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Public transportation with electric traction: Experiences and challenges in an Andean city

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ABSTRACT

The paper studies the energy behavior of a battery-electric bus (BEB) operating on commercial routes as well as the technical feasibility of a total replacement of the current public transport fleet by BEBs in an Andean city. The electrical variables in the BEB charging process are evaluated obtaining THD current distortions of less than 4%, values that meet national and international standards. Regarding the energy demand, the study uses an estimate that allows quantifying the energy consumption of the fleet of 424 BEBsthat would operate the 28 routes. It is estimated that the maximum demand during the charging process can reach 33.92 MW if the fleet is charged at a rate of 80 kW per BEB and 19.96 MW if the charge is at 40 kW, whereas the charging time can range from 4 h to 9 h, respectively. The daily energy needed to power the fleet is 115 MWh, which represents about 4% of energy demanded per day by the city. The estimation of the energy efficiency of the BEB under analysis presents values that vary between 0.67 and 0.94 km/kWh, an indicator that depends on the conditions of the route. The article includes and study on the preference of BEB users as compared to conventional buses. Finally, the study shows a feasible alternative to integrate renewable energy sources for BEB charging, based on photovoltaic solar generation and the use of energy storage systems, as a contribution to the sustainability of the public transport.

1. Introduction

Primary energy for electricity generation and transportation represents currently around 60% of the total consumed in the world [1].

If it is consider the high dependence of our development model on the use of fossil fuels, whose emissions have a negative impact on the climate and ecosystems, renewable energy sources (RE) for electricity generation and transport electrification present a great potential for a transition to a new energy paradigm [1]. There are multiple international efforts, such as the Kyoto protocol or the most recent Paris agreement, that look for reducing greenhouse gas emissions, particularly CO_2, through the development of new technologies that contribute to a cleaner and more efficient electricity generation matrix as well as to a sustainable mobility. Electric vehicles (EV) are a clear example to promote the change towards the use of more efficient and environmentally friendly means of transportation. Additionally, among the most important challenges to advance towards sustainable mobility are: increasing the quality of public transport, improving urban planning, promoting shared transport, or the massive use of bicycles, thus challenging the exponential growth of private cars that occurs in many cities around the world [2,3]. If EV can be powered by electricity from renewable sources, then the positive impact would be twofold and we would be moving towards a more sustainable energy model.

In terms of public policy for the promotion of RE and EV, recently in the Republic of Ecuador there have been a series of events that arouse the research interest in different areas. For example, the Ecuadorian Constitution, in its article 413, establishes that the State must promote energy efficiency, the development and use of environmentally clean and healthy practices and technologies, as well as renewable, diversified, low-impact energies that do not jeopardize food sovereignty, the ecological balance of ecosystems or the right to water [4]. In October 2018, the country's Electricity Regulation and Control Agency (ARCONEL) approved regulation ARCONEL-003/18 where solar photovoltaic-based generation for self-consumption of final users is allowed, opening the possibility that this small-scale energy can be connected to the national interconnected system - SNI [5]. In March 2019, the Energy Efficiency Law was ratified by the National Assembly [6], where article 14, on energy efficiency in transport, indicates that from the year 2025 all vehicles that join the urban and inter-parish public transport service must only be electric traction-based. Added to

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this are the actions by local authorities to improve the transportation service, through regulations that set, for example, the useful life of transport units to 20 years [7]. The new regulatory context creates a challenge for Ecuador's energy sector, taking into account that 48.8% of the country's total energy consumption corresponds to the transport sector, and 6.2% of diesel is used in vehicles such as vans and buses dedicated to public transport [8]. This last number may seem like a small portion from the energy point of view, however, the impact from the long-term economic and environmental point of view is representative. On the other hand, the installed capacity of the electricity system in Ecuador reached 8662 MW in 2018, of which 60.8% is renewable energy [9]. In power generation, at least 70% comes from renewable energy, mainly hydroelectricity, and values of up to 90% have been reached [8]. This fact has not only displaced existing thermoelectric power plants, reducing pollution and fuel imports, but also allows the country to have an important generation reserve. This has led to a significant increase in the export of electrical energy in recent years, reaching 265 GWh in 2018 [8]. All this supposes that a transition to electric mobility is feasible in Ecuador from the energy point of view (small energy segment destined for vans and buses), considering the installed electrical capacity and the low costs of power generation. Faced with this scenario of vehicle replacement, it is necessary to apply short-term measures to face this challenge, in terms of energy logistics, taking advantage of its cost, which is precisely one of the critical aspects for electric mobility [10].

The benefit of having electric public transportation can be analyzed from different technical, environmental, and socio-economic aspects. The technical-environmental part considers the reduction of aspects such as noise, thermal sensation due to poor insulation between the internal combustion engine (ICE) and the passengers, vibrations, and continuous acceleration and deceleration due to the change in speed by the manual transmission in most of existing buses [11]. In addition, avoiding the emission of polluting gases harmful to health and the environment is one of the greatest advantages of electric mobility. In Ref. [12] the environmental impact of public transportation in Taiwan is studied, where this sector represents 14.4% of total emissions of polluting gases. Economically, energy security aspects for the transport sector, due to its dependence on fossil fuels, is a relevant issue. For example, in countries like New Zealand, diesel imports can reach 98%, making their transportation system more vulnerable to variations in oil prices and scarcity [13]. In the case of electric transport, energy can come from different sources, prioritizing that from renewable sources. In the case of Ecuador, despite being an oil country, fuel for transportation is still imported due to the limited capacity in refineries in the country [8] while the electric generation matrix is increasingly renewable, considering at least 70% contribution from hydroelectricity [9,13]. Finally, in the social part, it is important to know the perception of citizens about the service with the Battery Electric Bus (BEB), an aspect to consider before undertaking the spread of these new technologies that imply considerable changes in their operation and maintenance.

Research on the required infrastructure for the implementation of BEB with charging stations integrated into the operation routes have been analyzed in different studies. For example, in Ref. [14], where multiple partial recharges of the BEBs are required for a day of operation, it is proposed to locate the charging infrastructure along the route and the need for a coordinated logistics of charging and operation that allows acquiring the necessary energy for the next journey. This arrangement is being subject at all times to the reliability of the charging system and energy availability. However, the option of the infrastructure associated with BEB when they are not in operation, is an alternative that has not been totally explored [15]. This alternative aims to supply energy when the BEBs are out of service considering the eventual recharging generally overnight at the end of the public transport service, allowing a longer charging period which contributes to a more reliable charging logistics. This alternative is studied in Ref. [16], and highlights multiple benefits to the power system such as increasing the load factor, reducing the impact on the life of the transformers at the sub stations, also reducing losses compared to other load configurations. The study indicates that overnight charging does not have a significant impact on the voltage profile of transformers and that the power system would not need an expansion unlike fast charging where the system would need to be expanded between 5 and 6 times its capacity.

There are emblematic cases such as the one developed in the city of Shenzhen, China, where from a pilot program for energy conservation and zero emissions in vehicles promoted in 2009, a first BEB was presented in the city in 2011. In 2017 there were more than 16,000 units operating in the city [17].

From an environmental point of view, worldwide the transport sector produces about 15% of the emission of greenhouse gases and about 74% of these gases is Carbon Dioxide (CO_2) [18]. In Ecuador, the transport sector represents 48.5% of emissions and the largest source of greenhouse gas emissions is diesel with 36.4%, followed by gasoline with 28.6%, and fuel oil with 8,8% [8]. Additionally, those diesels powered engines are responsible for emissions of particulate matter (PM) and the largest portion of Nitrogen Oxides (NO_x). Faced with this situation, more environmentally friendly alternatives have been studied, managing to develop hybrid alternatives. In this sense, in Ref. [19] the performance of diesel and hybrid buses in the region has been compared, where the average reduction in emissions, by using hybrids, was 25% for CO_2, 61% for nitrogen oxides, 72% for particulate matter, 72% for unburned hydrocarbons, and 79% for carbon monoxide.

