopted were 0.1941 tCO_2/MWh for the rainfall worst-case (emissions factor for 2014), and 0.1029 tCO_2/MWh for the rainfall best-case (emission factor for 2009). Thus, the calculation of emissions for best and worst-case of scenario 2 was based on Equation 4.

$$\text{Emissions}_{\text{electric national matrix}} = \frac{\sum C_i . ER_{\text{electric national matrix}} . T}{1000} \tag{4}$$

where: *Ci* – daily consumption of the line *i* (MWh/day); $ER_{electric\ national\ matrix}$ – electric CO_2 emission rate: 0.1941 and 0.1029 tCO_2/MWh (Miranda, 2012; ONS, 2020); *T* – analysis time interval: 240 days.

The Life Cycle Analysis methodology was applied to estimate the photovoltaic solar energy emissions related to the fleet energy demand (scenario 3). The analysis was performed to provide more concrete results about the contributing potential that reducing CO_2 has for the environment considering the production of photovoltaic panels. Dones & Frischknecht (1998) highlight that most greenhouse gases emissions during the life cycle of photovoltaic panels comes from energy and resource consumption in

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the production of components. Even though polycrystalline silicon is more applied nowadays, in the future, the reduction in costs will turn viable the use of monocrystalline modules in large scale. On the other hand, if only the energy generation and transmission were considered, the emissions would be zero. So, the adopted emission rate from solar technology was of about 0.0707 tCO_2eq/MWh, which comes from the photovoltaic system with monocrystalline modules (Miranda, 2012). The calculation of emissions for scenario 3 was performed using Equation 5.

$$\text{Emissions}_{\text{solar technology}} \frac{\sum C_i.\ ER_{\text{solar technology}}.T}{1000} \quad (5)$$

where: C_i – daily consumption of the line i (MWh/day); $ER_{solar\ technology}$ – solar technology GEE emission rate: 0.0707 tCO_2eq/MWh (Miranda, 2012); T – analysis time interval: 240 days.

After calculating CO_2 emissions for each of the scenarios considered, the values were compared aiming at analysing the impact of adopting electric vehicles in the city's public transport system. An analysis was also carried out with respect to the gas emissions inventory for 2016 (Curitiba, 2019) for the city of Curitiba.

3. RESULTS

In relation to the observed steps from Figure 1, the calculations fall into a 68% level of confidence with 5% margin of error.

3.1. Energy conumption

Table 6 shows the total annual energy consumption for each type of bus for all three scenarios.

TABLE 6 - ENERGY CONSUMPTION FOR ALL THREE SCENARIOS ANALYZED

Category	Type	Annual energy consumption	
		Scenario 1 (l)	Scenario 2 and 3 (kWh)
Blue Express	Biarticulated	1,307,000	3,828,000
Red Express	Biarticulated	4,420,000	12,840,000
	Articulated	1,147,000	3,021,600
Direct Lines	Articulated	1,284,000	3,028,800
	Padron	4,300,000	9,960,000
Inter-Neighborhoods	Articulated	3,410,000	8,016,000
	Padron	26,300	62,400
Feeder Lines	Articulated	2,660,000	6,240,000
	Common	5,740,000	18,864,000
	Micro Special	446,000	1,408,800
Trunk Lines	Articulated	146,900	362,880
	Common	862,000	2,810,400
	Micro Special	36,100	120,720
Conventional Lines	Common	1,577,000	5,256,000
	Micro Special	1,409,000	4,420,800
	Micro	30,600	104,400
Circular	Micro	33,600	112,560
	Total	28,800,000	80,500

Source: URBS (2019) (URBS, 2013) adapted by Authors (2019)

For scenario 1 the total energy consumption was 28,800,800 liters of diesel, while for scenarios 2 and 3 this value was 80,500 kWh.

3.1. CO_2 emissions

Table 7 shows the total annual CO_2 emission for each type of bus for all three scenarios.

TABLE 7 - CO_2 EMISSIONS FOR ALL THREE SCENARIOS ANALYZED

Category	Type	Annual emissions (tCO_2)				
		Scenario 1		Scenario 2		Scenario 3
		Diesel consumption	Diesel production	Rainfall worst-case	Rainfall best-case	
Blue Express	Biarticulated	3,530	300	743	394	271
Red Express	Biarticulated	11,940	1008	2,490	1,320	908
	Articulated	3.100	271	587	311	214
Direct Lines	Articulated	3,460	293	588	312	214
	Padron	11,600	988	1,930	1,025	704
Inter-Neighborhoods	Articulated	9,200	783	1,560	820	567
	Padron	71	6.2	12	6	4.40
Feeder Lines	Articulated	7,190	611	1,210	643	442
	Common	15,500	1322	3,660	1,940	1,333
	Micro Special	1,204	102	274	145	99.60
Trunk Lines	Articulated	397	35.50	70	37	25.70
	Common	2,320	197	545	289	198.70
	Micro Special	97.6	8.75	23	12	8.50
Conventional Lines	Common	4,260	368	1,020	541	372
	Micro Special	3,810	320	858	455	313
	Micro	82.6	7.20	20	11	7.40
Circular	Micro	90.9	7.75	22	12	8
	Total	77,000	6,630	15,620	8,280	5,690

