Environmental Assessment of Urban Public Transport's Shift from Conventional to Electric Buses: A Case Study

Michelle Leichter\textsuperscript{1}, Laura V. Lerman\textsuperscript{2}, Vinicius G. Maciel\textsuperscript{3,4}, Ana Passuello\textsuperscript{*5}

\textsuperscript{1} Postgraduate Program in Civil Engineering: Construction and Infrastructure (PPGCI)
Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brasil
e-mail: michelle.leichter@ufrgs.br

\textsuperscript{2} Department of Industrial Engineering
Federal University of Rio Grande do Sul, Porto Alegre, Brasil
e-mail: laura.berman@ufrgs.br

\textsuperscript{3} Postgraduate Program in Civil Engineering: Construction and Infrastructure (PPGCI)
Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brasil

\textsuperscript{4} Systemic Solutions in Organizational Sustainability, Porto Alegre, Brazil
e-mail: vinicius.maciel@ufrgs.br

\textsuperscript{5} Postgraduate Program in Civil Engineering: Construction and Infrastructure (PPGCI)
Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brasil
e-mail: ana.passuello@ufrgs.br

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ABSTRACT

The number of Life Cycle Assessment studies in urban public transportation focusing on modals that aim to reduce global warming impacts are increasing significantly in the last few years. These studies suggest that the insertion of green modals on local public transportation systems could be a solution to reach sustainable development. However, the impact of this insertion in developing countries is not clear yet. Then, our main objective is to evaluate the environmental impact of an emerging city’s public transportation system, considering different public policies.

Consequently, we conducted a Life Cycle Assessment study considering the transitions from diesel to biodiesel buses and electric buses from 2020 to 2030. Three scenarios were performed, with the following criteria: battery changes, the increase of biodiesel percentage used in the fuel mix and buses’ expected average lifespan transitioning to electric vehicles. The results show a decrease in impact by 2030 in analysed scenarios and may support policymakers to decide whether to focus on a short-term or long-term transport policy to reduce the fleet sustainable impact. Particularly, electric buses emerge as an option to reduce environmental impacts in the public transportation system in Porto Alegre, Brazil.

KEYWORDS

urban planning, electric vehicles, biodiesel, public transport, policies, life cycle assessment.

INTRODUCTION

The transportation sector is responsible for approximately 24% of the World’s Greenhouse Gases emissions (GHG), while road travel accounts for three-quarters of transport emissions. Most of this comes from passenger vehicles – cars and buses – which contribute 45.1% to road travels [1]. In addition, transportation modes are responsible for more than half of global petroleum consumed [2]. In Brazil, this reality is more emphasised, mainly due to road...
transport predominance, that has a significant contribution in a generally low economic and energetic performance [3], as well as in difficulties to implement sustainable practices in developing cities [4]. In such context, it is confirmed the notable influence of such displacement category on environmental impacts.

In Brazil, transport accounts for the largest share of energy consumption, contributing to negative environmental impacts. Only in 2019, at least 196.5 million tons of CO₂eq came from transport – a 47% share of all energy emissions. These pollutants are mainly generated due to the use of fossil fuel vehicles, being trucks and automobiles the two main emitters, responsible for 40% and 31% of greenhouse gases, respectively [5].

Hence, several strategies to mitigate impacts on urban zones using mobility patterns changes are reported, such as improvements in vehicles' fuel economy, controlling of emission and fuel changes [6]. However, it is estimated that the reduction in the fuel consumption on urban transport vehicles, despite its crescent technological evolution, will not be enough to offset the increases of more than 160% in demand for passenger and cargo transport forecasted for the period 2020-2050 [7]. In contrast to other sectors, urban mobility emissions still do not show a reduction and the sector does not present the expected level of eco-efficiency, as it continues to increase annually by 2.5%, on average per year, between 2010 and 2015 [8].

Many contributors can be associated with such circumstances including low use of active and public modes of transport, as modal choices are often associated with socio-economic interactions [9]. Nonetheless, as widely demonstrated, mobility becomes more sustainable, the greater the barriers to private vehicle use and the better the public transport system or other more environmentally friendly forms of displacement become [10]. Studies related to public transport have high relevance, since such form of shifts take advantage of an already existing infrastructure and public authorities’ involvement, as public transport is often an already consolidated service in the market with high demand [11].

