LOGIOS

Accelerating the Transition to Sustainable Mobility and Low Carbon Emissions in Panama City

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Progress Report: Deliverable 3.2

Charging Strategy for Initial Electric Bus Deployments in Panama City

Prepared for the United Nations Industrial Development Organization and the Climate Technology Centre & Network

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Cover photograph: Electric bus in Casco Viejo, Panama City, Panama (2018). © LOGIOS.

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Acknowledgments

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Executive Summary

Introduction

This report presents the analysis of charging strategies for electric buses that would be operated for public transport in Panama City. A charging strategy can be defined as the set of integrated practices adopted in order to supply electrical energy to the buses. The focus is on seven service routes that Transporte Masivo de Panamá (MiBus) selected for the prospective deployment of an initial group of electric buses. Opportunity fast charging and overnight slow charging are considered for the analysis. The results integrate digitally processed real-life measurements with software simulation based on mathematical models of two bus typologies, one for each charging method.

Route topographical and operational characteristics, impact of auxiliary loads, as well as energy consumption during route cycles and over the day of operation are presented. These will first help assess the technical viability of different bus typologies for each route given the existing operational conditions, and then make estimation of the energy and power requirements at each charging event. The analysis highlights that identifying an optimal charging strategy is a complex problem that necessitates of expert technical analysis and knowledge of on-the-ground conditions.

Energy Consumption Analysis

Two different charging methods are assessed in this study, considering simulations of two bus configurations similar to two commercial buses, one suitable for each method of charging. The slower charging method uses power of up to 200 kW. Charging usually occurs once a day and is ideally performed at night, taking a few hours. Thus, this method constrains the operation time. This charging method will be herein referred to as *overnight charging*. The faster charging method uses higher power, typically 350 kW and higher, that occurs several times throughout the day. Unlike the overnight charge method, this fast method allows charging a battery pack to nearly 100% SoC in the order of minutes. This charging method will be herein referred to as *opportunity charging*.

Based on the information provided by MiBus, driving cycles for 7 routes were built. The average velocity for each cycle is of paramount importance in Panama, due to its correlation with the energy consumption of the heating, ventilation, and air conditioning (HVAC) system. Three driving cycles were selected for each route: one for the start of the day, which is usually the fastest, another for the late afternoon, which is the slowest period, and one for midday, which is around the average value for the daily operation. The repeatability of the average velocities was assessed for 3 different days (see example in Figure ES 1).

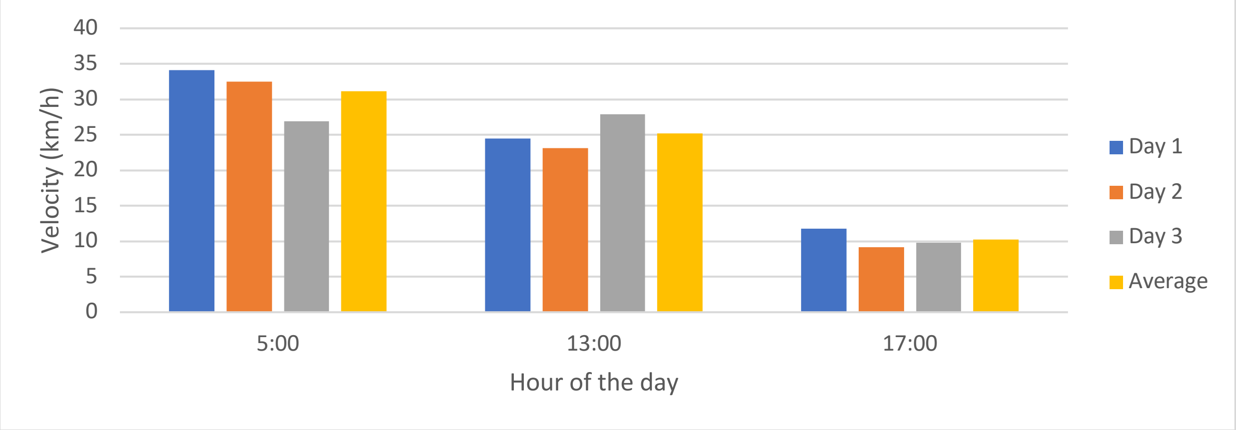


Figure ES 1. Average velocity for different days – Route C850

The bus model is based on the previous general knowledge of the technology used such as type of motor, energy storage system, and mechanical transmission. The model is parameterized using the specific parameters described in Table ES 1. The inputs for the model are defined as a set of times [s], velocities [m/s], and grades [rad], corresponding to each point in the route. For the purposes of this analysis, the main output of the simulation is the energy consumption, expressed in kilowatt-hours (kWh) over each one of the cycles for the particular route.

Table ES 1. Technical data of buses used for the study

Parameter	Overnight charge bus	Opportunity charge bus
Total mass of the vehicle [kg]	14,300	10,500
Cargo capacity [kg]	6,000	6,000

Frontal area [m2]	6.6	6.5
Max velocity [km/h]	60	60
Rolling resistance coefficient	0.0098	0.0098
Aerodynamic drag coefficient (cd)	0.66	0.65
Chemistry of the cells	LiFePO4	LTO
Nominal battery capacity [kWh]	348	55
Nominal charging power [kW]	210	350
Motor type (N° of motors)	AC-PMSM (2)	AC-RPM (1)
Motor and power train position	Rear wheel drive	Rear wheel drive
Max power [Kw]	300	180
Max torque [Nm]	1,100	10,000
Min voltage [V]	500	500

Table ES 2 shows key characteristics of the routes of interest, along with the ranges of energy consumption obtained with the LOGIOS model. Energy consumption varies as a function of a multitude of factors, including bus efficiency, the passenger load, and the power demand of the HVAC system. The average velocity varies depending on time of the day and driving behavior, which ultimately have considerable impact on the traction and HVAC consumption.