Finally, one of the key aspects for the spread of electric mobility lies in the improvement of energy storage systems. The technology in electrochemical batteries is in continuous improvement, highlighting Li-ion batteries for EV applications, where one of its categories is the mixture of Lithium Nickel Manganese Cobalt Oxide (NMC) [20] recognized for its high energy density. Another type of these batteries are those built from Lithium Iron Phosphate (LiFePO4), that have a lower specific energy, but with a longer life cycle compared to the previous ones. These and other storage systems are important not only for use on BEB but as a support for the integration of ER sources in order to reduce their impact on power electrical systems. In Ref. [21], the integration of these sources is studied using genetic algorithms that allow optimizing the charging of EVs in fast charging stations, improving profitability due to the intermittency of renewable energy.

2. Methodology

The study analyzes the energy behavior of a battery-operated electric bus (BEB) under commercial operation. The BEB was provided to the city, through the corresponding manufacturer. The study analyzes the state of charge (SOC) of the batteries in different commercial routes in Cuenca, Ecuador, an Andean city located at 2500 m above sea level (m.a.s.l.) and whose population is around 500,000 inhabitants. In all the routes the electrical variables in the charging process were measured, among which stand out voltage, current, active and reactive power, harmonic distortion of current and the daily energy consumed. Simultaneously, the existing public transport system (based on ICE-type diesel buses) in the city of Cuenca was monitored, recording the behavior of the conventional bus in relation to its speed and altitude for each of the 28 routes that cover the city with 7 private companies that make up the Chamber of Transport in charge of the public transport service. With the data obtained, with a sampling rate of 1 s, profiles of speed and altitude were determined in order to know, using a first-order model, the energy consumed in a specific route for estimating the energy consumption in the rest of unmeasured routes. In this study, data collection begins in the micro grid laboratory of the University of Cuenca [22]. The study accounts for energy consumption under the assumption of a total substitution of the current bus fleet in the city, that is, the incorporation of BEB instead of the same number of diesel buses. On the other hand, the installed capacity of the power distribution network of the city of Cuenca is compared with the energy demand of the BEB. This is done by showing the location of the electrical sub-stations and their available capacity, and comparing the typical energy consumption with the energy consumption if the eventual fleet of electric buses is added.

For the energy estimation, the model used is the one shown in equation (1), where the SOC of the BEB battery is estimated along the operating routes.

$$SoC[n] = SoC[n-1] + \alpha \Delta SoC[n] \tag{1}$$

where $\Delta SoC[n]$ is the differential of the state of charge of the battery in each state n, defined by equation *2*.

$$\Delta SoC[n] = \gamma_{\Delta} \Delta S[n]^{*} \Delta H[n] \tag{2}$$

The SOC differential is defined by altitude variations (ΔH) and speed between consecutive samples (δS), determined by equations (3) and (4). The gain γ_{δ} (equation (5)), for each type of condition of the route according to Fig. 1, it is calculated by an iterative process obtaining $\alpha = 0.01689, \gamma_{I} = -1, \gamma_{II} = 0.32, \gamma_{III} = 0.42, \gamma_{IV} = -0.11$, with less than 15% error in the routes under test.

$$\Delta S[n] = S[n] - S[n-1] \tag{3}$$

$$\Delta H[n] = H[n] - H[n-1] \tag{4}$$

$$\gamma_{\delta} = \left\{ \begin{array}{l} \gamma_{I} \; if \; \Delta S[n] \geq 0 \; and \; \Delta H[n] \geq 0 \\ \gamma_{II} \; if \; \Delta S[n] \geq 0 \; and \; \Delta H[n] < 0 \\ \gamma_{III} \; if \; \Delta S[n] < 0 \; and \; \Delta H[n] < 0 \\ \gamma_{IV} \; if \; \Delta S[n] < 0 \; and \; \Delta H[n] \geq 0 \end{array} \right\} \tag{5}$$

The quadrants in Fig. 1 represent: Quadrant γ_{I} BEB on the rise and accelerating, (Regime more energy demanding), Quadrant γ_{II} BEB descending and accelerating (Regime with lower energy consumption), Quadrant γ_{III} BEB descending and decelerating, (Regime with higher energy return to the battery or regenerative braking) and finally Quadrant γ_{IV} BEB going up and slowing down (Regime with less aggressive regenerative braking).

3. Public transport in a Latin American city, case of study cuenca

Cuenca is the third city in Ecuador, it has about 70 km^2 of extension and a population of 500,000 inhabitants. Its main source of income is associated with tourism, agriculture, handicrafts, as well as small and medium industry. This Andean city, located at 2500 m above sea level, has a historic downtown that is a World Heritage Site by UNESCO since 1999, where the need to reduce greenhouse gases and polluting emissions is a priority. For example, air quality is continuously studied [23], where gases such as NO_2 and SO_2 are tracked as well as particular matter (PM10 y PM2,5). The impact of the fossil fuels-based transport sector on the city's air quality is extremely important since it contributes 24% of global emissions of CO2 [24]. On the other hand, the automotive fleet registered in Cuenca by the Municipal Mobility Company (EMOV) in 2014 was approximately 146 thousand vehicles, of which more than 56% are light, 5% are diesel trucks and only 2% are buses that belong to the public transport system [25].

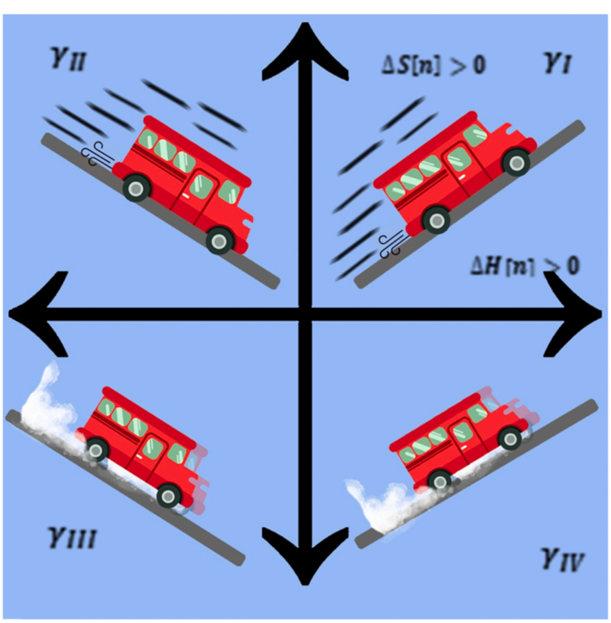

Fig. 1. Operating regimes during a route.

The public transport system (Buses) of the City of Cuenca includes 28 routes, served by 475 buses of 12 m in length, with a nominal capacity of 90 passengers each. These buses, with diesel engines exceeding 200 HP of power, can generate emissions of 1073 g/km of CO_2, 10.07 g/km of NO_x and 0.1 g/km of PM1.5 [19,26]. The transportation service is offered every day of the week, including Saturday and Sunday with reduced hours. On working days, the fleet usually starts its operation at 06h00 and ends between 20h00 and 23h00 depending on the routes. According to Ref. [27] 72.3% of the routes carried out by public transport in the city are for the commute to the places of work and study, and 71% of its users are in the range between 18 and 64 years old who make more than one route per day.

Cuenca's public transport system also has an integration project with a tram system that is built but not yet in operation. The tram system has 14 trains that cover a route with a length of 10.2 Km, made up of 27 stops separated between 400 and 600 m with an altitude profile that ranges from 2585 to 2489 m. a.s.l. The installed trains correspond to the Alstom Citadis 302 model, which contains 5 wagons of which 2 are motorized, with capacity for 58 seated passengers, and a total of 255 counting standing passengers. The total electrical power of each unit is 692 kW divided in four 175 kW water-cooled asynchronous motors [28]. The route is fed from 5 substations with a capacity of 1 MVA each separated approximately every 2.5 km and fed by the city's 22 kV-electrical distribution system. These substations feed uncontrolled AC/DC power converters with the 12-pulse rectifier topology to achieve a nominal voltage of 750 V DC on the overhead catenary line for most of the route and a ground-based power sector mainly in the historic downtown. The tram system is intended to complement the public bus circuit, since it only has a line that runs across the city. It is expected that once the operation of the tram begins, the buses will undergo a change in their routes so as to complement the feeder routes to the tram system.

Another alternative of motorized public mobility in the city of Cuenca is the use of the taxi. This segment is made up of approximately 6000 units, where the exclusive service reduces the occupancy rate, and is slightly higher than the unit, which influences vehicle congestion considerably. In order to reduce crowding and promote active mobility in Cuenca, at the initiative of the Municipality, the use of public bicycles has recently been implemented. The system, initially composed of 10 stations in its first phase and more than 240 bikes, allows the use of them through a membership, at a cost of $ 25 ¢ each way or $ 30 for its annual use [29].