Taking into account this multiplicity of factors, the reduction of fossil fuel consumption in urban transport vehicles with the use of alternative energy sources such as hydrogen [12] and electricity [13] is regarded as a feasible propellant in reducing the sector's emissions. Once this substitution starts taking effect, public transport in particular can have a great contribution, as it can reduce final energy consumption and concomitantly create a favorable condition for a sustainable urban mobility plan that lessens the use of private transport [10]. In this scenario, electric vehicles (EV) are viewed as an alternative, allowing technological evolution to diminish CO₂ emissions and increase the use of natural resources, as EV can provide lower carbon emissions [14].

Indeed, this transition to electric public transport is aligned to the sustainable and smart cities trend, which focuses on the use of cleaner energy [15] and the stimuli of public transport [16]. Accordingly, studying the transition from conventional to electric transport is a good opportunity for policymakers to start erecting a smarter and more sustainable city. Emerging studies attack these issues from different fronts; Ajavonic and Haas [17] show the importance of a sensitivity analysis in assessing the environmental benignity of different electricity mixes. On the other hand, Bugaje calls attention to renewable energy sources as a tool to provide clean energy to electric-mobility solutions based on the performance of a decentralized photovoltaic system in Kenya [18].

In this regard, Brazil emerges as a good case to analyze the transition from conventional to electric vehicles considering the increase in the number of EV in the country’s fleet could be environmentally positive and favourable, since its electric energy matrix was composed of 88.8% of electricity from renewable energy sources in 2020 [19].

Thus, a plausible deduction is that motorized transportation vehicles should undergo a decarbonization process and public transport should be a priority target. Such decarbonization degree can be analysed through life cycle assessment (LCA) [20]. In fact, this technique has already proved to successfully support decision making in the urban context, especially
considering that LCA is increasingly applied for impact analysis associated with transport systems [21].

Consequently, to support public policies formulation, LCA studies have been developed in different contexts, currently, the tool has been frequently used to compare motorized transport vehicles technologies [22], power sources [23] and planning or management of transport’s infrastructure [24]. Previous LCA studies have also focused on developed countries, comparing the use of buses with different energy sources, for instance, the use of fossil fuels in comparison to alternative transportation fuels like biodiesel [23] as well as comparisons between combustion and electric vehicles [25]. Furthermore, the field of transportation is so important that some studies have focused on the use of LCA for specific vehicle materials such as the tire industry [26].

In contrast, there is still a limited number of studies about urban related LCA, linked to mobility [17], wellbeing [27], as well as social and territorial specificities [28]. This comes as no surprise, since holistically evaluating environmental impacts of land planning policies understandably complexifies an analysis and implies the need to take into account several aspects, intimately related both to territorial features and production-consumption patterns [29]. Researches also call attention that this possibly occurs due to the fact that environmental impacts of transportation in urban mobility are frequently overlooked due to a scarcity of appropriate assessment methods and a difficulty to capture the environmental consequences of the entire cause and effect chain at a city scale [30].

Therefore, this study aims to investigate the environmental impacts, present and future, of changes in energy sources of buses for urban public transportation. The proposed scenarios differ depending on (1) the share of electric buses, (2) the electricity supply mix (3) the choice of liquid fuel– Diesel or biodiesel and the latter increase in percentage added to the mix.

**METHOD**

LCA is performed according to the international standards ISO 14040 [31] and ISO 14044 [32]. The ISO 14040 methodology sets out the framework for the LCA by defining four separate phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation, the latter used to revisit and refine all phases as the study develops. Conformity to accepted international standards supports the quality of the study and improves reliability on the results. Therefore, the following subsections describe the LCA choices based on that.

**Goal and Scope**

The existing transport modes in Porto Alegre are buses, minibuses, shared bicycles, shared cars, and taxis [33]. Regarding them, there is a significant daily flow of passengers transported by bus, estimated as 22% of the passengers daily commute in the metropolitan region in 2018 [34]. Having this data in mind, the LCA aims to generate information of potential impacts based on a diagnosis of the current operation of the public bus transport system, and the projection of potential impact reduction according to public policies addressed to the variables in the system in Porto Alegre, Brazil.

It is also worth notice that Porto Alegre was selected because it is a metropolis located in southern Brazil, and cities can play an effective role in the global effort to comply with the Paris agreement [35]. Furthermore, Porto Alegre decision makers are conducting a master and a mobility plan review, where some of the city council members are developing climate change guidelines, trying to align with the sustainable development goals in its strategies [34]. Moreover, the city has had since 2015 a Sustainable Innovation Zone (ZISPOA) that aims to become the most sustainable and innovative region in Latin America by 2030.