Table ES 2. Summary of the routes included in the analysis

Route	Type	Distance (km)	Energy cons. Opportunity (kWh)	Energy cons. Overnight (kWh)	Average velocity (km/h)	Bus daily distance (km)
C850	Circular	22.2	28-55	35-60	9-30	133 – 311
C888	Circular	3.9	5-9	6-10	8-14	47 – 74
C898	Circular	8.6	12-24	15-26	8-17	163 – 181
C938	Circular	20.7	28-51	35-56	9-19	82 – 186
C968	Circular	6.0	7-18	8-20	6-17	102 – 139
E489-I	One way	5.7	4-9	5-11	22-30	45 – 130
E489-R	One way	6.4	7-11	8-13	17-26	51 – 141

The routes in a public transportation system, as exemplified by these seven routes, have very different characteristics. This makes it impractical to find one single electric bus configuration that charges once a day and that can effectively and efficiently serve every one of the routes. A bus that allows multiple on-route charging events is more flexible in this respect. This will be shown in detail for each route.

A recurrent question in the analysis has been the impact on vehicle performance of the disparate operational conditions facing the bus for a given route. Electric bus technical performance can be improved significantly creating favorable operational conditions. Taking inefficiencies in traffic operations as a given, will push the requirements on the technology to a point that either makes the investment inefficient or altogether non-viable.

Technical analysis: The case of route C898

A summary of the technical analysis done for route C898 is presented as an example of the analysis done for the set of routes selected by MiBus. Figure ES 2 shows the velocity profiles for the selected segments of the day. The tendency is representative of all the routes analyzed, showing that maximum velocity is higher for the 5 AM case. Traffic congestion affects the most the 5 PM case.

Figure ES 3 shows, as expected, that the opportunity charge bus has higher efficiency. The consumption tendency for the selected cases is evident. The gray bars show that the traction consumption is similar for the three cases. This situation is ideal to predict better the effect of other factors such as traffic and HVAC on energy consumption. Figure ES 4 shows the effect of HVAC consumption, which reveals that the effect of the traffic congestion is noticeable, especially for the 5 PM case, where the HVAC increases energy consumption by 46% to 96%, depending on the HVAC power demand.

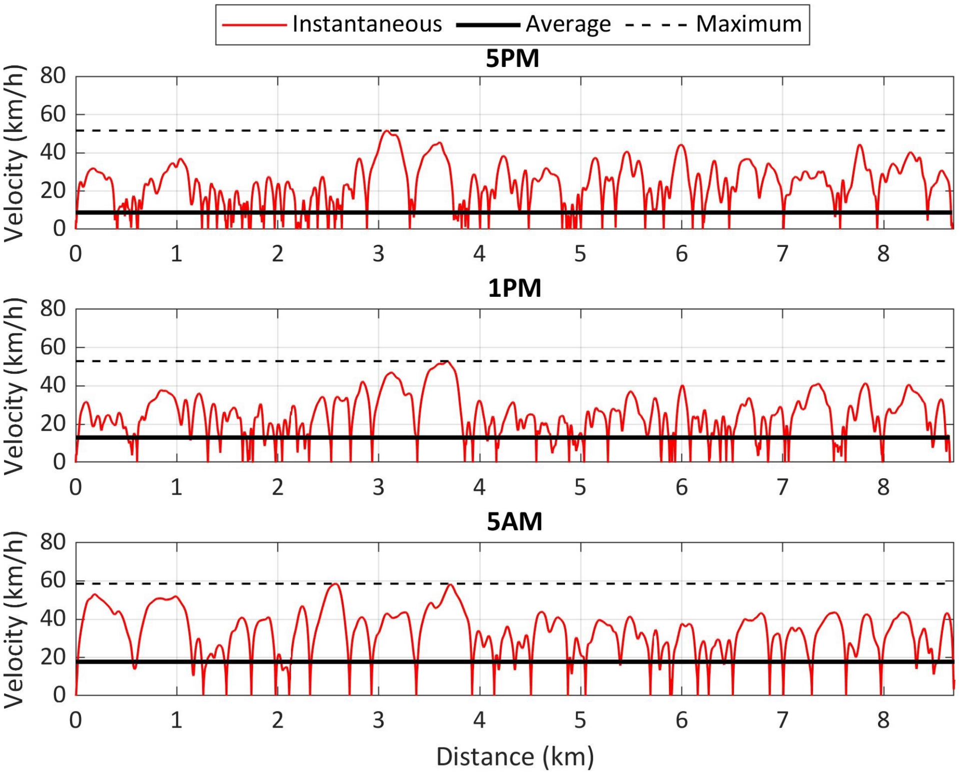


Figure ES 2. Velocity profiles for the three cases selected

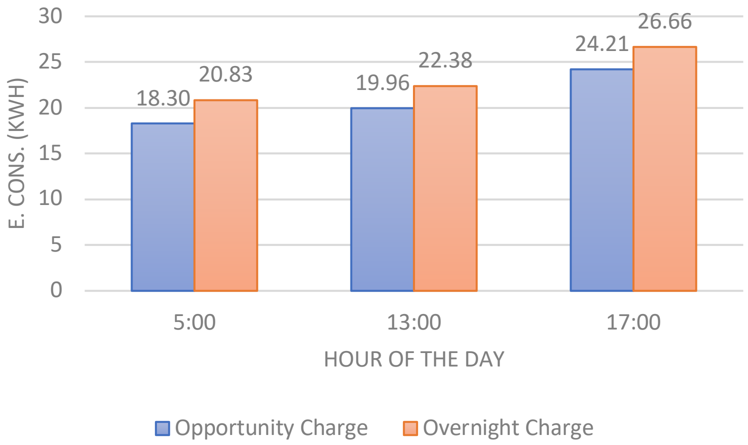
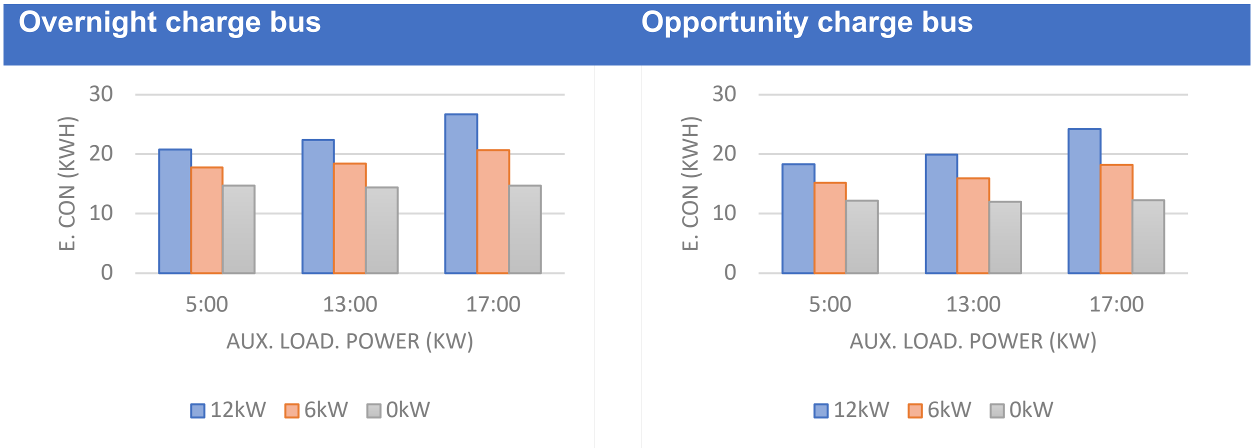