Source: URBS (2019) (URBS, 2013) adapted by Authors (2019)

The total CO_2 emissions for scenario 1 is the sum of emissions resulting from the fuel burning process counting the emission from its production, that is, 83.63 thousand tCO_2. For scenarios 2 and 3, the total emissions come from the electric energy production components manufacturing process. For scenario 2 the values found were 15.62 and 8.28 thousand tCO_2 for the rainfall best and worst-case, respectively, and for scenario 3 it was 5.69 thousand tCO_2.

Figure 2 shows a summary of the obtained emissions for each scenario analyzed.

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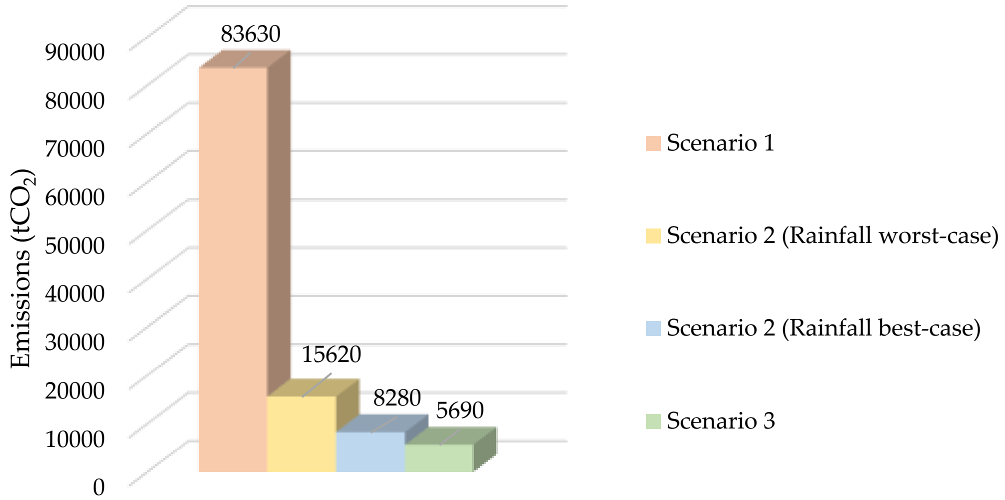

FIGURE 2 - COMPARISON OF TOTAL CO_2 EMISSIONS FOR THE THREE SCENARIOS.

4. DISCUSSIONS

In scenario 1, the Curitiba's public transport fleet consumed 28.80 million liters of diesel and emitted 77 thousand tCO_2 to the atmosphere in 2016. These numbers accounts for 3.30% of all emissions for the transportation sector in Curitiba (Curitiba, 2019), 3.72% of all emissions due to bus trips within the state of Paraná in 2016, and 0.367% of all bus trip related emissions in the country for the same year (SEEG, 2018). As shown in Figure 2, if the fleet switch to electric buses fueled by the national energy matrix (scenario 2), the possible reduction in emissions would be from 83.630 tCO_2/year to 15.620 or 8.280 tCO_2/year, depending on the rainfall patterns, meaning 81-90% decrease in emissions. It is important to mention that the emission rate for the energy matrix used for these calculations is from 2009 for the rainfall best-case and from 2014 for the rainfall worst-case. This value is dependent on rainfall patterns as the main energy source in the country are hydroelectric. Therefore, if rain volumes are low, there is a tendency to produce more energy in thermoelectric plants, which would increase the emissions rates for the matrix. On the other hand, if the fleet energy demand is supplied by photovoltaic systems (scenario 3), it would be possible to reduce emissions between 83.630 tCO_2/year and 5.690 tCO_2/year, or a 93% decrease in emissions.

When analyzing scenarios for reducing CO_2 emissions in a public transport system, the expected reduction depends on two main factors: (I) the amount of CO_2 emitted by the system considering the current energy source in the production and consumption phases; and (II) the amount of CO_2 that will potentially be emitted considering the alternative source of energy, also in the production and consumption phases. The greater the difference between these two values, the greater the potential reduction in emissions that the system can achieve with the analyzed energy transition. In the case of Curitiba, the potential reduction values found were relatively high for three main reasons. First, the energy source currently used in 97% of the fleet is diesel, a fuel with high CO_2 emissions rate. Second, the city's public transport system is operated exclusively by buses, resulting in a large fleet (1,187 vehicles) and daily distance traveled (227,828 km). And third, the emissions factor of the two alternative sources of energy considered (national electric matrix and solar electric matrix) have low CO_2 emissions rates. This means that the difference between the amount of current CO_2 emissions and the amount in the two alternative scenarios is large, resulting in large percentages of potential reduction.