Notwithstanding, most of these initiatives have not yet got off the ground as the transportation sector has proven to be a particularly difficult territory for the advancement of
sustainable development policy. Particularly in Brazil this context is exacerbated, since passenger transport is especially carbon intensive [36]. As a result, Porto Alegre still does not have a concrete sustainability plan, limiting the scenario choices to data gathered from national policies, public procurement agreements, information from the municipality and plans not yet implemented locally.

The LCA goal is to compare the potential environmental impacts related to the use of conventional buses (CB) and electric buses (EB), including the production of fuels, electricity, as well as batteries. The study is based on data from an existing bus lot (no. 7), with vehicle type, efficiency, and operation data provided by the local bus operator, Public Transport and Circulation Company (PTCC). Carris, a public entity licensed to provide municipal transport service, was chosen due to its quantitative influence on Porto Alegre’s fleet. In all, there are 342 vehicles divided into 37 different lines that, in a base month, October 2018, perform 88,202 trips and transport 5,085,869 passengers [34].

Another reason why Carris was selected was due to the provider close relationship with electric vehicles, having been the main testing site of the Chinese company BYD (Build Your Dreams) in 2016, which operates and implements such technologies in several cities around the world [36]. Herein, a gradual transition from the current CB to EB is assessed. Also, the gradual increase of the content of biodiesel mixed with diesel oil as provided in the CNPE nº 16 Resolution [37] is considered. In accordance with the schedule established by the resolution, the minimum biodiesel content in the diesel oil will be increased by 1% per year, until it reaches 15% in 2023 as seen in Table 1.

Moreover, based on a review of transportation electrification studies, it was found beneficial to expand the environmental impact calculations beyond just global warming potential (GWP) and to include ozone formation, human health impacts (HH) [38].

<table>
<thead>
<tr>
<th>Source*</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>12%</td>
<td>13%</td>
<td>14%</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>88%</td>
<td>87%</td>
<td>86%</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
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<td>85%</td>
</tr>
</tbody>
</table>

Source: CNPE nº 16 Resolution [37]

For the development of the LCA, three scenarios were created to verify the operational impacts in public transport. Such scenarios were chosen due to their contribution on the implementation of green strategies and bring to light the possibility of a transition to a more sustainable fleet. This occurs especially because there is a measurement of fleet switching impacts over the years.

Furthermore, operational impacts are verified through changes in the vehicle power source through the time frame analyzed. The buses examined correspond to 20.72% of Porto Alegre’s current bus fleet in circulation. The analysed scenarios are described below and represented in Figure 1 which shows changes in the bus fleet from 2020 to 2030.
Figure 1. Diagram of scenarios assessed in this study. Scenario 1: BAU; Scenario 2: ELE1, and Scenario 3: ELE3

- Scenario 1 - BAU (Business as usual): Analysis CB use impacts considering diesel mixed with biodiesel content as fuel, in accordance with CNPE Resolution No. 16 [37].
- Scenario 2 - ELE1 (Electric 1): Scenario in which the increase of biodiesel on the mixture and the gradual replacement from CB to EB occurs in parallel, according to the end of life of the vehicle, 14 years [39]; as a result, a total replacement of the fleet to EB occurs in 2029.
- Scenario 3 - ELE2 (Electric 2): Scenario in which the increase of biodiesel on the and the replacement of 10% per year from CB to EB happens, in accordance with Public Competition Notice No. 01/2015 - SMT [40] following two criteria: (i) renewal of at least 10% of the total fleet each year; (ii) maximum average age of the fleet of 5 years.

It is also worth mentioning that the evolution of electric power generation over the years in Brazil was taken into account, due to the great importance in assessing the environmental impacts of different alternative scenarios, not only of fuel consumption but also of the contribution of different energy sources in Brazilian conditions. A prognosis of the share by source in total electricity generation in Brazil was estimated based on data provided by the Climate Centre [19] represented in Error! Reference source not found..

Finally, it is worth pointing out that the study does not take into account the possible need for a growth in the vehicle's numbers due to unexpected demand. Such decision was made considering the complex analysis that would need to be added for such projection and the lack of data available at the time of the execution of this analysis. It is also essential to add that bus lifespan and battery replacement in EB were included in the scenarios [41].