Figure ES 3. Energy consumption comparison. Overnight charge bus vs Opportunity charge bus.


Overnight charge bus

Opportunity charge bus

Figure ES 4. HVAC effect on energy consumption.

The effect of passenger occupation on traction consumption is shown in **Error! Reference source not found.**. Passenger loads of 100%, 60%, and 30% of the total passenger capacity were considered assuming an average passenger weight of 75 kg. To show the passenger load effect, it was assumed that the HVAC was off. Although the impact of passenger is lower than the one of the HVAC system, traction consumption increases around 25% to 28% when passenger demand increases from 30% to 100%. Passenger occupation will have an effect on HVAC consumption, but this effect was not included in the modeling, to avoid excessive complexity.

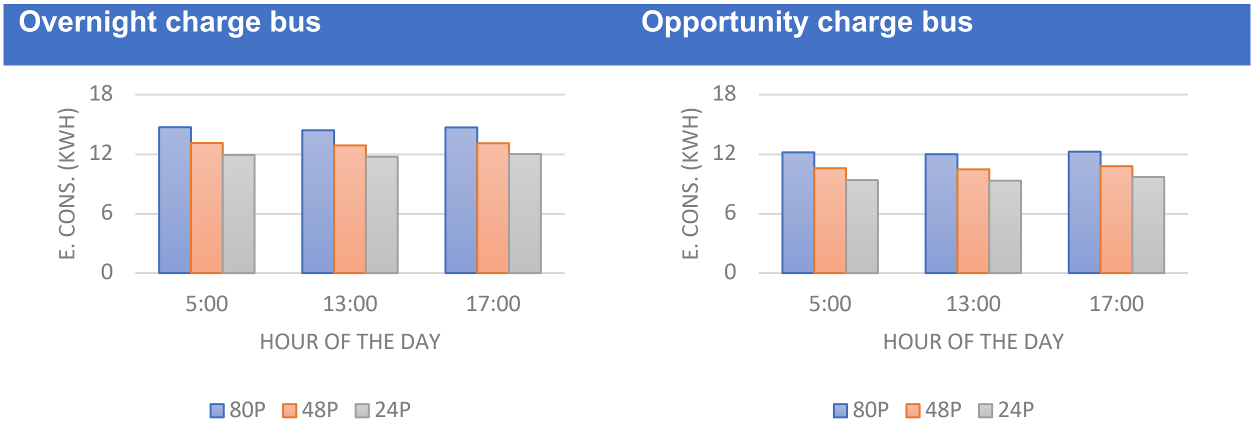


Figure ES 5. Passenger occupation effect on energy consumption.

A summary of the results obtained is presented in Table ES 3. Three scenarios are considered for the overnight charge bus, showing the effect of passenger occupation in the bus (80, 48, and 24 passengers).

Table ES 3. Performance summary

Test		Energy (kWh)	Avg. Vel. (km/h)	Efficiency (kWh/km)	Range (km)	
					Initial	End of life
Opportunity charge bus	Worst case scenario	24.21	8.72	2.78	15.81	11.86
Overnight charge bus	1 PM - 80 P scenario	22.38	13.09	2.57	108.25	81.19
	1 PM - 48 P scenario	20.85	13.09	2.40	116.16	87.12
	1 PM - 24 P scenario	19.71	13.09	2.27	122.89	92.17

The estimated range for the overnight charge bus goes from 108 km to 122 km, and the bus could complete around 12 to 14 consecutive cycles before reaching 20% of the SoC of the battery. The bus would lose around 30 km of range by the end of the battery's life cycle, which means that the bus could complete 9 to 10 consecutive cycles in this route. Figure ES 6 shows the cycles that bus 0I3002H currently performs in a day of operation. The bus considered in this study could not cover the expected daily range for the current buses, which is between 163 km and 181 km.

The estimated range of the opportunity charge bus for this route is 15 km, and no more than one cycle could be completed per charge. However, the bus could run 24 hours of service if the proper charging infrastructure is available. The estimated charging time will be around 4 minutes, depending on the final SoC at the end of each cycle. Figure ES 7 shows the discharging-charging events of bus 0I3002H, which completes 21 cycles in one day. Initial and end-of-life operation are presented, to show the differences in the DoD. It is important to notice that the opportunity charge bus could have a lower consumption at different times in the day, which could offer some flexibility to program the charging events.