4. Analysis of electrical variables in the charging process

BEBs can be classified according to their autonomy. There are those designed to operate with a short autonomy and need quick partial recharges during the day, with a dedicated infrastructure that requires specific electrical adaptations for BEB loading and, in some cases, must be adjusted according to the route presenting a higher cost [30,31]. Other topologies allow a continuous day of operation (greater autonomy), and during the night they are generally fully recharged. This feature is generally less efficient for the BEB due to the weight of having more batteries in the vehicle for greater energy storage capacity.

This section studies the behavior of the most important electrical variables during the load of the BEB under study. For the massification of BEB in consolidated urban areas, the integration of high consumption loads can lead to technical problems on the area's power system, from the need for greater distribution capacity or problems on the quality of energy in the near the charging stations. This is why two buses of the BYD brand K9 series single-decker bus (SD) have been studied, specifically the K9FE and K9G, with a battery of type LiFePO4 without determining its state of health, however the buses have very little distance (5000 kms), which means that the stored energy reaches the nominal capacity of 276.5 kWh and 324 kWh, respectively, whose behavior in the charging process is similar in terms of electrical variables (voltage, current, power, harmonic distortion, etc.) Both vehicles under study have a capacity of 80 passengers and are assisted by two motors of 150 kW each, have two charging connectors with the IEC 62196 type 2 standard, with a nominal power of 40 kW each, The estimated weight of the bus is 13,500 kg empty and 18,000 kg at full capacity.

Fig. 2 shows the behavior of power, voltage and current in the charging process. The study shows a comparison of the behavior during a charge with one or two charging connectors. In both cases 206 kWh were supplied to the BEB. These charges made at a nominal power of 80 kW and 40 kW show a duration of 2.62 h and 5.26 h, respectively. The measurement point is located in the primary winding of the isolation transformer of the charging station whose ratio is 1:1. Average active power and reactive powers are 78.09 kW and 6.07 kVAr, respectively for charging with two connectors. For charging with one connector the values are 39.06 kW and 2.99 kVAr, respectively. The existing reactive power is due to the inductive component of the isolation transformer. Regarding efficiency, the charging station is powered by a 220Δ/440Y transformer with a nominal efficiency of 97% at nominal capacity (100 kW), due to the nominal voltage in Ecuador (220 V_{pp}). The losses associated with the use of this type of transformer could be reduced by around 1% if the BEB is charged at 40 kW using a single connector during the charge. Regarding the power factor, the system presents a value close to one ($cos(\theta) \approx 0.99$). As for the behavior of voltage and current in both scenarios similar behaviors occur during the charging process. Note that the only profile presents only the constant current (DC) rating of a typical battery charge profile (DC-CV) [20,32], and at the end of the charge it decreases until it reaches the shutdown in approximately 2 min when charging with two connectors, Fig. 2.

Fig. 3 shows the behavior of harmonic distortion under 3 different scenarios. In scenario 1, charging process at 80 kW of nominal power, the BEB is charged with the two available connectors, presenting an average current distortion of 2.57%. In scenario 2, charging process at 40 kW of nominal power, the BEB is charged with one of the two available connectors indistinctly and, in this condition, an average current distortion of 3.67% is presented. Note in Fig. 3 that the system does not present a linear behavior, since a power converter is available between the electrical network and the battery bank for each connector, which doesn't operate synchronously and the harmonics may eventually be canceled in the point of common coupling (PCC). In scenario 3, stand-by state, in which the energy consumed is associated with the control system, the managed power does not exceed 60 W with a current distortion of 10.83%. In relation to the average voltage distortion, under all scenarios, it does not exceed 1%. The behavior observed in relation to the quality of energy meets with the national regulation CONELEC 004/01 and international regulations such as IEC 61000 3–4 and IEEE 519–2014.

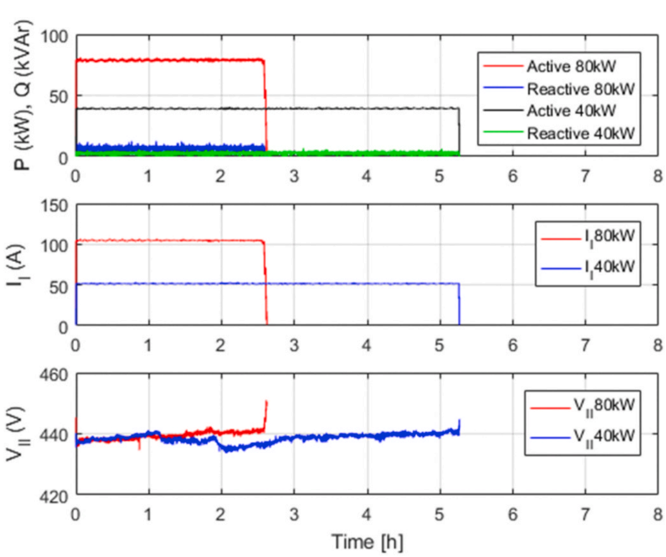

Fig. 2. Behavior of electrical variables in the BEB's charging process.

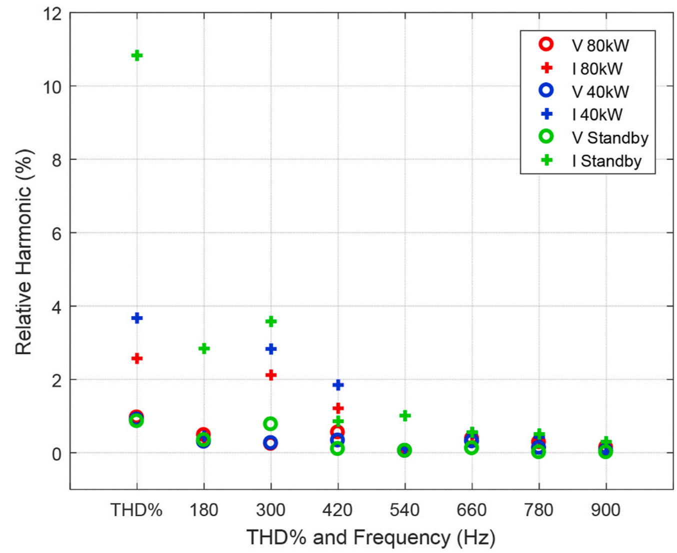

Fig. 3. Harmonic distortion of voltage and current in the BEB's charging process.

5. Energy consumption and projection of energy demand for a total substitution of buses in the study city

This section studies the energy behavior of the BEB on the routes of the city of Cuenca. Based on the data collected, an estimate of the energy demand for the replacement scenario of the current bus fleet that operates on urban routes is made, quantifying the total energy demand of the new BEB fleet for the city. The study shows the characteristics of two routes in the city of Cuenca, highlighting the typical altitude and speed profiles, in addition for estimating the state of charge (SOC) of the BEB under study during the tour. The used model allows estimating energy consumption and its efficiency under real operating conditions. Aspects such as vehicle mass and urban road conditions, such as cobblestone roads or expressway segments, are not taken into account nor are exogenous variables such as traffic limitations during peak demand hours where there are more passengers boarding the public transport service. Given these limitations, there are differences from the measured values, however, the study allows us to have initial estimates that contribute to decision-making and related planning in the field of electromobility.

Although there are studies that establish comparisons between the mass and autonomy of different models of electric buses [13], in the specific case of the BYD's BEB, the data provided only by the manufacturer are shown. Other studies establish comparisons with other public transport systems such as trolley buses and buses with ICE, where the BEB has the best energy efficiency [33].

The energy efficiency of BEB in commercial operation in Ecuador has been studied in Ref. [34], where the behavior in coastal cities, with a practically flat orography and temperatures between 24 °C and 30 °C most of the day, presents performances of 0.796 km/kWh. However, studies on BEB's efficiency under commercial operation in cities of the Andean mountain range such as Cuenca have not been found in the literature. Many intermediate cities and important capitals of Latin America such as Mexico DF, Bogotá or Quito are at similar altitudes as Cuenca and the results of this study could be extended to these cities. Aspects such as temperature play a particular role, since the air conditioning system (A/C) reaches a nominal power of a few kilowatts. In the BEB under study, the A/C system has a nominal power of 5 kW, which assuming that it is working 60% of the 12 h of average operation could reach a consumption of 36 kWh in addition to the energy required for the BEB's tour. This aspect, which is not taken into account thanks to the climatic conditions of Cuenca, differs from studies in other cities with more adverse climatic conditions.