Table 2. Estimated share by source in total electricity generation (%).

<table>
<thead>
<tr>
<th>Source*</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1: Energy mix and efficiency

<table>
<thead>
<tr>
<th>Component</th>
<th>1.2</th>
<th>1.2</th>
<th>1.2</th>
<th>1.3</th>
<th>1.3</th>
<th>1.3</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
<th>2.3</th>
<th>2.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane</td>
<td>8.5</td>
<td>8.3</td>
<td>8.1</td>
<td>7.8</td>
<td>7.6</td>
<td>7.4</td>
<td>7.4</td>
<td>7.5</td>
<td>7.5</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Bagasse</td>
<td>70.2</td>
<td>70.3</td>
<td>70.7</td>
<td>70.6</td>
<td>70.9</td>
<td>71.0</td>
<td>70.1</td>
<td>69.2</td>
<td>68.4</td>
<td>67.3</td>
<td>66.4</td>
</tr>
<tr>
<td>Hydro</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.1</td>
<td>8.1</td>
<td>8.3</td>
<td>8.4</td>
<td>8.6</td>
<td>8.7</td>
<td>8.9</td>
</tr>
<tr>
<td>Wind</td>
<td>5.5</td>
<td>5.4</td>
<td>5.2</td>
<td>5.1</td>
<td>4.9</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Oil</td>
<td>2.2</td>
<td>2.2</td>
<td>2.1</td>
<td>2.0</td>
<td>1.9</td>
<td>1.9</td>
<td>2.0</td>
<td>2.1</td>
<td>2.2</td>
<td>2.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Hard Coal</td>
<td>3.4</td>
<td>3.3</td>
<td>3.2</td>
<td>3.2</td>
<td>3.1</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1.0</td>
<td>1.3</td>
<td>1.5</td>
<td>1.9</td>
<td>2.1</td>
<td>2.4</td>
<td>2.6</td>
<td>2.9</td>
<td>3.2</td>
<td>3.5</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Source: contribution based on data from the Climate Centre [19] where imports were not considered.

System boundaries and functional unit

Regarding the aspects that influence the emission factors, the bus use phase generates most of the atmospheric emissions, mainly due to the combustion emissions in this type of engine and due to the lifespan of such vehicles [21]. In this context, having in mind fossil fuel as one of the main energy sources present in this study, the scope is limited from cradle-to-grave, and the system boundaries are defined with the primary focus on the vehicle's operating phase considering energy production components, such as the fuel or energy consumed to run the city buses. Currently, all buses run on diesel S10 (10ppm) with the gradual substitution from its pure form to a higher percentage of biodiesel in the mix in accordance to the CNPE nº 16 Resolution [37].

The available data classifies the Vehicle Consumption Category according to size and height (Micro; Light; Heavy; Bus 6x2; Special); the engine position (central, front and rear); the presence of air conditioning; and the type of gearbox (manual or automatic) [42]. Nonetheless only efficiency was considered as a factor regarding bus classification. It was assumed that both CB and EB are built utilizing the same bus shell, interior fittings and ad components, considering unlikely that these differences would significantly alter the results of the LCA study [41]. The bus production was for that reason not considered.

Manufacturing, maintenance and infrastructure stages as well as end of life were disregarded, as specified by [21], since the absence of locally collected data may increase outcome uncertainties [43]. Therefore, regarding energy sources impact in the operational phase, production impacts, transport and consumption (during operation) are included; for the electrification scenario, battery production and power generation for recharging electric vehicles were taken into account. In regards to the charging stations, their locations would be within public grounds on bus parking lots scattered in different regions of the city, in Carris’s case the area is located in Partenon neighborhood on the east end of the capital.

As shown in Figure 2, eventual changes in routes, adaptations and maintenance of urban infrastructure were not considered. Battery disposal was disregarded as well due to its uncertainties. In Brazil most residues are accumulated in landfills, in spite of that the final disposal of batteries since is controlled by CONAMA Resolution No. 401 [44]. Nonetheless a collecting system for rechargeable batteries is still tender; hence it is difficult to appraise its success rate [45] as current practices have yet a number of deficiencies [46]. In spite of that, it is important to point out that that the disposal of Li-ion batteries may lead to significant environmental burdens, but there are still very few studies about the corresponding impacts [47].

