Introducing Electric Bus Fleets in Rio de Janeiro City – Methodology and Analysis

C. G. da Silva e Silva and *IEEE Member* L. A. Pecorelli Peres

Abstract—**This paper describes the establishment of a methodology aimed at planning the electrification of public urban bus fleets in order to characterize the operational requirements of the battery recharge process. Specifically, it deals with obtaining the behavior of demand and the necessary electrical energy for battery recharging. The effects on the electrical system peak and the resulting environmental benefits are also evaluated by comparing with current internal combustion fleets. An innovative method is applied to a fleet in the city of Rio de Janeiro. The motivation for this work is due to the characteristics of the Brazilian energy mix that is highly favorable to the electrification of urban transport with greater energy efficiency, with a view to reducing the impacts of internal combustion drive and the respective atmospheric emissions that are harmful to the environment. Also, this work offers the steps to establish essential elements, as daily, month and year energy consumption in order to recharge an electric bus fleet and data for the transportation bus company contracts an electric power distribution utility in Brazil. In spite conservative premises were considered, the calculations show electric bus option attractive. The operational energy consumption of diesel bus fleet is 19.10 MJ/km more than three times the consumption of electric bus fleet, this is 6.10 MJ/km. Additionally, 153 ton of fossil CO_2 atmospheric monthly emissions are avoided. The results obtained indicate the need for public policies in favor of electric power and the environmental benefits of adopting electric buses.**

Index Terms—**Electric vehicles, Energy Efficiency, Load management, Public Transportation.**

I. INTRODUCTION

The report issued by Company of Energy Research from Brazil indicates that the transport sector in Brazil was the one that consumed the most energy and was responsible for 33% of the total energy consumption in the country [1]. This report indicates that 93% of this consumption is attributed to the road modal [1]. Most of it refers to oil byproducts, particularly diesel and gasoline, some 59.5%. Only 0.4% or electrical power consumption is geared for this sector [1].

Some 48% of greenhouse gas emissions associated with Brazilian energy consumption derive from the transport sector, while the world average is 24% [2]. On the other hand, emissions of pollutants corresponding to electrical power generation in Brazil revolve around 13%, while the world average revolves around 42%, considering the prevailing use of hydroelectric power in the country [2].

In comparing energy consumption/km and public road vehicle occupancy/passenger, public transport provided by electrical buses presents greater energy efficiency as well as urban mobility benefits [3].

Similar actions are observed in South America, in Chile's national capital of Santiago, with an electric bus fleet of 6.0% of the city's entire bus fleet. Their goal is achieved total electrification by 2040 [4]. In China's Shenzhen, the local government has determined public bus fleet electrification of 16,000 units distributed across three different concessionaires [4]. The market boasts 513,000 electric buses all over the world in 2019, with an indicated 17% growth over 2018. In Europe, there are approximately 4,500 electric buses in operation while in the USA there are 2,255, including 500 new registers in 2019 alone [4]. South America has a great market growth potential in this segment. In 2019, a 350% increase was observed in registrations of conventional battery run buses over the previous year, led by the city of Santiago [4]. Latin America now has 1,962 electric buses registered, 962 of which are the conventional battery run model (12-15m).

Looking at the energy flow from the fuel tank to the internal combustion vehicle (ICV) wheels, in a so-called tank-to-wheel analysis, low energy efficiency is observed. The battery-to-wheel flow in electric vehicles (EV) is much smaller than in ICVs: approximately 1/3 [5]. These arguments have inspired this new methodology establishes the parameters for contracting the supply for recharging the electric buses on a daily, monthly and annual basis.

II. PROBLEM STATEMENT

Considering the herein proposal to establish a methodology for bus fleet electrification plans in the context of Brazil's urban centers, this model was applied to a real fleet in Rio de Janeiro. The choice was made because of the world renown tourist nature of the city, which boasts a 7,564 internal combustion bus fleet [6]. In 2019, an estimated 688,000 tons of greenhouse gases were emitted by this fleet alone [7][8].

The chosen fleet comprises 16 units and serves Line 100, Troncal 01, which cuts across the city via Aterro do Flamengo. Round trips include the starting point at Platform C2 of Procópio Ferreira Bus Terminal, in the vicinity of the Central do Brasil Railroad Station, and the point of arrival at the General Osório Square on the Ipanema Street called Visconde de Pirajá, and connects the downtown area to the high-end southern part of the city that presents many tourist attractions.

The methodology and model developed for this study include an analysis of this bus fleet operation and the behavior of the electric grid in relation to vehicle recharge in the terminals involved as well as the garage, in addition to an evaluation of

C. G. da Silva e Silva, CBM University Center (UniCBE), Rio de Janeiro, caiosilvaa@hotmail.com

L. A. Pecorelli Peres, Rio de Janeiro State University (UERJ), Rio de Janeiro, lapecorelliperes@ieee.org

demand, energy and annual operation costs—including emissions avoided.

III. INITIAL CONSIDERATIONS

Transport concession related data referring to number of passengers and trips, operational fleet, travel distance and others have not been made totally available to the public. Therefore, this study required securing those data from the documentation gathered by a Parliamentary Committee of Investigation (CPI) established by Rio de Janeiro's city council in 2017 to examine the details of the public transport operation [9]. The number of passengers using Line 100 and the number of trips were extracted from the Daily Operation Reports (DOR) requested by the CPI. This study adopted the data related to working days in 2016. Concerning weekends and holidays and according to the DOR, this bus line was assumed to make 65.8% of the working day trips in a 22-working day month with 8 weekends days [10].

According to a transport application called MOOVIT (https://moovitapp.com/) accessed from smartphones, Line 100 covers a 15.49 km distance going from Central do Brasil to General Osório (C-G) in 60 minutes and 14.91 km going from General Osório to Central do Brasil (G-C) in 27 minutes, totaling 30.4 km travelled in an average of 87 minutes between each departure and arrival [11]. This study considered an average of 30 minutes G-C and 60 minutes C-G.

No access was obtained to official data concerning the number of buses as well as departure and arrival times for this line. However, according to the MOOVIT app, buses linger 15 minutes from one departure to another on working days between 4:50am and 7:30am and between 7:30pm and 11:50pm in both terminals. Between 7:30am and 7:30pm, another line is added at 15-minute departure intervals [11].

These assumptions allowed for the necessary adaptations to reach the number of buses for fleet operation. The number of buses leaving the terminal was assumed to be the same as the number of vehicles covering the return route back to the terminal. An operational fleet of 16 buses as therefore established to serve Line 100.