For the study, the number of passengers who used the public transport service was not counted. However, the concurrence observed in its operation does not differ from the typical use offered by a diesel-powered transport unit.

In other words, since the BEB was incorporated into one of the city's commercial bus routes, the user uses the BEB without knowing that he is using an electric bus. In this sense according to Ref. [7] it is estimated an average of 407,107 daily trips in the entire public transport system in the city of Cuenca, which implies that based on the buses operating in the city, there are close to 900 daily passengers per unit.

The study of the energy behavior of the BYD model K9G electric bus was carried out on lines 5, 20, 100 and 27 of the city of Cuenca. These commercial lines or routes are defined by the city's Chamber of Public Transport. The routes have an average energy performance that is summarized in Table 1.

Using the indicators shown in Table 1, it is possible to highlight that the behavior of the BEB on routes 100, 5, and 20 is similar, given that the altitude profile and number of stops are similar. Route 27, compared to the other routes, presents a considerably larger number of stops, as does the altitude differential, as explained in section 5.2, aspects that reduce energy efficiency. The following subsections deepen the analysis on routes 100 and 27 in order to establish the differences between them when they are operated by a BEB.

5.1. BEB's indicators: line N° 100

Line 100 of the city of Cuenca has a distance of approximately 37.5 km with a total of 53 stops. The tour route made with the BEB operating that line reached 206 km throughout the daily tour, as shown in Fig. 4. The route presents an average speed of 22.5 km/h, consuming around 237 kWh. To do this tour, from the recharging site located in the Micro-grid Laboratory of the University of Cuenca [22], the BEB runs east to take Av. de las Américas and start its journey at the start of the route stop in the Ricaurte parish. Once the route of line 100 has started, the unit presents an altitude differential close to 228 m. Fig. 5a and b and 6 show the speed behavior, altitude profile, and estimated energy behavior, respectively, during the journey on this route. Under this scenario, the BEB traveled only 5 of the 7 laps that ICE-buses usually travel on this route. However, the BEB's capacity would allow operation on the mentioned route without any modification, except that it is necessary to have more units to offer the same frequency of route trips. This is because, in order to safeguard the capacity to store energy in the battery bank, the BEB stopped its operation with a reserve of more than 20% SOC, given the high relationship between the depth of discharge (DoD) and the battery useful life [39]. Another aspect that must be highlighted is the relationship between the useful life of the batteries and the discharge rate. Generally, it is necessary to avoid accelerations that imply a discharge ratio greater than 3 times the nominal capacity (3C) of the batteries, since this affects their useful life [40].

Table 1
Summary on energy efficiency indicators [35–38].

Route type	Line	Distance (km)	Number of stops	Average Efficiency (km/kWh)
Inter-parish	100	37.5	53	0.8262
Inter-parish	27	44	78	0.6575
Urban	5	27	44	0.8480
Inter-parish	20	36	52	0.8543

5.2. BEB's indicators: line N° 27

Line 27 of the city of Cuenca has a distance of approximately 44 km. On the test tour, the BEB covered a distance of 172 km a day with an average speed route of 24.5 km/h, consuming 282 kWh. To make this journey, starting from the recharging site located in the Micro-grid Laboratory of the University of Cuenca, the bus travels in a northerly direction crossing the highest altitude point (2845 m. a.s.l.) to reach the starting point of the route (Fig. 7). On route 27, the altitude differential is close to 304 m. Fig. 8a and b shows the behavior of speed and altitude profile, respectively, whereas Fig. 9 present the estimated energy behavior of the BEB during the tour. Under this scenario, the BEB traveled only 4 of the 6 laps that ICE-buses usually travel on this route. However, the BEB's capacity would allow 5 laps to run in the operation on the mentioned route, since the round trip distance between the charging station and the starting point of line 27′s route is approximately 20 km. In addition, with the inclusion of eventual partial recharges at the beginning or end of the route it is possible complete the currently established itinerary for ICE-buses.

In summary, Table 2 shows one of the most important technical aspects of routes 100 and 27, where it is observed that the height difference is greater for route 27 where the energy demand is greater.

5.3. Opinion study on the use of the BEB during its commercial operation

During the testing process of the BEB under commercial operation in the city of Cuenca, an opinion study was conducted to customers on the use of electric buses on the operated routes, using a survey that contains 8 questions. The application of the instrument was carried out by a group of students of Electrical Engineering at the University of Cuenca, duly identified and trained. The survey was carried out randomly to the users of the BEB once they started their ride, in total 204 valid surveys were completed. From the results of the survey, it can be concluded that the users of public transport are mainly people between 25 and 45 years of age who use the transport service daily between 2 and 4 times per day. Two thirds of users (66%) take between 15 min and 30 min to reach their destination. Most of the surveyed users (74%) know that they are using electric transport, saying that their service is better than conventional (diesel) buses mainly due to the non-emission of polluting gases and the reduction of noise in their operation. The users surveyed mostly believe that the use of BEB improves the quality of public transport service and agree to implement this technology in the city. Finally, in relation to the economic aspect implied by the use of this technology, the majority of people (56.9%) are not willing to increase the cost of the service and, of those who agree to an increase, almost 80% only would be willing to pay USD ¢ 5 more for the use of this new service. The current rate of public transportation (bus) in Cuenca is 30 ¢ per trip.

5.4. Energy analysis of the BEB urban service fleet in the city of cuenca

As mentioned in section 2, the city under study has 28 public transport lines. Table 3 shows the number of units associated with each route, the distance of the route, the estimated energy efficiency with the model shown in section 2, and their respective energy demand for the entire route. For the purposes of energy estimation of the BEB, 2

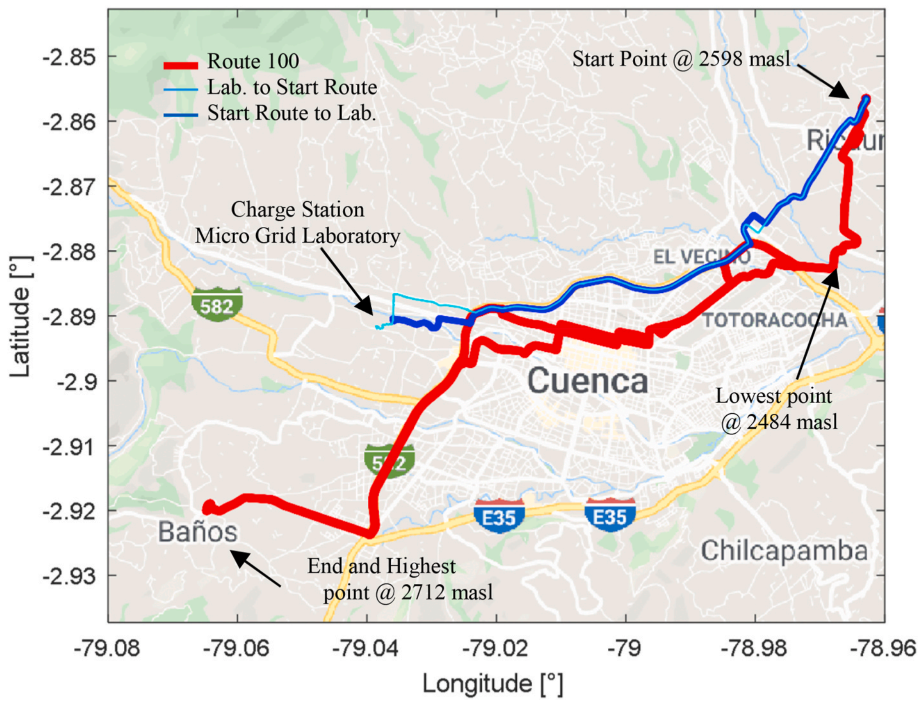

Fig. 4. Tour of the BEB under operation on route 100.