Considering the vastness of factors, the impact varies according to the scenarios projection where (i) vehicles are replaced in the fleet; (ii) distances are covered; (iii) mass of fuel transported; (iv) average vehicle efficiency values; and (v) fuel changes, the common unit considered are the km travelled, considering annual changes. This correlates with [25] who
regards that the Functional Unit (FU) of complete LCAs is defined as a vehicle life cycle, which is specified by a total number of driven kilometres per year.

Life Cycle Inventory

The LCA for this study was completed by combining four main data sources, the ecoinvent® v3.6 database [48], the Public Transport and Traffic’s company (PTCC) database [49], materials from the Energy Research Company (ERC) [50] and the Climate Centre (CC) [19], as well as complementary literature. Emissions from fuel combustion were calculated based on GHG emission factors reported in the 2021 National Energy Balance [50]. Furthermore, for the battery’s energy source production, data from the Brazilian matrix was adapted. Table 3 shows the quantities considered for each component of the system and the expenses per travelled km. The distance adopted for the use phase of vehicles under study was based on the mean life span of a public bus in Porto Alegre that is 842,268 km. With this data and with the bus efficiency per year, it is possible to determine the total quantity of fuel or electricity consumed on each scenario.

The fuel consumption and travel data were provided by the PTCC. In addition, the fleet database was also provided and promptly categorized by the bus prefix, identifying “Carris lot 7” individual characteristics, such as fuel consumption in litres/kilometre (l/km), buses models, quantities and efficiency for each year. Regarding the battery, the ion-lithium battery type is the most used in electric buses, presenting 32 cells [51]. It was assumed that the batteries are replaced every four years for a time interval which considers its maximum running capacity of 264,000 km [22] based on the average annual running of the vehicle described by PTCC [49], a battery consumes 126.5kWh for every 100km driven [52]. Consequently, to find the impacts of the use of vehicle batteries, the batteries data was tailored through an adaptation of the market type process from the 14-cell battery to a 32-cell example. It is also taken into account as previous studies pointed out [53] that the battery cell was unlikely to be produced in Brazil; hence, it was assumed that the battery cells are imported and the battery pack is assembled in the country. On the other hand, changes in consumption due to variation in capacity (number of people transported) were neglected in this study, this approach is justified.
because the primary data provided by PTCC is average data without information on this variation.

Table 3. Description and quantitative of materials related to the displacement of 1km considering the general fleet efficiency in 2020. (Source: Ecoinvent) [35]

<table>
<thead>
<tr>
<th>Material</th>
<th>Dataset</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel</td>
<td>Esterification of soybean oil (BR)</td>
<td>0.48 kg</td>
</tr>
<tr>
<td>Diesel</td>
<td>Diesel, low-sulfur (BR)</td>
<td>0.47 kg</td>
</tr>
<tr>
<td>Battery</td>
<td>Market for battery, Li-ion, rechargeable, prismatic (GLO)</td>
<td>3.78E-06 p</td>
</tr>
<tr>
<td>Electricity*</td>
<td>Electricity, high voltage, market group for electricity (BR)</td>
<td>1.26 kWh</td>
</tr>
</tbody>
</table>

*the electricity dataset considers the Brazilian energy matrix as described on Table 1.

Life cycle impact assessment

The stage of the Life cycle impact assessment (LCIA) was conducted in accordance with the ISO 14044 standard [32]. The characterization method applied was RECIPE version 1.04 (2016) that is a problem-oriented approach (midpoint) in a hierarchical structure (H). The midpoint approach was selected in an attempt to reduce the uncertainty of the results [54] and considering that it characterizes the impact categories based on impacts that are directly caused by emitted pollutants, that is the environmental impacts at intermittent stage of the cause effect chain in the form of indicators such as carbon dioxide (CO$_2$) and nitrogen oxides (NOx) [55].

The environmental impact assessment was developed at the Simapro v9.1 software faculty version. From the eighteen impact categories described in the method, Global Warming Potential (GWP); Ozone Formation - Human Health (HH) were selected for this study, as the emissions accounted are related the main environmental impacts by the transport sector. The impact categories chosen for evaluation are relevant for the studied system, since the selection follows an approach in case studies with similar topics [21]. In addition, the choice also correlates with a direct link between these emissions and two sustainable development goals (SDGs): SDG 11 (related to sustainable cities and communities) and 13 (take urgent action to combat climate and its impacts) and some specific indicators suggested by the UN [56]. Finally, considering the allocation procedure, the cut-off system was adopted, in which all the impacts raised remain with the main product [57]. The requirements for the data used were accuracy, completeness and representativeness, consistency, and ease of reproduction.