IV. METHODOLOGY AND DATA

The process of establishing energy consumption rates for each vehicle as a function of the travel distance is presented in the flowchart contained in Fig. 1.

This item IV contains a description of the different steps in Fig. 1, indicating that parameter calculations are presented in parts A through D.

The first step (item 1.1 and 1.2 of Fig. 1) establishes the average daily number of passengers using this transport system as well as passenger distribution across the day (hourly distribution) and their travel direction. A working day passenger average was calculated and passenger distribution was determined per time of day and travel direction (see details in Item A).

The second step (item 2.1 to 2.5 of Fig. 1) looks at estimating the number of passengers who will be simultaneously in a vehicle during each trip, because the energy consumed by ancillary equipment such as air conditioning, Global Positioning System (GPS), opening doors and others is directly related with the load being transported. At this stage, an hourly passenger average was calculated, initially on a per vehicle base. A capacity rate was therefore developed and that number was used to set a classification system for full vehicle capacity. This classification thus allowed for an estimated number of passengers traveling simultaneously in each vehicle. The power to operate ancillary service equipment can thus be determined as a function of that number of simultaneous passengers (see details in Item B).

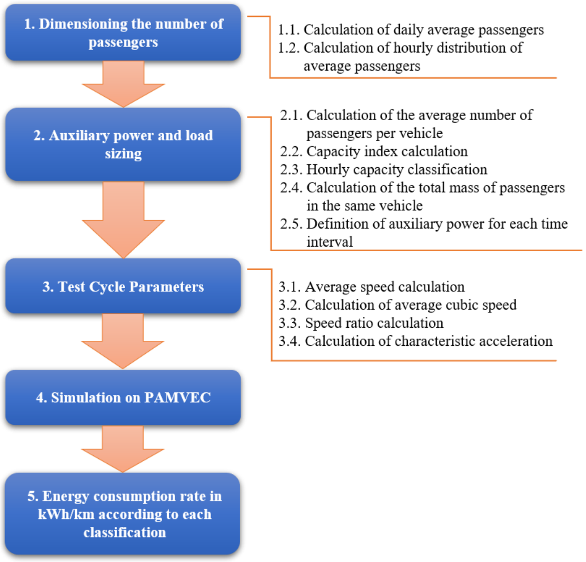


Fig. 1. Methodological flowchart.

A third step (item 3.1 to 3.4 of Fig. 1) is intended to establish bus speed behavior parameters related to the time of each trip by means of a real test cycle sample of the Line 100 route, as per Fig. 2.

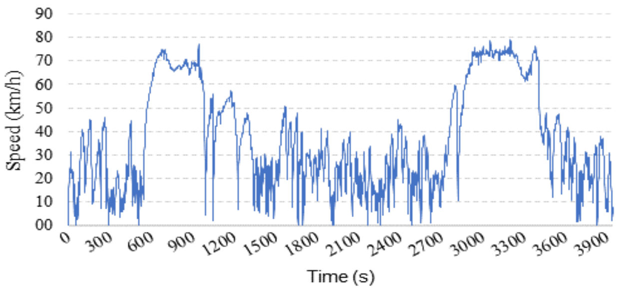


Fig. 2. Bus Line 100 Test Cycle.

That cycle's data were obtained according to [12], which used the GeoTracker application (https://play.google.com/store/apps/details?id=com.ilyabogdanovich.geotracker&hl=pt_BR&gl=US), which logs speed in km/h and time at each 2-second interval. This test cycle was started at the Central do Brasil terminal on April 5, 2019 at 2:36pm and ended at the same terminal at 4:13pm. Speed and acceleration data were thus obtained for a round trip.

Cycle parameters included average speed (m/s), average cubic speed (m/s), velocity ratio characteristic acceleration (m/s²), represented by equations (1), (2), (3) and (4), respectively according to [13].

$$v_{avg} = \frac{1}{T}\int_0^T v \cdot dt \tag{1}$$

$$v_{rmc} = \sqrt[3]{\frac{1}{T}\int_0^T v^3 \cdot dt} \tag{2}$$

$$\Lambda = \frac{v_{rmc}}{v_{avg}} \tag{3}$$

$$\tilde{a} = \frac{1}{2}\sum \frac{v_{final}^2 - v_{initial}^2}{v_{avg} \cdot T} \tag{4}$$

Where T is the total travel time (s), is the instantaneous speed (m/s), v_{final} and $v_{initial}$ are subsequent speeds of positive acceleration, that is, $v(v+\Delta v) > v(t)$.

Data obtained from equations (1), (2), (3) and (4), according to data in Fig. 2, were 37.09 km/h, 47.48 km/h, 1.28 and 0.132 m/s², respectively.

The last two steps, 4 and 5, are to determine energy consumption rate/bus and to compare that with the simulation by using the Parametric Modelling of Energy Consumption in Road Vehicles (PAMVEC) software [13].

A. Estimating Number of Passengers

According to DOR passenger data, the average passenger number on working days in 2016 for Line 100 was 35,419 [10]. It is convenient to have hourly data related to the respective number of passengers because a normal operations day includes peak demands for collective transport services. The solution provided here was to attribute an hourly distribution for a regular operations day presented in the Rio de Janeiro Metropolitan Region Transport Master Plan (PDTU) considering 2012 as a reference year [14]. Fig. 3 presents that hourly distribution on working days considering a total of 35,419 passengers.

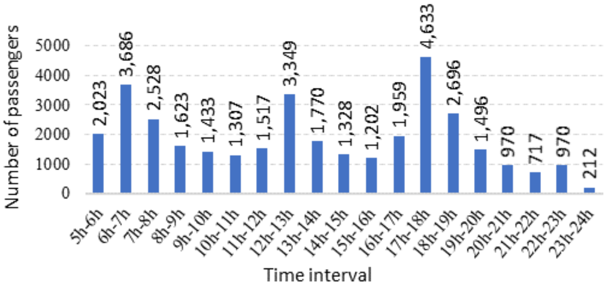


Fig. 3. Average hourly distribution of line 100 passengers.

B. Estimating Passenger Mass and Auxiliary Power

The MOOVIT app for smartphones allows for verification of an additional C-G line between 7:30am and 7:30pm. This direction was thus considered as transporting 2/3 of the total number of passengers. For the other periods, a distribution proportion of an equal number of passengers was adopted for each direction.

Application of this line direction-based passenger distribution proportionality is expressed in Fig. 4, which allows for an hourly number of passengers per vehicle as a function of the direction.