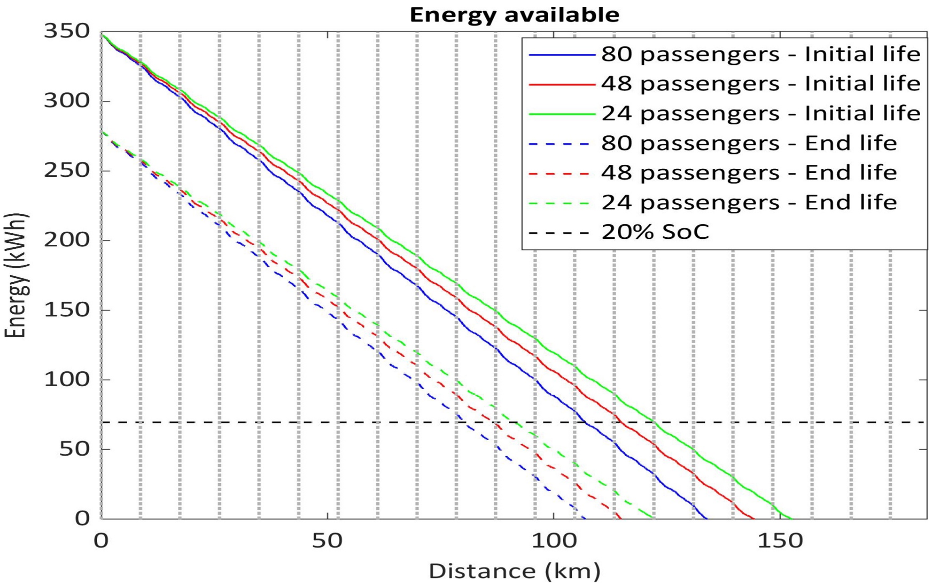


Figure ES 6. Energy consumption throughout the day (overnight charge bus).

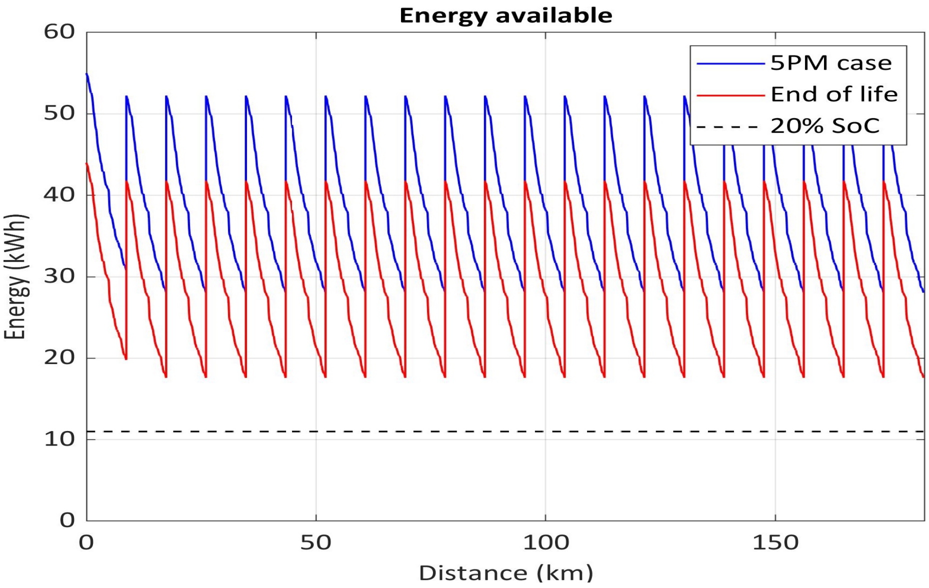


Figure ES 7. Energy consumption throughout the day (opportunity charge bus).

Energy consumption conclusions

The analysis of the seven routes confirms and quantifies the high impact that the driving behavior/conditions have on traction consumption. Energy consumption is also affected by traffic conditions in Panama City. It is observed that average velocities drop considerably at certain hours during the day and that such drop varies across routes. The load from the HVAC system can be considerable, depending on a complex interaction between ambient temperature and other factors. This load can have a great impact on per-kilometer energy consumption when the velocity is low. It is found that reductions in average velocity translate into 50% to 105% increments in energy consumption in some of the routes.

It is not realistic to expect the technology to perform efficiently and demonstrate viability under all and any operational conditions. Thus, the results of the analysis point to action areas for Panama, namely:

a. For MiBus, the education and training of drivers, to foster awareness about their role in the decarbonization of the transport system, and
b. For the municipal and national governments, the implementation of regulations and measures to improve driving conditions along bus routes.

Not only could these steps increase the viability of electric buses for more routes, but they would also reduce the amount of capital needed for fleet transformation.

Finally, passenger demand is an important variable that affects both traction and HVAC consumption. While bigger numbers of passengers will increase traction consumption, it is observed that increases in passenger capacity from 30% to 100% leads to traction consumption increments in the order of 20% to 25%. This suggests that energy consumption is more sensitive to HVAC load than to passenger load. This is a positive result because one of the metrics of the success of fleet electrification programs should be that ridership increases. Success looks like a fleet of electric buses that displace emissions from fossil fuels both by switching to zero emission technologies and by inducing travelers to switch modes from the automobile to public transportation.

Discussion of charging strategies

The selection of a charging strategy involves the optimization of the set of integrated practices adopted in order to supply electrical energy to the buses, with a given set of economic and social objectives in mind. In the definition of a charging strategy, LOGIOS considers the following key practices:

- The charging method
- The rating of the charging equipment
- The location of the charging assets
- The timing of charging events
- The duration of charging events
- The power demand of charging events
- The scalability of the charging solution
- The rate of utilization of the charging assets

A discussion of charging strategies is presented for both overnight and opportunity charging, in the context of the routes selected by MiBus in Panama City.

Overnight charging strategy

The planning of the charging events in the overnight charging strategy is usually straightforward. The buses are charged outside of service hours, typically during the night. The operator needs to allocate a certain time for the charging of these units, which will be determined based on (a) the rate at which the equipment can supply energy to the bus, (b) the state of charge of the battery when the bus arrives at the charging site, and (c) the capacity of the battery, which will decrease as the battery ages.