RESULTS AND DISCUSSION

The projections for future scenarios were developed from combining the variables described in...

Figure 1. Error! Reference source not found. Table 1 and Error! Reference source not found. It is also worth noticing scenarios 1 to 3 have possible combinations of power source changes: (1) BAU: following national law with stagnation of biodiesel percentage by 2023; (2) ELE1: the replacement from CB to EB occurs according to bus’s end of life and considering an increase of biodiesel percentage in the mix; (3) ELE2: in accordance with Public Competition Notice the replacement of CB to EB occurs in parallel to fuel changes.

Considering BAU, represented in Figure 3, only fuel changes are taken into account as the fleet remains the same with only conventional buses. In both ELE1 and ELE2 the fleet begins to be renewed in 2020, being that in ELE1 the full substitution from CB to EB happens in 2029 and in ELE2 the full renewal of the fleet is not reached until the end of the study time frame in 2030.

In the BAU scenario, the total and the percentage impacts of Diesel decreases over the years with biodiesel's gradual replacement until the year 2023, when the percentage changes of biodiesel in the mix ceases. However it is worth notice that Diesel's impact is the most...
representative in all the years and scenarios if present. For instance, in the BAU scenario, its percentage contribution in the analysis is also greater (83%) with approximately 2.64E+07 kg CO\textsubscript{2}eq. in 2020. In the other hand, during the same year, the impact of biodiesel corresponds to just over 16%, with around 5.28E+06 kg CO\textsubscript{2}eq in GWP.

In accordance to GWP, HH increased their total emissions among the years, from almost 2.20E+04 kg NO\textsubscript{X}eq. in 2020 to more than 2.28E+04 kg NO\textsubscript{X}eq. in 2030 at the BAU scenario. As happened in GWP impact, the total and the percentage impacts of Diesel decrease over the years from 76% to 71%. The total and the percentage of biodiesel increase from 23% to 29%, regarding the BAU scenario. In addition, the percentage of Diesel and biodiesel keeps constant between 2023 and 2030 at 71% and 29%, respectively as seem in Figure 3. Therefore it is apparent that despite the slight proportion of biodiesel in the mixture, its increment increases impacts of both GWP and HH as collaborated with previous studies [42]. The findings are in accordance with the literature that brings some trade-offs about bioenergy because the biomass cultivation could increase the nitrogen load while the harvesting could reduce the nitrogen load slightly [58].

Regarding the ELE1 scenario, Diesel and Biodiesel reached their lowest impact in 2029, while all electricity sources reached their highest. On the other hand, batteries reached their highest impact in 2030, where 88 batteries were replaced (0.06% and 1.59E+03 kg CO\textsubscript{2}eq.). Furthermore, ELE1 shows that the GWP impact decreases from 2.67E+07 kg CO\textsubscript{2}eq. in 2020 to about 2.82E+06 kg CO\textsubscript{2}eq in 2030, in which electricity encompasses 99.9% of the GWP impact. Additionally, the impact in 2030 is 10% of the impact in 2020 (ELE1). Thus, the transition to electric buses reduced almost 90% of the impact, counting almost 2.39E+07 kg CO\textsubscript{2}eq as observed in Figure 3.

Policymakers should also pay attention to the energy matrix they are using for the electric vehicle fleet, since an electric matrix based on renewables increases the benefits of electric vehicles, and instruments and energy policy play an important role in promoting such change [59]. This fact highlights the significance of regarding the contribution of each source within the energy matrix and its relationship with the total impact. In 2030 Brazilian electric energy matrix is expected to be composed of 89.2% of electricity from renewable energy sources in 2030 (66.4% hydropower, 2.6% sugarcane, 7.6% bagasse, 8.9% wind energy and 3.7% solar energy), while the electricity from non renewable energy sources was only 10.8% (4.8% natural gas, 0.5% oil, 2.4% hard coal and 3.1% nuclear).