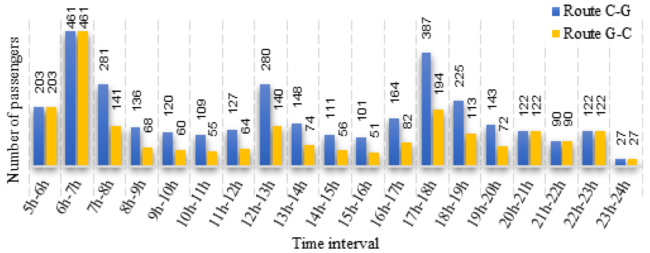


Fig. 4. Average number of passengers per vehicle depending on time and direction of route.

However, all passengers are not simultaneously inside the bus from terminal to terminal. At this point, an index was introduced in this study and termed "capacity index", which allows for a classification to estimate the average number of passengers simultaneously inside the vehicle in a round trip. This capacity index is calculated according to equation (5) and related classifications are shown in Table I.

TABLE I
CLASSIFICATION ACCORDING TO CAPACITY INDEX

Capacity index	Classification	Number of passengers considered inside the vehicle simultaneously
$I_C \le 1.0$	Empty	20
$1.0 < I_C \le 2.0$	Moderate	40
$2.0 < I_C \le 3.0$	Full	60
$I_C > 3.0$	Crowded	80

These capacity index related classifications were attributed to each time of line operation as presented in Table II.

$$I_C = \frac{N_{PV}}{2 \cdot n} \tag{5}$$

Where I_C is the capacity index, N_{PV} is the total number of passengers who are transported in each vehicle and n is the total number of seats in a bus.

To define the mass of passengers transported in each trip, the average Rio de Janeiro city resident's mass was used, considering 18+ year old men and women living in urban areas. According to the Brazilian Institute of Geography and Statistics (IBGE), the average mass is 66.4 kg [15].

Concerning ancillary services power, approximately 1.0 W/kg was factored in relation to the mass of passengers considering a minimum of 1,000 W. Table III shows the total mass of passengers and ancillary services power as a function of the capacity index classification, where "driver" refers to the moment when the driver is the only one on the bus, that is, in a route to the terminal upon start of the operation and back from the terminal bound for the garage at the end.

TABLE II
TIME CLASSIFICATION REFERRING TO THE CAPACITY INDEX

Time interval	Route (C-G)		Route (G-C)	
	Capacity index	Classification	Capacity index	Classification
5h-6h	2.74	Full	2.74	Full
6h-7h	6.23	Crowded	6.23	Crowded
7h-8h	3.80	Crowded	1.91	Moderate
8h-9h	1.84	Moderate	0.92	Empty
9h-10h	1.62	Moderate	0.81	Empty
10h-11h	1.47	Moderate	0.74	Empty
11h-12h	1.72	Moderate	0.86	Empty
12h-13h	3.78	Crowded	1.89	Moderate
13h-14h	2.00	Moderate	1.00	Empty
14h-15h	1.50	Moderate	0.76	Empty
15h-16h	1.36	Moderate	0.69	Empty
16h-17h	2.22	Full	1.11	Moderate
17h-18h	5.23	Crowded	2.62	Full
18h-19h	3.04	Crowded	1.53	Moderate
19h-20h	1.93	Moderate	0.97	Empty
20h-21h	1.65	Moderate	1.65	Moderate
21h-22h	1.22	Moderate	1.22	Moderate
22h-23h	1.65	Moderate	1.65	Moderate
23h-24h	0.36	Empty	0.36	Empty

TABLE III
TOTAL MASS OF PASSENGERS AND POWER OF AUXILIARY SERVICES IN RELATION TO THE CAPACITY INDEX

Capacity Index Classification	Mass of passengers (Kg)	Power considered for auxiliary services (W)
Empty	1328	1300
Moderate	2656	2600
Full	3984	4000
Crowded	5312	5500
Driver	66,4	1000

C. Simulating Power and Energy

Equations (6) to (12) were developed by [13]. Equation (6) presents the value of the total average power provided by the battery, which is necessary to cover the desired route [13].

$$\overline{P}_{total} = \overline{P}_{road} + \overline{P}_{braking} + \overline{P}_{drive-loss} + \overline{P}_{battery-loss} + \\ + \overline{P}_{accessory} - \overline{P}_{regen} \tag{6}$$

According to equation (7), the term $\overline{P}_{road}$, represents the average power the vehicle requires to overcome the dragging forces acting on the vehicle and, in equation (8), $\overline{P}_{braking}$, represents the average losses due to braking, where the regenerative braking fraction is also factored in. [13]

$$\overline{P}_{road} = \frac{1}{2}\rho C_D A \Lambda^3 v_{avg}^3 + C_{RR} m_{total} g v_{avg} \tag{7}$$

$$\overline{P}_{braking} = (1 - k_{regen})\overline{P}_{inertia} \tag{8}$$

Where ρ is air density (1.2 kg/m³), C_D is the aerodynamic drag coefficient, A is the vehicle's front area (m²), C_{RR} is the attrition coefficient of the vehicle's internal bearings, m_{total} is the vehicle's total mass (Kg), g is the acceleration of gravity (9.8066 m/s²), k_{regen} is the regeneration factor and $\overline{P}_{inertia}$, in equation (9), represents the average drive power for vehicle acceleration.

$$\overline{P}_{inertia} = k_m m_{total} \tilde{a} v_{avg} \tag{9}$$

Where k_m is the factor responsible for the rotational inertia of vehicle electromechanical drive.

Components $\overline{P}_{drive-loss}$, equation (10) and $\overline{P}_{battery-loss}$, in equation (11), represent average losses due to the drive system and to the battery, respectively [13].

$$\overline{P}_{drive-loss} = \frac{1-\eta_{trans}\eta_{mc}}{\eta_{trans}\eta_{mc}}(\overline{P}_{road} + \overline{P}_{inertia}) + \\ + (1-\eta_{trans}\eta_{mc})\overline{P}_{regen} \tag{10}$$

$$\overline{P}_{battery-loss} = \frac{(1-\eta_{battery})(1+k_{regen})}{2}\overline{P}_{inertia} \tag{11}$$

In equation 10, η_{trans} is the transmission system efficiency, η_{mc} is the motor/controller efficiency, $\eta_{battery}$ in equation 11 is the battery efficiency and $\overline{P}_{regen}$ in equation (12) refers to the average power absorbed by the drive system due to regenerative braking.

$$\overline{P}_{regen} = k_{regen}\overline{P}_{inertia} \tag{12}$$

Lastly, $\overline{P}_{accessory}$ is the average power necessary to feed the vehicle's ancillary services such as air conditioning, headlights, GPS and so on [13].