The charging schedules for overnight charging buses are not very flexible, and this can impose tighter constraints on vehicle range. For this reason, careful planning is needed so that the onboard energy storage system, accounting for battery degradation, is adequately tailored to the energy requirements of the particular route. This makes the direct, 1-to-1, replacement of conventional buses with overnight charging buses more difficult and, in general, a riskier investment. For instance, the analysis shows that, assuming that the buses are used exclusively in the analyzed routes (and not repurposed to serve other routes at different times in the day), some of the diesel buses serving routes C888, C938, and E489 could be replaced with overnight charge buses.

Certainly, for buses whose daily distance is longer than the range of the overnight charge electric bus, investors have the option to procure bus models with longer ranges, which most likely involve bigger batteries. It should be pointed out, however, that the marginal increase in route length that can be served by adding one unit of battery capacity is significantly lower for overnight charging buses than for opportunity charging buses.

The large power demand required at the bus depot to charge several buses simultaneously is the question that requires the most attention in the development of a charging strategy for overnight charging buses. It is critical to develop an energy supply plan that not only is economically viable but that is also scalable. Conversations with the electric utilities serving Panama City suggest that there should be no problems with access to power, even in depots located in the city.

The integration with the grid via demand response and auxiliary services is a critical element in an overnight charging strategy for the near term. This integration essentially involves the management of charging so that it reacts to price signals and can create win-win situations for the bus operator, investors, and electric utility.

Opportunity charging strategy

Bus fleet operators, and particularly their planning and operations divisions, are used to fleets with one single type of bus technology, that can be assigned to any one of the routes in their service. While this expectation is not appropriate for a fleet of electric buses, it can be more closely met with technology solutions that involve more frequent charging events, such as the overhead (or opportunity) charge systems.

The design of an opportunity charging strategy is an order of magnitude more complex than that for overnight charge buses. This complexity is however the key to unlock a host of potential efficiencies that may increase the bankability of the project or, alternatively, the return on the use of public money. In the most basic form of an opportunity charging strategy, overhead charging infrastructure is installed at the one site along the route, and the bus charges for a few minutes every time it arrives at it, to then continue on to the next route cycle. This simple description includes several parameters that are, to varying degrees, under the control of the operator. The selection of these parameters, with the goal of maximizing the efficiency of the operation and, more broadly, the investment, constitutes the *charging strategy*.

The results show that electric buses under an opportunity charge strategy could operate seamlessly throughout the day in routes C888, C898, C968, and E489, *even in a worst-case scenario* with high HVAC power demand, highest passenger load, and most challenging driving cycle. The most demanding cycles for routes C850 and C938 could not be served with opportunity charge buses with the assumed battery size (3 times smaller than that assumed for the overnight charge bus). In these cases, the addition of one charging point or a bigger battery would enable the electric buses to run the entire operational day.

1. Introduction

This report presents the analysis of charging strategies for electric buses that would be operated for public transport in Panama City. The focus is on seven service routes that Transporte Masivo de Panamá (MiBus) selected for the prospective deployment of an initial group of electric buses. Opportunity fast charging and overnight slow charging are considered for the analysis. The results integrate digitally processed real-life measurements with software simulation based on mathematical models of two bus typologies, one for each charging method. The objective is to highlight the opportunities and limitations that each bus typology offers to MiBus operation, based on predictions of energy consumption, charging time, range of operation of the buses, and some assumptions regarding the infrastructure and operation.

For each route, three moments of the day are identified to characterize average-consumption and worst-case scenarios. This is important to assess each charging strategy. As part of the process toward evaluating charging strategies, route topological and operational characteristics, impact of auxiliary loads, as well as energy consumption during route cycles and over the day of operation are presented. These will first help assess the technical viability of different bus typologies for each route given the existing operational conditions, and then make estimation of the energy and power requirements at each charging event. The analysis highlights that identifying an optimal charging strategy is a complex problem that necessitates of expert technical analysis.

The report closes offering general conclusions, and a discussion of hypothetical opportunities for and challenges of each charging strategy.

2. Energy consumption analysis

To perform an energy consumption analysis of the potential electric buses that will be deployed in Panama City, LOGIOS used proprietary mathematical models that replicate the components of electric buses and their dynamic interactions, and can generate projections of the energetic behavior of the buses, considering the operating conditions and the technical specifications of any particular vehicle. Two different charging methods are assessed in this study, considering for the computations bus configurations similar to two commercial buses, one suitable for each method of charging.

The slower charging method uses power of up to 200 kW. Charging events usually occur once a day and are ideally performed at night, outside of service hours. This method requires a big battery pack that can deliver the daily mileage, typically in the range of 100 to 300 km, per charge. For this type of charging, vehicles typically use Lithium Iron Phosphate (LiFePO4) batteries, which necessitate charging times in the order of a few hours, depending on the size of the battery pack and charging facility. Thus, this method constrains the operation time for a few hours at a time every day, in the best-case scenario. This charging method will be herein referred to as *overnight charging*.

The faster charging method uses higher power, typically 350 kW and higher, that occurs several times throughout the day. The battery size required for this type of charging is smaller than that of overnight charging since it only needs to deliver range for no more than the most demanding route cycle in the day. Each charge event is usually translated into a few tens of kilometers. This type of charging requires a very efficient battery technology, such as Lithium Titanite Oxide (LTO), that is comfortable with very high currents. In high intensity applications such as electric buses, the battery pack needs an active cooling system that prevents the cells from exceeding temperatures above 50-55°C during charging. The objective with this method of charging is typically not to fully charge the battery pack, but to return as much energy as possible to the battery in a short time. The duration of charging events depends on the initial state of charge (SoC) of the battery, the capacity (or Amp-hour) of the battery pack, and the available charging power. Unlike LiFePO4 batteries, LTO batteries can be charged to nearly 100% SoC in the order of minutes. This charging method will be herein referred to as *opportunity charging*.

The parameters of the buses used for the analyses in this report are presented in Table 1. The selected buses represent the behavior of an overnight charge bus and an opportunity charge bus. It should be noted that the battery of the overnight charge bus is larger, containing almost three times the energy storage capacity of the battery in the opportunity charge bus. As a consequence, the overnight charge bus is significantly heavier.