Accordingly, in ELE1 in the same year hydropower was the energy source with the highest contribution (45.8% and 1.29E+06 kg CO\textsubscript{2}eq.), yet two non renewable energy sources despite the low percentage in the electric energy matrix presented the second and third highest impacts respectively: (1) hard coal, 27% and 7.61E+05 kg CO\textsubscript{2}eq.; (2) natural gas, 21.9% and 6.19E+05 kg CO\textsubscript{2}eq.
Concurrently, regarding HH, Diesel and Biodiesel emissions decrease at both ELE1 and ELE2. For instance, Diesel decreases from 72% (2020) to 0% (2030) at ELE1 (the emissions decrease from more than 1.39E+04 kg NOxeq. to no more than 0 kg NOxeq.), while at the
ELE2, it reduces from 73% (2020) to 44% (2030) (the emissions decrease from more than 1.51E+04 kg NOx eq. to 5.32E+03 kg NOx eq.). In addition, biodiesel decreases from 22% (2020) to 0% (2030) at the ELE1 (the emissions reduce from more than 2.26E-01 kg NOx eq. to more than 0 kg NOx eq.) while ELE2 ranges from to 23% (2020) to 18% (2030) (the emissions reduce from more than 4.74E+03 kg NOx eq. to more than 2.17E+03 kg NOx eq.). Simultaneously, electricity impact increases at both ELE1 and ELE2. For example, in ELE2, from 2.9% more than 6.04E+02 kg NOx eq. (2020) to 36.7% more than 4.35E+03 kg NOx eq. (2030) as showed in Figure 3.

However, it is necessary to point out that the reduction or increase of the respective emissions regarding different energy sources is intrinsically linked to the transitions considered during the elaboration of the scenarios and not exclusively related to their individual impact.

Though it should be noted that in comparison to GWP, in HH (2030) bagasse was the energy source with the highest contribution (23.8% and 2.82E+03 kg NOx eq.), while once again hard coal came in second (6.2% and 7.40E+02 kg NOx eq.). The literature [60] highlights these drawbacks in bagasse, considering the correlation between its combustion and harmful emissions which causes many public health issues such as breathing and lung problems. Moreover, the indiscriminate use of resources as chemical products (e.g., fertilizers or herbicides), water, fossil fuels, electric power or land use have caused severe environmental impact to Human health and ecosystem quality[61]. Furthermore, the study by Gasparotto [62] calls attention to the dangers of coal to human health since coal-fired power plants are prodigious generators of environmental pollution, releasing large quantities of particles as aerosols in the atmosphere presenting an invisible risk to human health.

Moreover, it is possible to observe that the variation in impacts is not proportional, due to differences in the annual number of vehicle replacements. For instance, public bus transport companies deal with some challenging decisions because they should maximize their available and scarce resources in a smart way to achieve their business goals, reduce their costs and maximize their investments [63]. Therefore, new bus purchases should be assessed to optimize the bus replacements. Besides, the battery shows the lowest impact in all years, ranging from 4.51E+02 kg CO$_2$ eq. (2021) to 1.59E+03 kg CO$_2$ eq. (2030) in ELE1 and ranging from 1.57E-05 kg CO$_2$ eq. to (2023) to 4.45E-05 kg CO$_2$ eq. (2028) in ELE2. Considering ELE1, in 2029, the replacement of CB by EB already has reached more than 99%. It has a significantly lower impact than the others, demonstrating the potential transition to EB in Porto Alegre.

**Comparison between scenarios**

Figure 4 shows a comparison of the impact values for the different scenarios along the evaluation period. As can be noted in the graph, EB adoption reduces GWP and HH impacts of the three evaluated scenarios. The scenarios ELE1 and ELE2, if adopted, can reduce the emissions significantly in comparison with BAU. Hence, the results presented on the study corroborate with other assessments carried out by [41] and [25] in developed countries. Besides, the findings expand the research in emerging countries, as [64] have already demonstrated that the use of low-carbon buses can contribute to the decarbonisation of urban transport and help in the achievement of carbon targets in the BRT system in Brazil. According to researchers [65] battery replacements and bus fleet updates must also be analysed to compare the different types of fuels effectively. These factors have been poorly explored in the literature. Therefore, it is important to point out that these aspects were inserted in the developed scenarios, as mentioned in the method. However, in all three analysed scenarios, the impacts of batteries production represented small contributions to the CO$_2$ emission results. Nonetheless, even though such impact represents a low percentage, it is fundamental to mention the production results of the impacts are aligned with the LCA literature about urban public bus transport, since the impacts of battery production are not as great as ever in the developed country contexts [25].
The ELE1 scenario has the greatest impact reduction potential among those scenarios, followed by the ELE2 scenario compared to the BAU scenario, regarding GWP results. In the ELE1 scenario, in the years 2029 and 2030, there is already a total replacement of CB by EB, demonstrating the potential to reduce 90% GWP impacts compared to the BAU scenario. Consequently, based on the graphic shown in Figure 6, decision-makers through the results showed can obtain a wide view of a possible EB scenario transition, facilitating the understanding and the comparison between the scenarios. However, the graphic is only a tool in the decision-making process on LCA in the transport sector; it is recommended that decision-makers include other stakeholders for the discussion of public policy development.