If electric buses are incorporated into the public transport system in Curitiba, and if fed by the national matrix or photovoltaic panels, the system would be able to improve air quality in the city, in addition to reducing emissions in diesel producing regions. This could contribute to reach the targets proposed in agreements such as the C40 group and COP-21. Moreover, the production of 1 liter of diesel requires about 4 thousand liters of water. As Curitiba's public transport fleet consumption was of 28.80 million liters of diesel in 2016, it would be possible to save about 115 billion liters of water per year.

It is also important to highlight the contributions to public health from reducing the dependency to fossil fuels. According to a study from Ipea (2011), about 200 diseases and 3,000 deaths per year are associated with greenhouse gases emissions due to transportation in the great São Paulo. Among the issues are irritation, asthma, bronchitis and lung cancer, which can reduce life expectancy in about 12 years.

Moreover, as the overall electric fleet increases, the Brazilian energy system will have to deal with an increase in demand. Increasing the electric power system generation capacity and, consequently, transmission and distribution capacities, implies in the planning and implementation of large-scale energy projects, which are usually costly and bring several socio-environmental impacts. In this sense, the distributed generation is a viable option to meet the demand in a decentralized way, especially as photovoltaic solar systems become more popular. As an advantage, these systems have a low emission rate during its operation. Additionally, they enable reducing energy costs, increase job generation, and can be implemented rather quickly.

It is also worth mentioning that cities and public transport operating companies face several barriers to adopting electric bus fleets (Ahmad & Choi, 2010). They range from lack of information, financial constraints, and limited institutional and policy support. Even though the total life-cycle costs of e-buses are usually lower than that of conventional buses, the up-front costs are still larger than for other options (Sclar et al., 2019; Wang & González, 2013). In this sense, a more widespread adoption of electrified bus fleets would mostly rely on national or local policies promoting a shift from conventional technologies.

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Such policies may be based on tax or other financial incentives, transition strategic plans, public financing lines, and changes in law or tendering regulation processes concerning public transport and urban mobility.

The CO_2 emission reduction estimate presented in this study has a limited scope, since only data on fleet-distance travelled on business days was considered (240 days/year) as it was the only data available. Another potential limitation is related to the spatial scope of the study. Also due to data availability, only the Curitiba's public transport fleet was considered, excluding from the calculation the buses from the metropolitan area. This means that the potential of CO_2 emissions reduction could be relatively greater, considering the 365 days of the year and the entire fleet in the metropolitan region of Curitiba.

5. CONCLUSIONS

In this research, we identified the possibility of an expressive contribution to reduction in greenhouse gases emissions from Curitiba's public transport by switching the fossil fueled fleet to electric buses. Three scenarios were showcased: the first representing the current emissions situation (diesel fueled fleet); the second considered that the buses would be powered by electricity, and this energy demand would be supplied by the national electric matrix; and the third, considered feeding the system with photovoltaic solar panels. The overall CO_2 emissions reduction potential was of 81 and 90% by using electric buses fueled by the national electric matrix considering a best and worst rainfall pattern respectively, and of 93% by supplying the energy demand with photovoltaic solar panel systems. This implies a 75 and 68 thousand tons of CO_2 reduction in the two cases of the second scenario, and 78 thousand tons of CO_2 reduction for the third one scenario.

The findings of this study suggest that public transport systems operated exclusively by buses have the potential to be the focus of decarbonizing transport measures, for two main reasons. First, the bus fleet is normally fueled with diesel, a fuel with a high rate of CO_2 emissions. Second, the size of the fleet and the distance traveled are considerably large.

Finally, the use of electric buses would assist the city to reach the agreed targets from the C40. Consequently, the carbon dioxide reduction would also help the country to meet the goals set in the 2015 Paris Agreement. As co-benefits, it would also reduce water consumption from reduced diesel production and, in the long term, would improve air quality in the city. However, cities and operating companies still face many barriers for the adoption of electric buses, which are likely to require further research and strong policy support to be overcome.

Some topics still deserve to be further studied. First, the impact of the energy transition of the city's public transport system on the generation, transmission and distribution of electricity needs to be analyzed, specially in relation to the target scenario. Second, this article only made an analysis on CO_2 emissions from public transport system. In the future, the research should be gradually expanded to private cars, taxis, trucks and other vehicles, as well as to emissions from other greenhouse gases.

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