The most salient difference and the reason why different charging methods are applied to each type of bus is the chemistry of their battery packs. On one hand, the overnight charge bus uses LiFePO4 cells, which are typically limited to 2-3 C charging rates[1]. Also, as the battery SoC approximates its maximum, the charging current must be considerably reduced to protect the battery from overvoltage and overheating, thus, protecting the state of health of the battery and extending its life cycle. These characteristics make this technology suitable for slower charging events than the case of LTO, with power of 200 kW or lower. Considering this, the bus operator must plan on several hours to charge the battery to a 100% SoC and use the bus as efficiently as possible to ensure maximum usability.

On the other hand, batteries in opportunity charge applications use LTO cells, which have a much higher charging capacity than their LiFePO4 counterparts, allowing currents of 6 C and greater. Also, it has similar behavior to LiFePO4 cells when the SoC is reaching its maximum, but some studies show that LTO cells perform better at high SoC thanks to its greater charging efficiency. These features make LTO batteries a suitable solution for fast charging.

Another important difference between these energy storage technologies is their life cycles. The LiFePO4 cells have a nominal life of around 2,000 to 3,000 cycles, with a 100% depth of discharge (DoD). This means that one cycle is complete when the battery is discharged from its 100% SoC to 0% and charged back to 100%. The number of cycles grows as the DoD is reduced; a feature with implications for the design of charging strategies. In any event, it is always recommended that the DoD do not go beyond 80%, to avoid early damage and/or acceleration of the degradation of the battery.[2] The same logic applies for LTO batteries, with the difference that for this technology the number of complete cycles can go up to between 7,000 to 15,000, increasing thereon for lower DoD.

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[1] C rate is the charging rate based on the ratio between the charging current and its nominal capacity in Ah. In a 10 Amp-hour battery, charging at 1 C means that the charging current is equal to 10 A. 2 C refers to charging current of 20 A, 3 C refers to charging current of 30 A, and so on.

[2] Detailed information should be requested from the technology provider during the procurement process.

Table 1. Technical data of buses used for the study.

Parameter	Overnight charge bus	Opportunity charge bus
Total mass of the vehicle [kg]	14,300	10,500
Cargo capacity [kg]	6,000	6,000
Frontal area [m2]	6.6	6.5
Max velocity [km/h]	60	60
Rolling resistance coefficient	0.0098	0.0098
Aerodynamic drag coefficient (cd)	0.66	0.65
Chemistry of the cells	LiFePO4	LTO
Nominal battery capacity [kWh]	348	55
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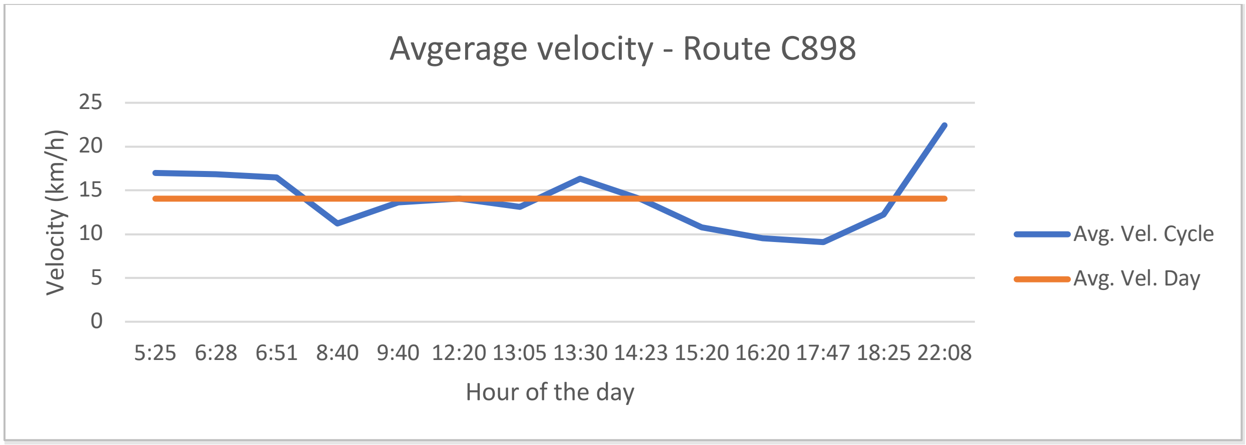
Motor type (N° of motors)	AC-PMSM (2)	AC-RPM (1)
Motor and power train position	Rear wheel drive	Rear wheel drive
Max power [Kw]	300	180
Max torque [Nm]	1,100	10,000
Min voltage [V]	500	500

2.1 Routes information

Based on the information provided by MiBus, driving cycles for 7 routes were built. Five of them are circular routes, and the other 2 are Go-Return routes. The information of the driving cycles was first reorganized in such a way that the average velocity of each cycle of the route can be calculated. This variable is of big importance, due to its correlation with the energy consumption of the heating, ventilation, and air conditioning (HVAC) system. Figure 1 shows the average velocity of each cycle and the average velocity of the day for route C898. It can be observed that the earlier and later hours of the day present higher average velocities, and there is a range of hours, from 16:00 to 18:00 approximately, when the average velocity of the cycles decreases considerably. Furthermore, around noon, the cycle average velocity of is close to that of the day. This behavior is similar in other routes.

Considering this, three driving cycles were selected for each route. One for the start of the day, named 5 AM, which is usually the fastest; another for the late afternoon named 5 PM, which is the slowest period; and one for midday named 1 PM, which is around the average value for the daily operation.

Figure 1. Average velocity for the Route C898.



After doing this, the repeatability of the average velocities was assessed for 3 different days. Figure 2 shows this for Route C850. The average velocities for the three days are similar for days 1 and 2. On the other hand, the third day presents higher variations for 5 AM and 1 PM. However, these variations are reasonable and can be linked to operational factors such as driver behavior and traffic.