On the one hand, when deciding for the transition from CB to EB when analysing BAU in comparison to both ELE1 and ELE2, the decision-makers must consider the choice of the energy matrix about electricity, which correspond to more than 99% of the impacts in the ELE1 scenario from 2029 onwards based on GWP impact. Even though ELE1 and ELE2 appear as the best scenarios in comparison with BAU (see Figure 4), the HH findings show the importance in considering the energy source when making a decision, as there were variations in the impact results through the years despite the reduction of fossil fuel consumption. Such findings align with the literature since researchers have shown that HH emissions depend heavily on the electricity energy matrix [65]. For example, when countries use a renewable matrix, they could possibly reduce HH emissions [66] and if the electricity comes from fossil fuel sources the damage to the environment and human health may persist [65]. Bicer also [65] shows that HH values may be higher in electric vehicles because of the manufacturing and maintenance stages in comparison to conventional fuelled vehicles. On the other hand regarding the operation phase the author [65] highest global warming potential per kilometre travelled is obtained from a conventional vehicle in comparison to an electric one confirming the results found in this study regarding the use phase.

Finally, it is important to note that the scenarios were based on projections of the Brazilian electricity mix, but the choices should also consider local electricity mixes, such decision may change the results considerably, especially in large countries with significant differences between regions, such as Brazil.

Furthermore, the EB insertion can positively impact the reduction of fossil fuel dependence (such as Diesel used as fuel for buses) in cases where electricity production is based mainly on renewable sources. It is crucial to highlight that EB is preferred by users who use transport to commute to work concerning other users of public transport, even if the decrease emissions cannot be considered as a priority item for passengers as congestion time and travel time are [67]. Consequently, it is essential that policies for promotion of low emission vehicles address customer preferences and habits as well as territorial specificities, as different parts of the
world need different approaches [68]. Thus, decision-makers should create different mechanisms that engage a target population to use EB, including other aspects, such as security, price, travel time, and quality of service offered.

FINAL REMARKS

This study shows that EB is an option to reduce environmental impacts for the public transportation in Porto Alegre, Brazil, based on average Brazilian electricity mixes. According to the GWP results, the transition from the BAU scenario to the ELE1 scenario can be presented as the solution that has a greater reduction in impacts, however several factors were not considered, such as the financial investment for this transition. Particularly, the maintenance of ELE2 scenario favours the gradual perception of fleet replacement by the population; such gradual change could engage and encourage the population to adhere to public transportation modes. However, the choice of scenario ELE1 is an alternative in case of the need to obtain results in a short-term, but it depends on the main municipal climate change plan goals that should be aligned with GWP impacts and the local availability of renewable energy. Thus, intermediate scenarios should also be evaluated given that decisions should be aligned with the strategic objectives and priorities of each region.

The analysis presents an evaluation of the use of public buses, considered the most relevant stage of public transportation system life cycle impacts. As a transition to a cleaner energy matrix is reached, other parts of the system, such as infrastructure maintenance, as well as end of life of vehicles and its parts may become more relevant into public transportation system life cycle. So, future studies shall consider these stages, as well as assess the future availability of clean energy supply, giving support to broad and transparent decisions.

Finally, as a suggestion for further studies, the importance of analysing the economic feasibility of each scenario can be emphasised since the study is limited to understanding global warming potential and human health impacts in relation to the environmental perspective. Therefore, the economic feasibility analysis should consider other aspects such as the costs of recharging and replacing batteries as well as the availability of cleaner electricity to supply Porto Alegre, since the increase in demand may contribute to the use of fossil sources. In addition, the costs of Brazilian electric energy can be considered, compared to the costs of the diesel and of the biodiesel, performing an extrapolation period for fifteen years, for example. Another suggestion is to analyze results using sensitivity and uncertainty analysis to evaluate time related and territorial variabilities, especially considering the energy pricing and availability.

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