As mentioned before the last step is to determine energy consumption rate/bus and to compare that with the simulation by using the PAMVEC software [13]. The input parameters are very relevant and also adopted for the PAMVEC simulation described on Table IV. These parameters are also important to the next step calculations as presented in item D, namely energy consumption, demand and atmospheric emissions.

TABLE IV
INPUT PARAMETERS FOR SIMULATION IN PAMVEC

Parameters	Values
Glider mass	11.800 Kg [16]
aerodynamic drag coefficient	0.79 [17]
Rolling resistance coefficient	0.0098 [17]
Acceleration: 0 to 80.4672 Km/h	48.59 seconds [18]
Maximum speed	100 km/h [16]
Gradeability	5%
Gear box efficiency	92% [17]
Motor efficiency	88% [17]
Total battery storage energy	324 kWh [16]
Specific battery power	1400 W/Kg [19]
specific battery energy	133 Wh/Kg [20]
battery energy density	220 Wh/l [21]

D. Energy Consumption, Demand and Atmospheric Emissions

This section presents the methodology developed to obtain the necessary demand and energy to recharge the electric bus fleet. It also includes an energy comparison between EVs and ICVs and the estimated atmospheric emissions that were avoided by electrifying the Line 100 fleet. The steps described in this part are illustrated by the flowchart in Fig. 5.

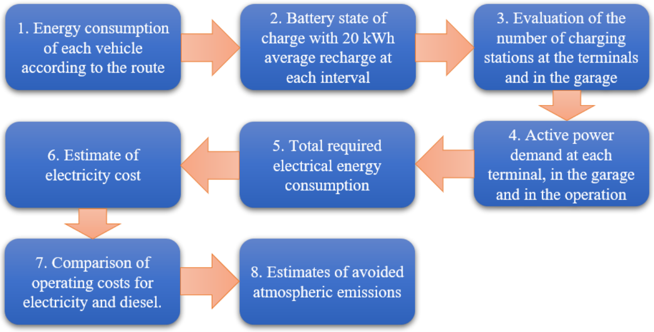


Fig. 5. Flowchart for analyzing energy consumption, demand and atmospheric emissions.

Results obtained from the PAMVEC simulation allowed for a calculation of the energy consumption of each bus, considering every trip made during its operation. A full day's operation could not be achieved with a single battery charge, at every 15-minute arrival-departure interval in the terminal. Partial recharge was thus introduced at an equivalent 20 kWh, admitting that every recharge station has an 80-kW power availability [16]. Energy consumption and battery charge status were thus obtained for each bus trip, in addition to final consumption at the end of each day operation.

Partial recharge is not enough to replenish the batteries. Recharge stations ought to be provided in the fleet's garage for full battery recharge during nighttime if the fleet is to be operational the next day.

Two recharge stations per terminal are therefore enough for daily operation of the fleet, sufficing there are six recharge stations in the garage, totaling ten recharge stations. Those considerations led to calculating the daily active power demand for the operation, at each individual terminal, as well as the demand of the two terminals together and the demand from the garage recharge, where each recharge station has, as mentioned before, design power of 80 kW [16]. That enabled an estimate of the energy consumption and the battery charge status in each bus trip, in addition to total consumption at the end of the operation.

Seeing that partial recharge is not enough for full battery recharge at the end of daily operations, recharge stations had to be provided in the fleet's garage for full battery recharge during nighttime for fleet operation availability the next day.

The need for two recharge stations per terminal was therefore observed for due daily fleet operation, as well as six recharge stations in the garage. Given that, the daily active power demand was calculated for the operation, which enabled a study of each individual terminal demand; that is, the demand of two terminals together, the garage demand and the total demand for complete fleet operation.

The active power demand curve was therefore defined for an estimate of monthly electrical power demand for Line 100 fleet and then the average vehicle consumption was calculated. This result allowed for extrapolation in order to estimate both consumption and cost of electrical power for the entire bus fleet in the city of Rio de Janeiro. That analysis required both peak and off-peak electrical power demand and consumption as informed by the local utility distribution company. In addition to that, the most adequate fare modality to be adopted by the Line 100 fleet was verified.

The average annual distance covered by the Line 100 fleet enables calculations to estimate diesel consumption at 0.538 liters/km according to [22].

Quantification of annual diesel costs factored in average prices at the local Rio de Janeiro utility distribution company between September and November 2020. The average price adopted for that fuel with and without taxes was R\$3,11/liter [23] and R\$1,90/liter [24], respectively.

Lastly, atmospheric emissions avoided by electrification of Line 100 fleet were estimated. Atmospheric emissions considered for this study were: carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), methane gas (NH_4), nitrogen oxides (NO_X), particulate matter (PM) and nitrous oxide (N_2O), with which monthly emissions and vehicle average were estimated according to equation (13).

$$Em = 10^{-3} \cdot F_e \cdot D \tag{13}$$

Where, Em is the amount of pollutant emitted, in kg, F_e is the vehicle emissions factor, in g/km, for urban buses, according to the São Paulo State Environment Company [7], and D is the distance traveled by the fleet, in km.

V. RESULTS

Average energy consumption rates per kilometer and the autonomy of the electrical bus model that was adopted, considering classifications on Table III referring to Line 100 were obtained by means of the PAMVEC mathematical model, including the cycle test in accordance with Fig. 2 and the data in Table IV. Those results are presented in Table V.

TABLE V
ENERGY CONSUMPTION RATE AND AUTONOMY ACCORDING TO CAPACITY INDEX CLASSIFICATION

Capacity index classification	Mass of passengers (Kg)	Power considered for auxiliary services (W)	Energy consumption rate (kWh/km)	Autonomy (km)
Empty	1328	1300	1.56	207.7
Moderate	2656	2600	1.70	190.6
Full	3984	4000	1.84	176.1
Crowded	5312	5500	1.98	163.6
Driver	66.4	1000	1.46	221.9

A. Distance, Energy Consumption and Battery Charge Status

Fig. 6 presents the total distance traveled, in km, by each vehicle at the end of a working day operation and the total electrical power consumption, in kWh, that each vehicle consumes to cover its daily operation routes. Considering the recharges during stationary intervals in the terminal, each vehicle's battery charge status at the end of its daily operation is presented in the first column of Table VI. Remarkably, as explained in Item III, weekends and holidays assumed 65.8% of those amounts for annual calculations.