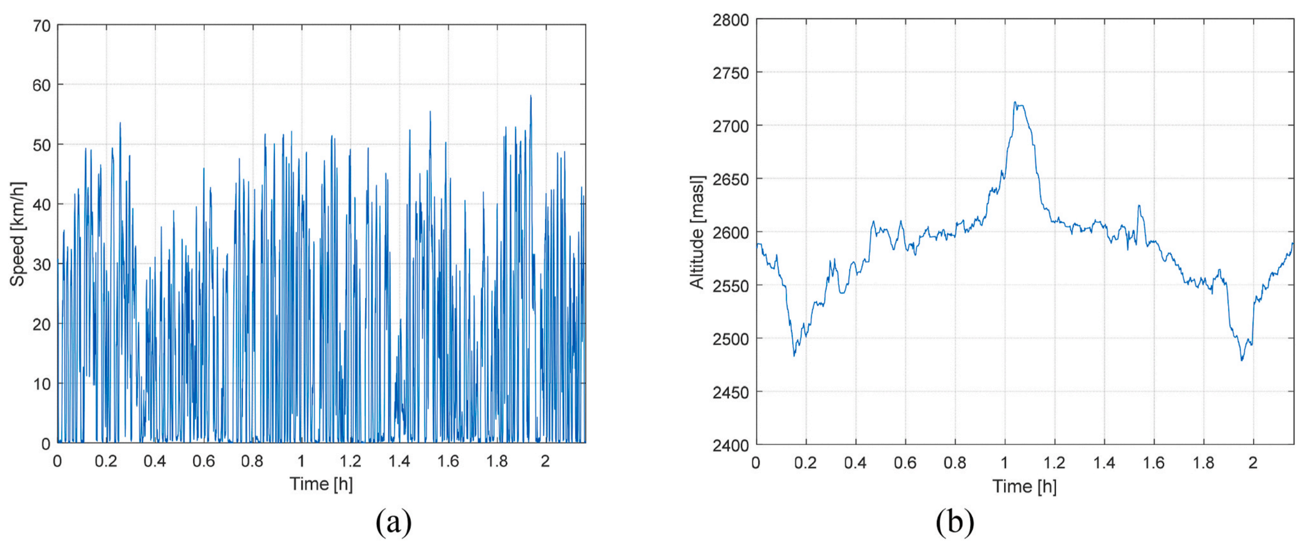

Fig. 5. (a) Speed behavior and (b) Altitude profile, BEB under operation on route 100.

scenarios are presented, which depend on the charging power of each bus, that is: load capacity at 40 kW or at 80 kW. Fig. 10a shows the behavior of energy demand with both scenarios, from the point of view of impact on the power grid. The scenario with charge at 80 kW presents a maximum power with everyone at once at the start of the charge of 33.92 MW, while if the charge is at 40 kW it is 16.96 MW with twice the time to reach 100% SOC. In the simulation carried out, charging starts at 22:00, the time at which most routes end their daily operation. However, this coincidence can be reduced in practice as routes end at different times.

In the case of those routes whose end of service is earlier, it is estimated that these could begin charging their BEBs in the same order of completion. However, the charge may coincide with schedules where no tariff incentives are available, compromising the economic feasibility of the BEB. Fig. 10b shows the demand and the estimated energy to satisfy the needs of the public transport system in the city under study. Under both scenarios, 115 MWh is reached, the difference lies in the simultaneous charging time, which can range between 4 h with 48 min and 9 h with 30 min for the most demanding routes. In order to reduce the time on the routes with the highest energy demand, these could be charged at a power of 80 kW while the least demanding at 40 kW, so that they can be adapted to the resting times for the charging process during the night.

Once the daily energy demand estimate has been done in the case of a 100% substitution by BEB in the city of Cuenca, it is necessary to know if the existing electricity network could supply this demand. The power distribution system has an installed capacity of 218 MVA, distributed mainly in 8 sub-stations as described in Table 4 [41].

S/E 17 (Los Cerezos) with 24 MVA of capacity and S/E 13 (Chaullayacu) with 24 MVA of capacity are currently under construction in the expansion program of the city's power system. These two new

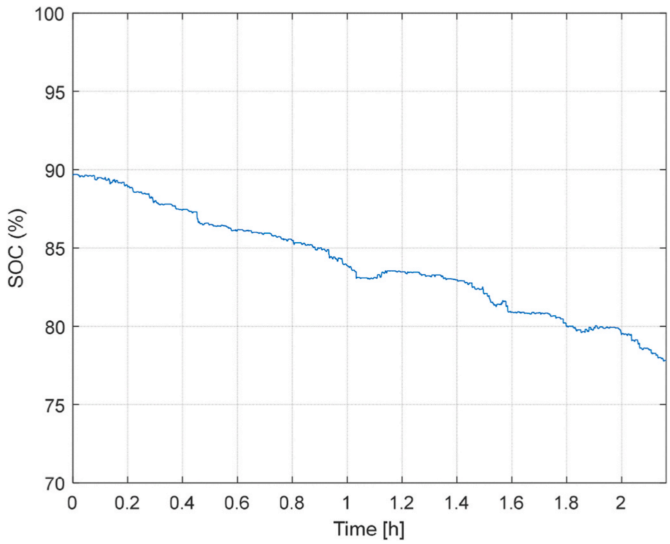

Fig. 6. Energy Behavior (SOC) during a typical BEB operation tour on route 100.

substations will make it possible to improve the distribution system in view of the possible increase in demand. In relation to the tram public transport system, it is powered by S/E 04 and S/E 05. In Fig. 11, the geographical distribution of the available substations is observed, the size of the circle is proportional to its available power capacity in blue. The location of the administrative and operational headquarters of the 7 private companies, that conform the City's Transport Chamber, is also shown, represented in red circles. These companies group the 424 buses that circulate daily in the city, the location and size of these circles is associated with the centers of operation and number of buses that each of these companies operate. Initially, these companies could make the adaptations to locate the BEB charging centers in their operations centers, an aspect that represents a challenge for the infrastructure of the power system, taking into account that the available capacity of the system does not coincide geographically with the possible locations of eventual charging centers.

It is important to note that currently Cuenca does not have large night-time parking centers for ICE-buses, and these spend the night in small squares throughout the city and even in the homes of their owners, so the replacement BEB represents a challenge not only from the point of view of the availability of the electrical system, but also of urban infrastructure that allows adequate spaces for charging at night.

From the energy point of view, Fig. 12 shows the typical profile of daily power demand in the city of Cuenca, where the contribution of the BEB charging under 40 kW and 80 kW regimes is also included. In both scenarios, the charging process coincides with the valley period of the demand curve. In percentage terms, the new load from the BEB incursion for public transport, which could reach 115 MWh per day, represents about 4% of the daily energy demand of the city.

6. Incorporation of renewable alternative sources for BEB charging

Given BEB's nighttime charging scenario, the use of alternative sources for such charging represents an additional challenge, due to the mainly non-deterministic nature of non-conventional renewable energy (NCRE) such as wind power or solar energy. In order to promote a sustainable mobility system in the city, it is desirable, however, that the BEB charging be carried out with renewable sources since, otherwise, the charging stations would be being fed, at least partially, by thermoelectricity. Although in Ecuador's power system there is an important contribution from hydroelectricity, this source is seasonal and should be complemented by other non-conventional renewable sources. At the beginning of 2020, the generation mix in Ecuador comprised 76% hydroelectricity, 21.5% conventional thermoelectricity, and less than 3%