After the driving conditions for the day are analyzed, the data of the driving cycles is organized to be used as input to the computational simulations. As the altitude for points along the routes were not included in the information provided by MiBus, these were obtained separately. Regardless, verification of altitude values from GPS measurements is always recommended. Figure 3 shows the topographical profile for Route C888.

Following this procedure, 21 driving cycles were obtained. The velocity and elevation signals were processed with filters to exclude noise from the simulations. The simulation process and results will be described in the next section.

Figure 2. Average velocity for different days – Route C850.

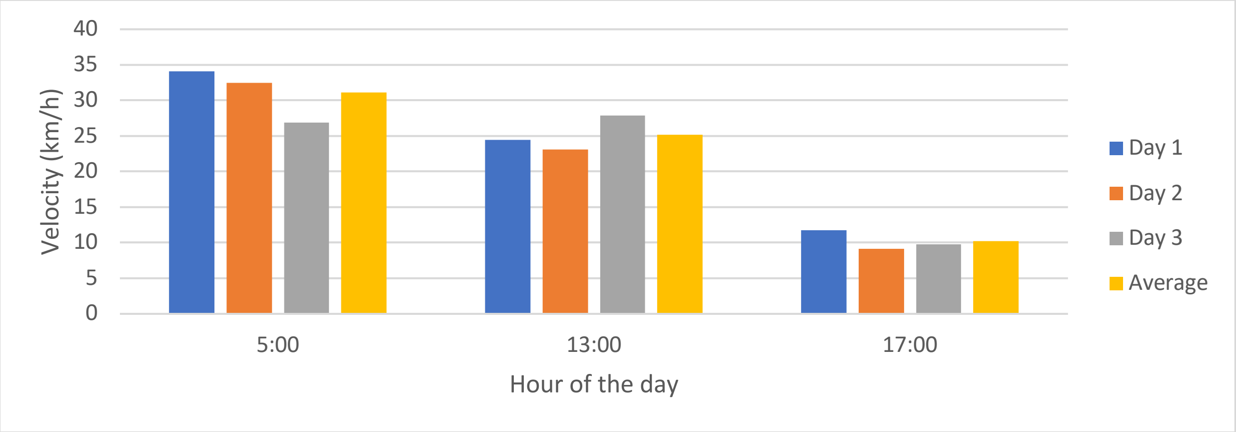
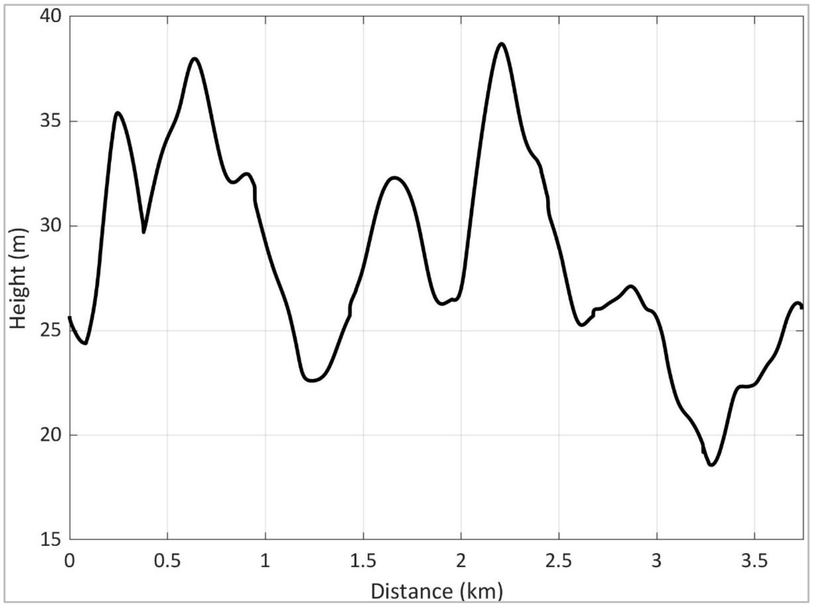


Figure 3. Topographical profile of Route C888.



2.2 Bus model and simulation results

After the buses' technical data and driving cycles are organized, a mathematical model of the electric bus is used to predict the energetic behavior of each bus considering its charging method. For the case of the overnight charge bus, no charging events are assumed during the service operation. On the other hand, for the opportunity charge bus, it was assumed that charging facilities are located at routes' terminals. Moreover, it is assumed that each bus can take a few minutes to charge after each cycle is finished. Regarding the daily mileage for each route is based on the number of cycles that buses currently perform in one day (information provided by MiBus), which in turn varies across bus units.

2.2.1 Bus model

The bus model is based on the previous general knowledge of the technology used such as type of motor, energy storage system, and mechanical transmission. The model is parameterized using the specific parameters described in Table 1. The inputs for the model are defined as a set of times [s], velocities [m/s], and grades [rad], corresponding to each point in the route. For the purposes of this analysis, the main output of the simulation is the energy consumption, expressed in kilowatt-hours (kWh) over each one of the cycles for the particular route. Additional internal results on variables such as current and voltage, torque, angular speed, and others, were obtained but not included as they are not relevant for this report.

2.2.2 Simulation results

In the next subsections, the results of the computational simulation of the seven routes are presented. Detailed information on each route is presented and the implications on energy consumption are discussed. On the foundations of the simulation results, preliminary conclusions are briefly included for each route, focusing on the charging strategy and bus technology for each case.

Table 2 shows a summary of key characteristics of the routes of interest, as well as the ranges of energy consumption obtained with the LOGIOS model. These data can be visualized geographically in a dashboard prepared for this project.[3] Energy consumption varies as a function of a multitude of factors, including bus efficiency, the passenger load, and the power demand of the HVAC system. Meanwhile, the average velocity varies depending on time of the day and driving behavior, which ultimately have considerable impact on the traction and HVAC consumption. It is worth to mention that the velocity profiles and average values were obtained from measurements taken from diesel buses that currently cover the routes analyzed in this report.