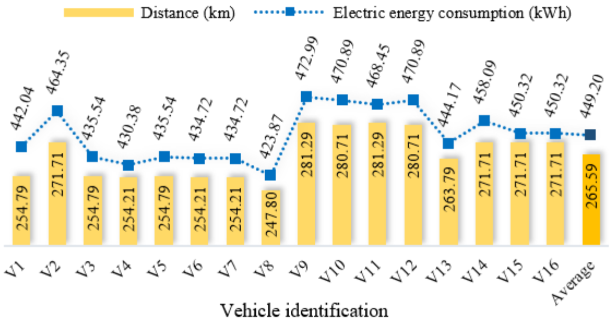


Fig. 6. Total daily distance traveled and electric energy consumption by each vehicle.

B. Demand Curves

Fig. 7 presents the recharge demand curve in relation to each terminal and the recharge demand curve referring to Line 100 fleet operation during the day. Contents in Fig. 7 provide that 160 kW is the maximum demand for both terminals. The Central do Brasil terminal presents an average demand of 131 kW, a 0.82 charge factor and average daily consumption of 2,353 kWh. The General Osório terminal presents an average demand of 130 kW, a 0.81 charge factor and average daily consumption of 2,400 kWh.

TABLE VI
FULL RECHARGE OF VEHICLES IN THE GARAGE

Vehicle	Battery state of charge	Remaining battery energy (kWh)	Energy required for a full recharge (kWh)	Time to full recharge (minutes)	Recharge start time	Recharge end time
V1	50,0%	161,96	162,04	122	00:00	02:02
V2	43,1%	139,65	184,35	139	00:00	02:19
V3	52,0%	168,46	155,54	117	00:00	01:57
V4	53,6%	173,62	150,38	113	00:00	01:53
V5	52,0%	168,46	155,54	117	00:00	01:57
V6	52,2%	169,28	154,72	117	00:00	01:57
V7	52,2%	169,28	154,72	117	01:57	03:54
V8	49,4%	160,13	163,87	123	01:53	03:56
V9	54,8%	177,68	146,32	110	01:57	03:47
V10	55,5%	179,78	144,22	109	01:57	03:46
V11	56,2%	182,22	141,78	107	03:54	05:41
V12	55,5%	179,78	144,22	109	02:02	03:51
V13	57,6%	186,50	137,50	104	02:19	04:03
V14	53,3%	172,58	151,42	114	03:46	05:40
V15	55,7%	180,34	143,66	108	03:47	05:35
V16	55,7%	180,34	143,66	108	03:51	05:39

Table VI presents nighttime recharge results for the fleet's garage, in order to achieve full charge for plain next-day operation. From Table VI, a new garage recharge demand curve and a complete Line 100 fleet demand curve were established, comprising operation recharge demand and full recharge demand, according to Fig. 8. From Fig. 8, recharge in the garage has shown to reach maximum demand of 480 kW, 430 kW of which refer to medium demand, a load factor of 0.90 and daily average consumption of 2,445 kWh. Considering the two terminals, recharge during operation reached maximum demand of 320 kW, medium demand of 257 kW, load factor of 0.80 and daily average consumption of 4,753 kWh.

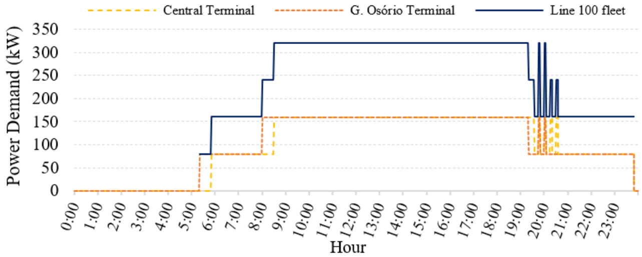


Fig. 7. Recharge demand for each terminal and for the line 100 fleet.

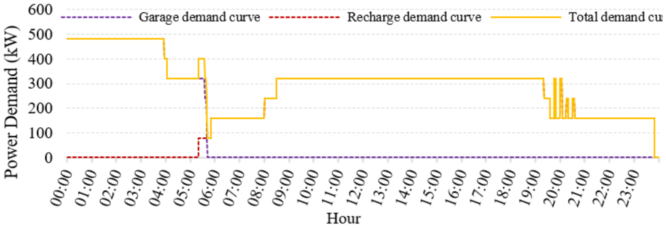


Fig. 8. Recharge demand curve in the garage and during operation.

C. Estimated Electrical Power Consumption

Electrical power consumption of Line 100 operation on a working day is 7.199 kWh. Energy consumption on weekends and holidays was considered at 65.8% of a working day, therefore equal to 4,735 kWh.

From those results, an estimated daily average consumption was established for the month and for the year of Line 100 operation. Extrapolations were therefore made for Rio de Janeiro's total bus fleet which, according to the Municipal Secretary of Transport, in August 2020, added up to 7,564 units in operation [6], as presented in Table VII.

TABLE VII
ELECTRICITY CONSUMPTION ESTIMATES

	Period	Line 100 fleet (MWh)	Average per vehicle (MWh)	Estimate for the city of RJ (MWh)
Working days	Diary	7.199	0.45	3,403.17
	Monthly	158.37	9.90	74,869.73
	Yearly	1,878.85	117.43	888,227.28
Weekends	Diary	4.74	0.30	2,238.53
	Monthly	37.88	2.37	17,908.24
	Yearly	492.45	30.78	232,807.06
Working days + Weekends	Monthly	196.25	12.27	92,777.97
	Yearly	2,371.30	148.21	1,121,034.34

Though results for Rio de Janeiro's total fleet were obtained from an average based on the study of a single line, that provides an important order of magnitude for energy planning and electrification of bus-based public urban transport in the city.

D. Estimated Cost of Electrical Power

Results obtained in Table VII provide the average monthly cost of electrical power for the Line 100 fleet. This analysis considered 320 kW and 480 kW for peak and off-peak demand, respectively. Monthly peak electrical power consumption reaches 18,274.67 kWh while the off-peak consumption reaches 177,976.98 kWh.

Those values show that the structure classified as horo-sazonal azul (peak hour blue), according to regulation 414 issued in 2010 by the National Electrical Power Agency in Brazil (ANEEL) [25], is the most applicable fare modality for electrical power consumption and demand for this fleet's recharge.

The monthly average cost estimated before taxes for Line 100 fleet operation is R$ 104,990.80 where R$ 8,827.20 and R$ 10,889.60 refer to peak and off-peak demand, respectively, while electrical power consumption alone was R$ 74,326.75 for off-peak consumption and R$ 10,947.26 for peak consumption.

Estimated average cost of electrical power after taxes considered 32% referring to the Brazilian tax on goods and services (ICMS) and 2.92% to Brazilian social security taxpayer contribution (PIS/COFINS) for December 2020 [26].