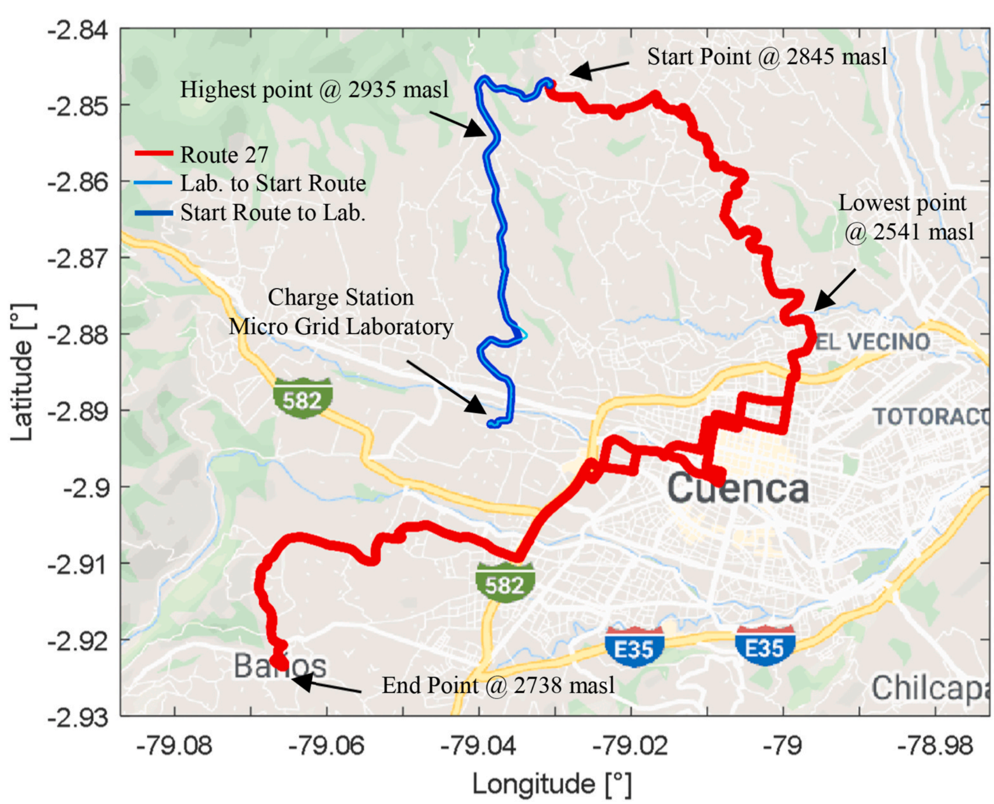

Fig. 7. Tour of the BEB under operation on route 27.

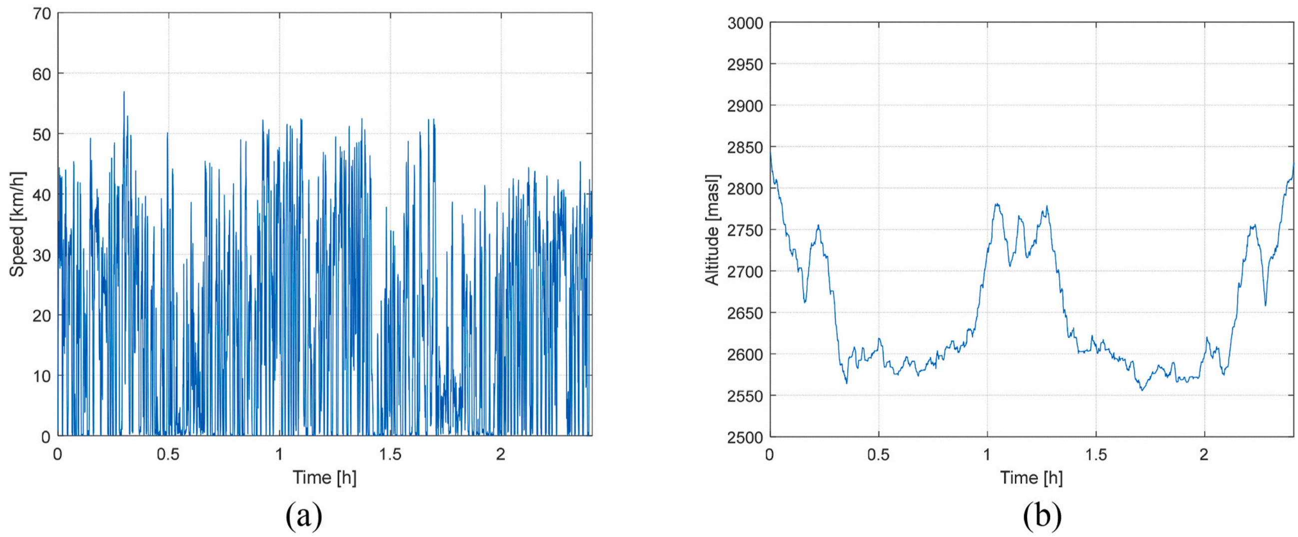

Fig. 8. (a) Speed behavior and (b) Altitude profile, BEB under operation on route 27.

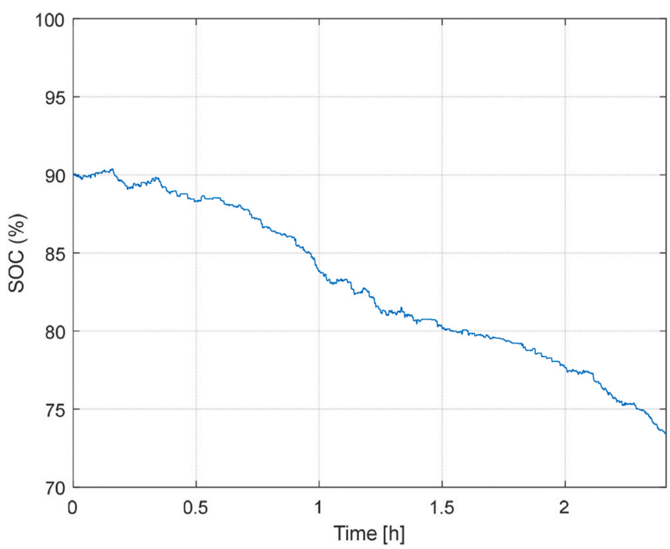

Fig. 9. Energy Behavior (SOC) during a BEB operation tour on route 27.

Table 2
Summary of technical aspects of route 100 and 27.

Route	Max. altitude	Min. altitude	Distance (km)	Time route (min)	Average speed (km/h)	Max. speed (km/h)
100	2712	2484	37.5	135	22.5	58.2
27	2845	2541	44.11	152	24.5	58

NCRE [8]. Despite the minimal contribution of NCRE, Ecuador's natural resources, mainly solar energy, are abundant and could open up the possibility of increasing their contribution to the generation mix. Various studies predict that renewable energy capacity can expand by 50% between 2019 and 2024, led mainly by photovoltaic solar energy. This 1200 GW increase is estimated to be equivalent to the current total installed capacity of the United States [42]. Photovoltaic solar energy alone represents almost 60% of the expected growth, and onshore wind energy represents another 25%. Given this background, and despite the abundant solar resource in Ecuador, the incorporation of photovoltaic solar generation to be used for BEB charging processes at night represents additional challenges related to storage and energy management.

A case study with the integration of non-conventional renewable sources was carried out during the BEB testing process in Cuenca, where the integration of photovoltaic solar generation, interconnected national system, and storage systems allowed the use of free solar energy during peak hours. Fig. 14 shows the test bench with the photovoltaic solar system, the energy storage system (both belonging to the University of Cuenca's microgrid laboratory) and the BYD's BEB. The study was carried out during 80 h. In this interval, the BEB charging process was carried out by combining energy from the public power system and a storage system available in the microgrid laboratory [22]. The BEB was powered by a 35 kWp photovoltaic solar generation system made up of different technologies for fixed and tracking solar panels, the Flow Redox battery model Cell Cube 20–100 with power of 20 kW and nominal capacity of 100 kWh.

This type of electrochemical battery consists of the reduction and oxidation of two active materials, hence the name REDOX [43]. The most common of these technologies is the one that uses vanadium in its electrolyte. The battery has two electrodes, which are active materials permanently immersed in the electrolyte in solution, their advantage over conventional battery types lies in the possibility of designing the system with an optimal power/energy ratio, without the need to maximize energy density [44].

The vanadium flux technology in REDOX batteries is the most commercially successful, presenting the highest number of charge-discharge cycles and a lower levelized cost of energy compared to the others in its category [45].

The battery is managed by a SCADA system that is part of the microgrid. This system operates under the premise of minimizing the exchange of energy with the public power system and it aims to supply the energy necessary for the operation of the entire laboratory facility, including the BEB charging process. The behavior during the study days is similar, therefore, it will only be explained in detail on day 1. At the start of the study between the hours (0h00-4h00) and (11h00-14h50) a battery discharge is observed due to consumption laboratory's own loads (control systems, lighting computing, etc.) and absence of solar photovoltaic generation. Then, between 4h00 and 11h00 an increase in the SOC of the battery is observed as a result of the energy generated by the photovoltaic solar system shown in Fig. 13a, at the same time there is a surplus (if PV production is greater than 20 kW) which is reflected negatively in Fig. 13b.