So, when taxes are factored in, the estimated average monthly cost for Line 100 fleet operation is R$ 161,350.25 with R$ 13,565.67 and R$ 16,735.18 referring to off-peak and peak demands respectively while electrical power consumption amounted to R$ 114,225.62 for off-peak consumption and R$ 16,823.78 for peak consumption.

E. Comparing Operational Costs Between Diesel Fuel and Electrical Power

This session includes comparisons for average energy cost for Line 100 fleet operation when diesel oil was used as fuel and when electrical power was used as the driving force. Based on the average 115,856.46 km distance covered by the fleet and considering an average diesel consumption of 0.538 liters/km [22], the monthly average diesel consumption of Line 100 fleet is 62,330.78 liters. Since the price of a liter of diesel oil is R$ 3.11 tax included [23], the estimated monthly average cost for Line 100 fleet operation is R$ 194,027.37. Table VIII contains a comparison for monthly operation costs between diesel and electrical power, considering prices both with and without taxes.

TABLE VIII
COMPARISON OF AVERAGE OPERATING COSTS USING DIESEL AND ELECTRICITY

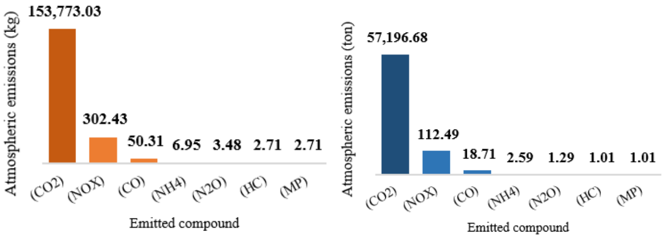
Cost / Consumption	With taxes		Without taxes	
	Diesel S10	Electric energy	Diesel S10	Electric energy
Monthly Cost Estimate	R$194,027,37	R$161,350.25	R$118,388.79	R$104,990.80
Monthly Energy Consumption (MJ)	2,212,617.86	706,505.94	2,212,617.86	706,505.94
Energy Cost (R$/MJ)	R$ 0.09	R$ 0.23	R$ 0.05	R$ 0.15
Energy consumption rate (MJ/km)	19.10	6.10	19.10	6.10
Cost per km	R$1.67	R$ 1.39	R$ 1.02	R$ 0.91

If we look at scenario with taxes, we see that even though electrical power costs are 2.55 times higher than diesel costs, use of electrical power is presents less expenditures. Indeed, use of electric buses is more efficient because energy consumption in MJ/km is 3.1 times greater with diesel than energy consumption with electricity.

Energy wise, it takes three times more (MJ) diesel to cover the same distance that it would take if electrical power drive was used. That bears directly upon cost per kilometer and, consequently, on monthly costs of operating Line 100; that is, use of electrical power drive provides an approximate 16.84% operational savings. The authors consider this promising different can be scaled up with the introduction of public policies in favor of electric buses, particularly when the inherent environmental benefits are considered in view of the significantly renewable Brazilian energy matrix.

F. Atmospheric Emissions

Fig. 9 (a) and (b) present monthly average estimates for avoided atmospheric emissions after electrification of the Line 100 fleet and after electrification of the entire Rio de Janeiro bus fleet, respectively, according to equation (12).



(a) Monthly average of atmospheric emissions avoided by the 100 line fleet.

(b) Monthly average of atmospheric emissions avoided by the Rio de Janeiro fleet.

Fig. 9. Monthly average of atmospheric emissions avoided.

VI. CONCLUSION

The results presented in Table V were similar to those found in Chilean electric fleets according to the World Bank report. In this report, energy consumption rates between 1.13 kWh/km and 1.74 kWh/km and autonomy between 90.9 km and 222.3 km were pointed out [27]. These values were obtained in the laboratory, considering the "TS-STGO" driving cycle, which represents the operation of an urban bus in the city of Santiago, the vehicle weight, the driver's weight and a load relative to the weight of 50 % of passenger occupancy [28].

This study shows that for Line 100, two partial recharge stations need to be built at the final bus stations. Full bus battery recharge at the end of daily transport operation will require six recharge stations at the nighttime garage. Considering the fleet comprises 16 vehicles, there is a bus/recharge station occupation rate of 4 during daytime operation and approximately 2.6 during nighttime at the garage.

Demand curves indicate that the biggest electrical power demand and consumption take place during the nighttime, reaching approximately 480 kW. It provides benefits for both the bus company and the utility company, considering electrical power system load reductions during peak periods and electricity rate reductions for the transport company.

The average energy consumption per bus of line 100 resulted in 450 kWh on working days and approximately 300 kWh on weekends or holidays, totaling 7,199 kWh and 4,740 kWh of daily energy consumption for the entire fleet, respectively.

Monthly consumption estimates are 196.25 MWh. Remarkably, with a single full battery charge, daily operations can be conducted, except for working days.

Based on the abovementioned results, a total of 4,801 recharge stations are estimated for the entire Rio de Janeiro city bus fleet, with 1,891 at passenger boarding terminals and 2,910 at the various company garages.

The novelty of the methodology is to establish the parameters for contracting the supply of electricity on a daily, monthly and annual basis. Further studies must include electric buses performance tests. It is also recommendable to stablish proposals of sustainable financial schemes in order to road urban transportation companies invest in electric buses fleets.

These results allow us to infer a daily average energy consumption for the entire Rio de Janeiro city bus fleet at 3,403.17 MWh on working days and 2,238.53 MWh on weekends and holidays. Considering a load factor of 0.90 at nighttime during garage recharge and 0.80 for fleet operation recharge, a maximum demand of 233.75 MW was obtained and a 151.76 MW demand was obtained for working day operation. On weekends and holidays, those demands would be 153.75 MW and 99.83 MW, respectively. Based on these results, annual energy consumption is estimated at approximately 1,121 GWh, corresponding to 42.7% of the Nilo Peçanha Electrical Power Plant generation in 2020, for instance, in the State of Rio de Janeiro [29] and to only 6.6% of the total municipal consumption in 2019, which was 16,899.92 GWh [30].

Concerning operational costs, benefits of employing electrical power are self-evident. Despite its higher cost per energy unit (R$/MJ), the greater efficiency of this option over the use of diesel has provided expressive operational savings of approximately 16.84%. Remarkably, values adopted to estimate the costs of using diesel were refinery values rather than the final amounts at fuel stations. If these final amounts had been used, the benefits of using electrical power drive would have been much higher.

Electrification of Line 100 avoids at least 153,000 kg of monthly atmospheric emissions and 1,845,000 kg yearly considering only fossil CO_2. If we consider total Rio de Janeiro city bus fleet electrification, at least 57,000 tons of fossil CO_2 emissions would be avoided every month, reaching 686,000 tons yearly.

Remarkably, electrification of bus fleets provides operational cost savings as it also increases quality of life in urban centers because of reduced atmospheric emissions from ICVs while strongly contributing to reduce deleterious effects of climate change.

The process of road bound public transport electrification—deployed in various countries, including some in Latin America, after the Chile experience and now in progress in Peru and Colombia—points this way. In Brazil, the process presents great potential since the country already has electric bus assembling companies in place.

According to [31] and [32], public policies should be established so that public transport electrification is enabled as well as vehicle fleets belonging to electrical power companies across the country [33]. A comparison between operational costs with and without taxes underlines a high tax burden on electrical power prices for urban bus fleets recharge. This study has indicated that electrical power costs including the relevant taxes increases final amounts by 53.65%.

It is clear that increased fleet bus autonomy will contribute significant operational benefits. It will avoid bus battery recharge stops, thus increasing travel time during passenger peak hours, which usually coincide with electrical power grid peaks, eventually leading to lower operational costs.

The favorable perspectives for the introduction of urban electric bus fleets deserve the inclusion of this subject in the elaboration of the strategic planning of electric energy companies [34]. The possibilities of higher billing combined with an effective reduction of harmful emissions into the atmosphere, as well as of fuel consumption, establish arguments with sufficient potential for attractiveness for these issues to be examined more deeply. Thus, it is convenient to improve short-term load prediction techniques [35] and the use of methods based on computational intelligence [36].

REFERENCES

[1] "Balanço energético nacional", Empresa de Pesquisa Energética – EPE, 2020. [online]. Available: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-479/topico-528/BEN2020_sp.pdf. Accessed on: May, 2021.

[2] "Propostas de novas ações para o setor de transportes", Plano Nacional de Eficiência Energética – PDEF. 2021. [online]. Available: https://eletrobras.com/pt/AreasdeAtuacao/iX%20-%20Eletrobras%20-%20PDEf%20-%20Produto%2006_vfinal%20-%20gravado%20e%20impresso.pdf. Accessed on: May, 2021.

[3] "Transporte e meio ambiente - Série cadernos técnicos 6", Associação Nacional de Transportes Públicos – ANTP, Banco Nacional de Desenvolvimento Econômico e Social – BNDES, São Paulo, 2007.

[4] "Global EV Outlook", International Energy Agency – IEA, 2020. [online]. Available: https://iea.blob.core.windows.net/assets/af46e012-18c2-44d6-becd-bad21fa844fd/Global_EV_Outlook_2020.pdf. Accessed on: May, 2021.

[5] W. B. Pereira, L. A. P. Peres and J. F. M. Pessanha, "Stochastic Model for Simulation of Transformers Supplying the Recharge of Electric Vehicles," *in IEEE Latin America Transactions*, vol. 15, no. 10, pp. 1908-1916, Oct. 2017, doi: 10.1109/TLA.2017.8071235.

[6] "Cadastro das linhas de ônibus", Secretaria Municipal de Transportes do Rio de Janeiro – SMTR. 2020. [online]. Available: http://www.rio.rj.gov.br/web/smtr/exibenoticias?id=9437691. Accessed on: May, 2021.

[7] "Relatórios de Emissões Veiculares no Estado São Paulo", Fator de emissão. Apêndice L, Companhia Ambiental do Estado de São Paulo – CETESB, 2019. [online]. Available: https://cetesb.sp.gov.br/veicular/wp-content/uploads/sites/6/2020/08/Fator-de-emissao-2019.xlsx. Accessed on: Apr, 2021.

[8] "Transparência da mobilidade", Prefeitura do Rio de Janeiro. 2020. [online]. Available: http://www.rio.rj.gov.br/web/transparenciadamobilidade/indicadores. Accessed on: May, 2021.

[9] C. C. L. S. Lima, "Transparência no serviço público de passageiros por ônibus do município do rio de janeiro", X Congresso Brasileiro de Regulação, Florianópolis, Santa Catarina, Set. 2017.

[10] Comissão parlamentar de inquérito dos ônibus – CPI, Rio de Janeiro, 2017. [online]. Available: https://cpidosonibus.com.br/documentos/. Accessed on: Apr, 2021.

[11] "Troncal 1 - General Osório - Central (BRS 1 - via Aterro do Flamengo)", Moovit. 2021. [online]. Available: https://moovitapp.com/index/pt-br/transporte_p%C3%BAblico-line-100_TRO1-Rio_de_Janeiro-322-856537-700039-0. Accessed on: Jun, 2020.

[12] R. S. S. de Miranda and D. S. C. Barbosa, “Avaliação de rotas de transporte público através de ônibus elétricos no Rio de Janeiro”, XXIX UERJ sem muros 2019 – 22º Mostra de extensão. Universidade do Estado do Rio de Janeiro – UERJ, 2019. [Online]. Available: http://www.gruve.eng.uerj.br/poster.php?aed=0. Accessed on: Jan, 2021.

[13] A. G. Simpson, “Parametric Modelling of Energy Consumption in Road Vehicles,” Ph.D. dissertation, School of Information Technology and Electrical Engineering, Queensland Univ., Queensland, QLD, AUS, 2005.

[14] Plano Diretor de Transporte da Região Metropolitana do Rio de Janeiro – PDTU. Rio de Janeiro. 2014. [online]. Available: http://www.rio.rj.gov.br/dlstatic/10112/5333332/4139325/25PDTUGovEstado092014.pdf. Accessed on: Jan, 2021.

[15] “Pesquisa de orçamentos familiares”, Instituto Brasileiro de Geografia e Estatística – IBGE, 2010. [online]. Available: https://sidra.ibge.gov.br/tabela/2645. Accessed on: Jan, 2021.

[16] “The BYD K9”, Build Your Dreams – BYD, 2019. [online]. Available: https://en.byd.com/wp-content/uploads/2019/07/4504-byd-transit-cut-sheets_k9-40_lr.pdf. Accessed on: Jan, 2021.

[17] Z. Gao, Z. Lin, S. C. Davis, A. K. Birky, “Quantitative evaluation of MD/HD vehicle electrification using statistical data”, 2018. Transportation Research Record, vol. 2672, no. 24, pp. 109-121.

[18] T. D. Larson, “Federal Transit Bus Test”, 2014. [online]. Available: https://www.altoonabustest.psu.edu/bus-details.aspx?BN=1307. Accessed on: Jan, 2021.