During the BEB charging process (14h50 – 20h36), a constant consumption of 40 kW nominal is observed, which at the beginning comes approximately in similar amounts from the public power network and the storage system. Once the SOC reaches approx. 30%, the energy

Table 3
Energy consumption estimation of BEB fleet, City of Cuenca case study.

Route	Estimated length per lap (km)	Estimated ΔSOC per lap (%)	Estimated energy per lap (kW/h)	Estimated Energy Efficiency (km/kWh)	Laps per day	Buses per route	Consumed energy per route (kWh)
1	39,33	15,01	48,62	0,81	7	18	6126,01
2	26,23	8,65	28,04	0,94	6	10	1682,51
3	33,46	14,25	46,18	0,72	6	20	5541,61
5	27,17	11,08	35,90	0,76	8	19	5456,24
6	20,15	8,85	28,67	0,70	11	6	1892,31
7	36,54	12,08	39,15	0,93	7	25	6851,40
8	33,75	11,54	37,41	0,90	7	19	4974,89
10	42,99	17,39	56,35	0,76	6	9	3042,99
12	35,6	14,99	48,58	0,73	7	20	6801,19
13	32,84	12,31	39,88	0,82	4	11	1754,83
13 (2)	26,86	11,94	38,69	0,69	4	11	1702,19
14	26,31	9,01	29,18	0,90	7	20	4085,44
15	33,34	14,07	45,58	0,73	6	13	3554,94
16	42,12	15,47	50,12	0,84	7	18	6315,39
17	27,58	9,11	29,52	0,93	6	8	1417,04
18	27,07	8,92	28,91	0,94	6	15	2601,51
19	30,35	10,15	32,88	0,92	6	15	2959,22
20	34,74	15.09	48.89	0.71	6	18	5280,29
22	29,2	13,13	42,56	0,69	7	29	8639,09
24	39,61	18,35	59,46	0,67	6	20	7135,49
25	32,27	10,93	35,41	0,91	6	9	1912,05
26	36,17	12,39	40,15	0,90	6	9	2168,16
27	43,6	18,80	60,90	0,72	6	17	6211,87
28	34,05	11,29	36,57	0,93	6	9	1974,74
28 (2)	40	15,92	51,56	0,78	6	9	2784,51
50	26,39	10,10	32,71	0,81	6	12	2355,01
100	36,54	12,70	41,14	0,89	7	32	9214,90
101	9,05	3.72	12.05	0.75	14	3	506,22
					Total	424	114,942,01

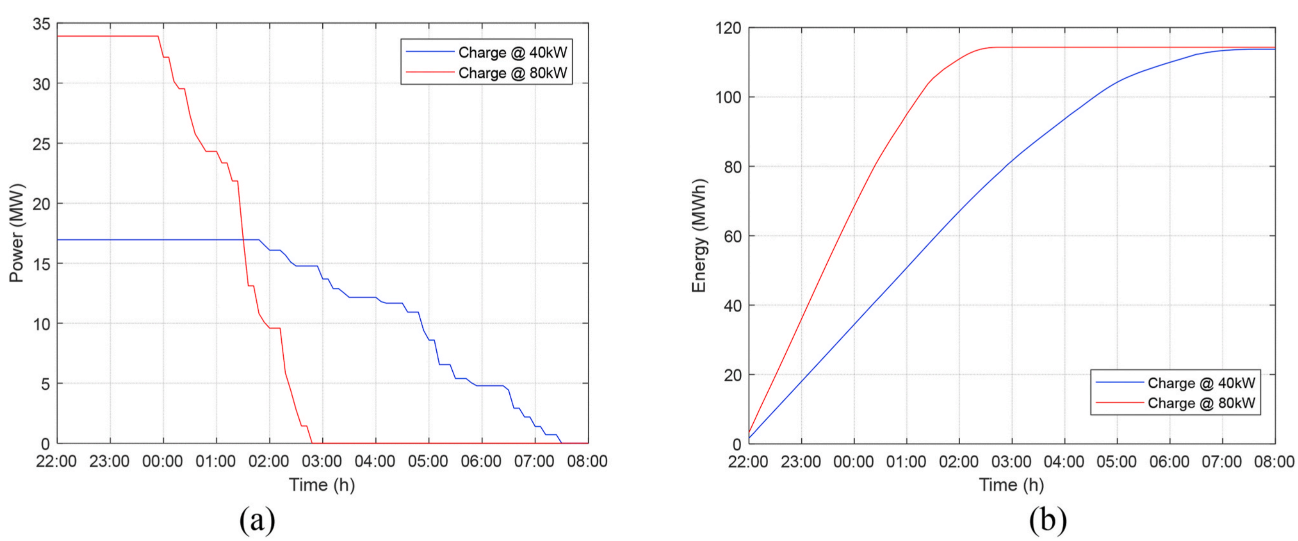

Fig. 10. Profile of daily power demand (a) and energy demand (b) for the BEB fleet in Cuenca.

Table 4
Load factor available in sub stations of the city of Cuenca.

S/E Number	Name	Operative Capacity (MVA)	Load Factor (%)
01	Luis Cordero	13.76	36.70
02	Centenario	13.76	47.81
03	Monay	48	37.75
04	Parque Industrial	48	57.04
05	Arenal	48	72.66
06	El Verdillo	7.52	83.64
07	Ricaurte	15.04	86.36
08	Turi	24	81.25

contributed by the storage system begins to decrease progressively until its contribution is negligible in a SOC 10.5% @ 18h30. Finally, between 6:30 p.m. and midnight, the public electrical system provides power of around 2 kW for system operation, while the storage system exhibits a typical self-discharge behavior of 1% per day due to the consumption of the control, cooling, and other systems. In the case of an exclusive dedication of the storage system to charge the BEB daily, the effective energy capacity of the system under study is approximately 75 kWh. This would imply an energy relationship (E_{Bat}/E_{BEB}) during the charge close to 25%, as seen in Table 5. If an energy efficiency of 65% is assumed in the Flow Redox battery, it would require 115 kWh for a full charge, power that could come from a 30 kW capacity photovoltaic solar installation with panels' area of 195 m^2, if a 3.92 peak solar hours (PSH)

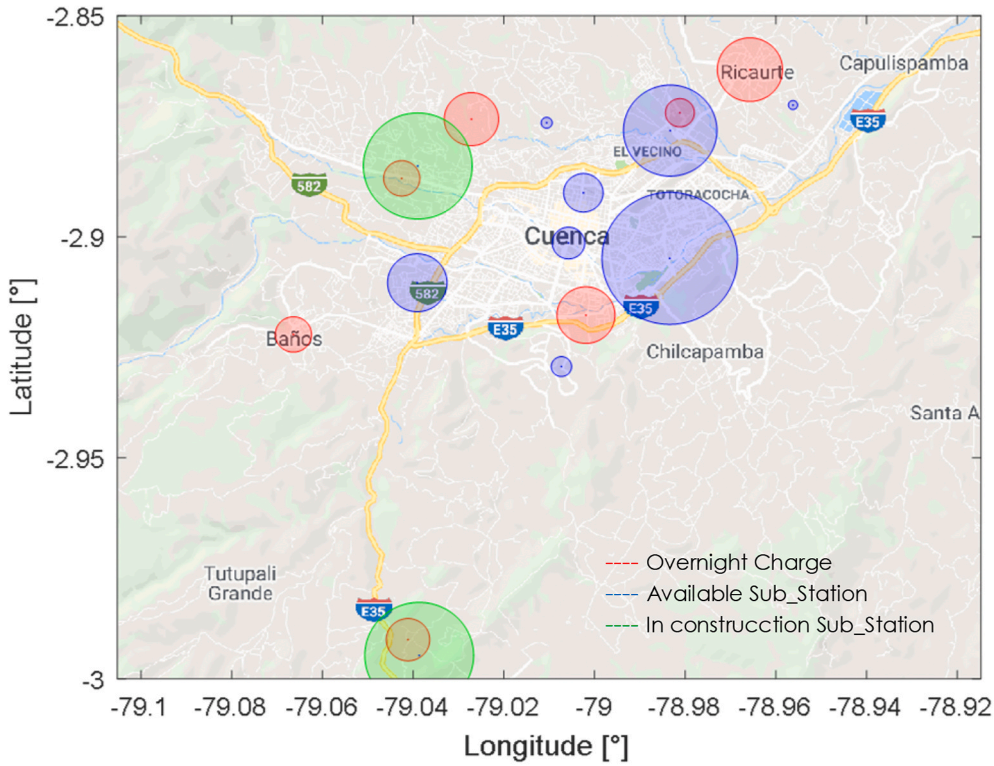

Fig. 11. Distribution of sub stations of the city of Cuenca and possible location of charging stations.