[19] P. H. L. Notten, D. Danilov, "From battery modeling to battery management.", In: 2011 *IEEE 33rd International Telecommunications Energy Conference* (INTELEC). IEEE, 2011. pp. 1-8.

[20] “BYD electric vehicles prsentation”, The International Council on Clean Transportantion – ICCT, 2017. [online]. Available: https://theicct.org/sites/default/files/BYD%20EV%20SEDEMA.pdf. Accessed on: Jan, 2021.

[21] Y. Ding, Z. P. Cano, A. Yu, J. Lu, and Z. Chen, “Automotive Li-Ion Batteries: Current Status and Future Perspectives”, *Electrochemical Energy Reviews*, vol. 2, no. 1, pp. 1–28, 2019.

[22] M. A. D’Agosto, D. N. S. Gonçalves, R. C. Queiroz. “Comparativo de consumo de combustíveis entre ônibus equipados com aparelho de ar condicionado e ônibus convencionais”, Fundação Coordenação de Projetos, Pesquisas e Estudos Tecnológicos – COPPETEC, Rio de Janeiro, 2015.

[23] “Preços de distribuição de combustíveis”, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis – ANP, Brasília, DF, Brazil, 2020. [online]. Available: https://www.gov.br/anp/pt-br/assuntos/precos-e-defesa-da-concorrencia/precos/precos-de-distribuicao-de-combustiveis. Accessed on: Jan, 2021.

[24] “Composição e estruturas de formação dos preços”, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis – ANP, Brasília, DF, Brazil, 2020. [online]. Available: https://www.gov.br/anp/pt-br/assuntos/precos-e-defesa-da-concorrencia/precos/composicao-e-estruturas-de-formacao-dos-precos. Accessed on: Jan, 2021.

[25] “Resolução normativa nº 414”, Agência Nacional De Energia Elétrica – ANEEL, Brasília, DF, Brazil, Set. 9, 2010. [online]. Available: http://www2.aneel.gov.br/cedoc/bren2010414.pdf. Accessed on: Jan, 2021.

[26] “Composição da tarifa”, Light S. A. 2020. [online]. Available: http://www.light.com.br/para-residencias/Sua-Conta/composicao-da-tarifa.aspx. Accessed on: Jan, 2021.

[27] “Lessons from Chile’s Experience with E-mobility : The Integration of E-Buses in Santiago”, World Bank. 2020. [online]. Available: https://openknowledge.worldbank.org/handle/10986/34435. Accessed on: Jan, 2021.

[28] “Protocolo Técnico para Obtener Consumo Energético en Buses de Transporte Público Urbano de la Ciudad de Santiago”, Chile. 2018. [online]. Available: https://www.mtt.gob.cl/wp-content/uploads/2018/08/Resex_2243.2018.pdf Accessed on: Jan, 2021.

[29] “Histórico da operação”, Operador Nacional do Sistema Elétrico – ONS. 2021. [online]. Available: http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/geracao_energia.aspx. Accessed on: Jul, 2021.

[30] “Consumo anual de energia elétrica segundo classe de consumo por Áreas de Planejamento (AP), Regiões de Planejamento (RP), Regiões Administrativas (RA) e Bairros no Município do Rio de Janeiro entre 2002-2019”, *Instituto Data Rio De Administração Pública* – DATARIO. [online]. Available: https://www.arcgis.com/sharing/rest/content/items/955ab891522140d6927d79d8f97bdda0/data. Accessed on: Jul, 2021.

[31] J. M. Domingues, L. A. Pecorelli-Peres, “Electric vehicles, taxes and public policies in Brazil”, *Green Taxation and Environmental Sustainability*. Edward Elgar Publishing, 2012.

[32] J. M. Domingues, L. A. Pecorelli-Peres, “Electric vehicles, energy efficiency, taxes, and public policy in Brazil”, Law & Bus. Rev. Am., v. 19, p. 55, 2013.

[33] L. A. Pecorelli Peres, J. F. Moreira Pessanha, F. d. M. Ferreira Particelli, A. C. I. Loma Caldas and J. V. Serra, "Analysis of the Use of Electric Vehicles by Electric Utility Companies Fleet in Brazil*," in IEEE Latin America Transactions,* vol. 9, no. 7, pp. 1032-1039, Dec. 2011, doi: 10.1109/TLA.2011.6129699.

[34] E. Costa, A. Horta, A. Correia, J. Seixas, Costa, G. Costa, D. Sperling. “Diffusion of electric vehicles in Brazil from the stakeholders' perspective”; *International Journal of Sustainable Transportation; Published online*: 09 Oct 2020.

[35] W. Marra, W. F. Lage, C. A. S. Miranda, G. Lambert-Torres, C. I. A. Costa, A. A. P. Silva. “Previsão de Carga de Curto Prazo”, 1999, XV SNPTEE Seminário Nacional de Produção e Transmissão de Energia, 17 a 22 de outubro de 2019, Foz do Iguaçu, Paraná, Brasil.

[36] A. F. Faria, G. Lambert-Torres, C. I. A. Costa; C. H. V. Moraes. “Desenvolvimento de Uma Metodologia Para a Contratação de Energia Via Técnicas Inteligentes”; 10th IEEE/IAS Conference on Industry Applications, November 5-7, Fortaleza, Brazil.

Caio Gonçalves da Silva e Silva received his M.Sc. in Mechanical Engineering and his B.Sc. in Electrical Engineering in 2016 and 2019, respectively, from Rio de Janeiro State University – UERJ. He also holds a 2009 certificate in electromechanics from the Celso Suckow da Fonseca Federal Center for Technological Education – CEFET/RJ, and did a 2014-2016 internship at LIGHT S.A. in Distribution Operation and Maintenance Planning. He is currently an Electrical Engineering Professor of Power Systems at the CBM University Center – UniCBE. His main research interest is in electric propulsion as well as photovoltaic energy systems.

Luiz Artur Pecorelli Peres received his D.Sc. in 2000 and M.Sc. in 1977 from the Federal University of Itajubá and his B.Sc. from Federal University of Rio de Janeiro in 1970. All three degrees are in Electrical Engineering. He is a retired Associate Professor at Rio de Janeiro State University – UERJ where he worked for over 40 years. He coordinates the Electric Vehicles Studies Group (GRUVE) founded in 2001at UERJ. Pecorelli Peres has more than 30 years of experience with power system planning and operation at ELETROBRAS and FURNAS. He is an IEEE member, a founder of the Brazilian Association of Electric Vehicles – ABVE and was a coordinating member of the Ministry of Science and Technology’s Electric Vehicle Network. His main research focus is on road transport electrification.