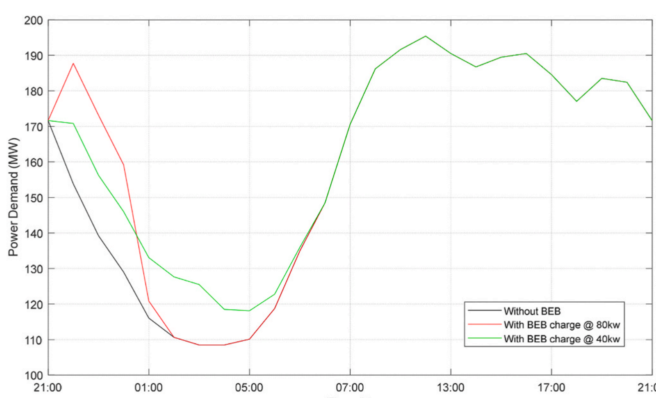

Fig. 12. Typical profile of power demand in the city of Cuenca with the incorporation of BEB.

is estimated in the region under study. For the other 2 days of study, it is observed that the energy delivered by the photovoltaic solar system is not enough to fully charge the battery, so the ratio E_{Bat}/E_{EB} decreases considerably and would require increasing the capacity of the renewable generation system.

With the study carried out, the incorporation of NCRE sources in the BEB charging process and the use of a storage system, the energy supplied by the battery under test can reach about 25% of the energy required to travel one of the average routes of Cuenca's public transport system.

7. Discussion and conclusion

The paper considers the public transport bus service in an Andean city, where both the energy performance of a BEB on commercial routes and the technical feasibility of a total replacement of existing buses by a similar fleet of BEB are analyzed. The study includes an opinion survey of users on BEB in commercial operation, which shows their preference for the electric alternative as compared to ICE-buses, mainly due to the non-emission of polluting gases and noise reduction. From a technical point of view, the electrical variables in the BEB charging process are evaluated by observing a current THD lower than 4% and a power factor close to one, a condition that complies with national standards and IEEE 519. Regarding energy demand, the study uses a model that allows estimating the energy consumption of the BEB fleet on the 28 urban public transport routes in Cuenca. It is estimated that the maximum demand in the charging process of the BEB fleet can reach 33.92 MW if the fleet is charged at the rate of 80 kW per BEB and 19.96 MW when the charge is at 40 kW whereas the charging time can range from 04h48min to 09h30min. The energy needed to charge 424 BEBs is about 115 MWh daily, a value that represents 4% of the energy demanded by the city under study. The estimate of the energy efficiency of the BEB under study presents values that vary between 0.67 km/kWh and 0.94 km/kWh, an indicator subject to trip conditions. The study also shows a charging alternative through the integration of renewable energy sources, from photovoltaic solar generation and redox flow type electrochemical battery backup. Indeed, although the use of energy storage systems is necessary for BEB charging during the night, the study carried out in the laboratory demonstrates the technical feasibility of charging by using renewable electrical energy systems.

Credit author statement

L. G. Gonzalez and J.L. Espinoza: Conceptualization, Software, L.G. Gonzalez, Daniel Cordero-Moreno and J.L. Espinoza.: Data curation, Writing – original draft. L. G. Gonzalez and J.L. Espinoza: Visualization, Investigation. J.L. Espinoza: Supervision.: L.G. Gonzalez, Daniel Cordero-Moreno and J.L. Espinoza: Software, Validation.: L. G. Gonzalez: Writing- Reviewing and Editing,

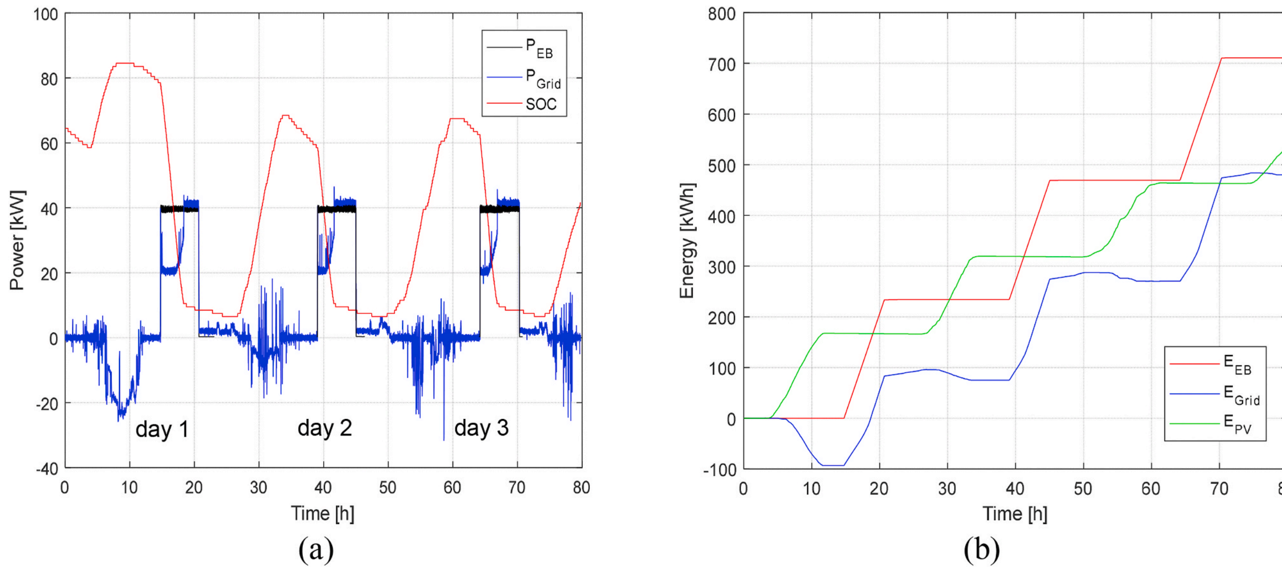

Fig. 13. (a) Power behavior of the charging process with solar photovoltaic generation and storage system, (b) Energy behavior during the test.

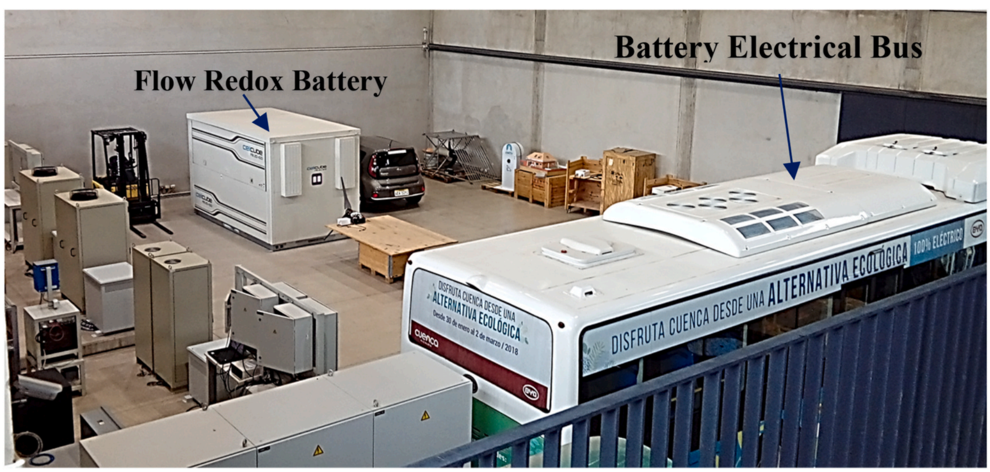

Fig. 14. Test bench, with BEB and Flow Redox Battery.

Table 5
Relationship of energy consumption for BEB charging with renewable energy.

	Day 1	Day 2	Day 3
Travel (Km)	190	198	199
Energy EB E_{BEB} (kWh)	234	235	241
Energy Grid E_{grid} (kWh)	177	201	206
Energy Battery (kWh)	57	34	35
Energy ratio E_{Bat}/E_{BEB} (%)	24.35	14.46	14.52

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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