Table 2. Summary of the analyzed routes

Route	Type	Distance (km)	Energy cons. Opportunity (kWh)	Energy cons. Overnight (kWh)	Average velocity (km/h)	Bus daily distance (km)
C850	Circular	22.2	28-55	35-60	9-30	133 – 311
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E489-I	One way	5.7	4-9	5-11	22-30	45 – 130
E489-R	One way	6.4	7-11	8-13	17-26	51 – 141

It is worth noticing that the seven routes have very different characteristics (distance, frequency, average velocity, cycles per day, etc.). This makes it impractical to find one single electric bus configuration that charges once a day and that can effectively and efficiently serve every one of the routes. A bus that allows multiple on-route charging events is more flexible in this respect. This will be shown in detail for each route. Also, from the data analyzed, various traffic issues were identified, which tend to be more noticeable toward the evening. This increases the dispersion of the velocity for different routes, which in turn has an important effect on the energy

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[3] The dashboard can be accessed at https://logios.shinyapps.io/BusesElectricosPanama/

consumption and the charging strategy selection.

A recurrent question encountered in the analyses that follow has been the impact on vehicle performance of the disparate operational conditions facing the bus for a given route. It is noted that the operational conditions on a given route at a given time should not necessarily be considered as exogenous. Electric bus technical performance can be improved significantly creating favorable operational conditions. Taking inefficiencies in traffic operations as a given, will push the requirements on the technology to a point that either makes the investment inefficient or altogether non-viable.

Extreme traffic conditions can be considered in worst case scenarios, which can be better managed using opportunity charging strategies and a properly sized battery. Since the distance and average velocity dispersion is high, it is difficult to find a technology that works better for all the routes and all the different scenarios. Therefore, the two strategies are presented in detail for each route, analyzing the energy consumption per cycle, and during different hours in the day. The impact of the heating, ventilation, and air conditioning unit (HVAC), and passenger occupation variables is assessed. Finally, the operation of the modeled buses under real daily consumptions are presented for both charging methods, analyzing the possibility of replacing one of the buses that currently operates in each route.

Important to note, three cases were used for the average HVAC power, namely 12 kW, 6 kW, 0 kW.[4] Additionally, the power for other auxiliary loads is taken at 2 kW. It is assumed that the energy capacity of the batteries suffers a 20% reduction by the end of life. This does not necessarily define the end of life of the battery, but it is a reasonable assumption made for electric vehicles. However, this analysis does not aim to predict the lifetime of the batteries. Furthermore, it should be noted that buses can be reallocated to routes with lower energy requirements, come the time when they are no longer capable of serving the route to which they were originally

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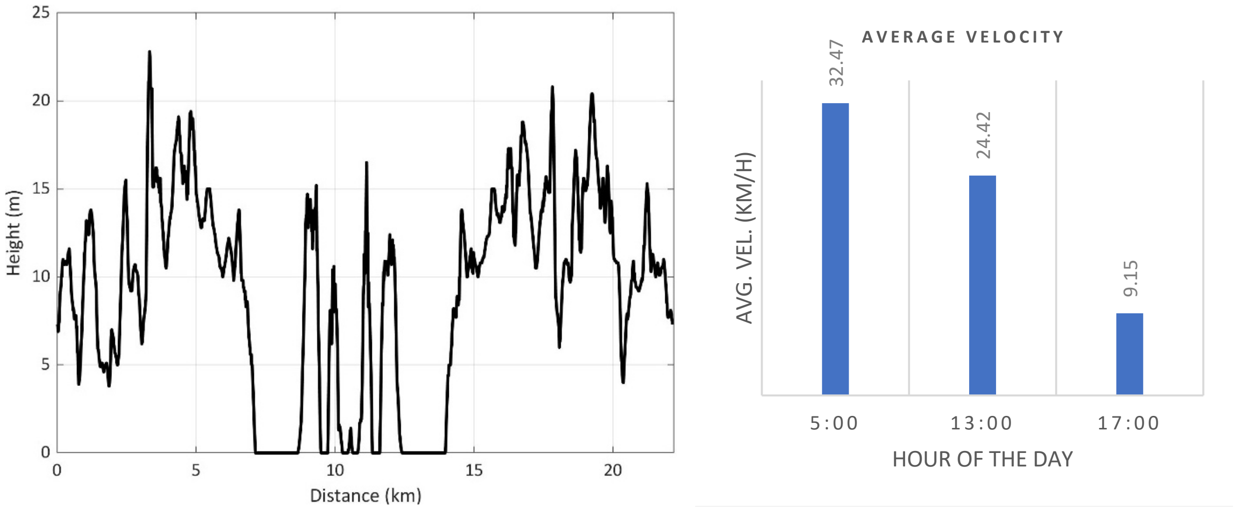
[4] The 0-kW condition is studied to obtain a reference performance without the power draw from the HVAC system. It is understood that this is not a realistic condition for Panama, where climate conditions make the use of air conditioning in buses imperative for passenger comfort.

assigned. This notion was discussed in a separate report of this technical assistance.[5]

Route C850

The route C850 is circular, with 22.2 km length, and a topographical profile characterized by some hilly sections; see Figure 4(a). The average velocity for the driving cycles selected are shown in Figure 4(b). The average velocity is significantly lower in the 5 PM case, which suggests heavy traffic conditions; an inference that was validated by MiBus. Figure 5 shows the map of the route obtained from LOGIOS's technical analysis platform.

Figure 4. Topographical profile and average velocity of the Route C850.



(a) (b)

Figure 6 shows the velocity profiles of each case, where, approximately from kilometer 2 to 4, the velocity at 5 PM is considerably lower than the other two cases. Furthermore, the maximum velocity in the 1 PM case is a bit lower, and the driving cycle is more relaxed compared to the other two cases, which can have a benefit in energy consumption. The 5 AM case is the more aggressive one.

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[5] LOGIOS (2019) Accelerating the Transition to Sustainable Mobility and Low Carbon Emissions in Panama City: Deliverable 2.3 https://www.ctc-n.org/technical-assistance/projects/accelerating-transition-sustainable-mobility-and-low-carbon-emissions

Figure 5. Map of route C850

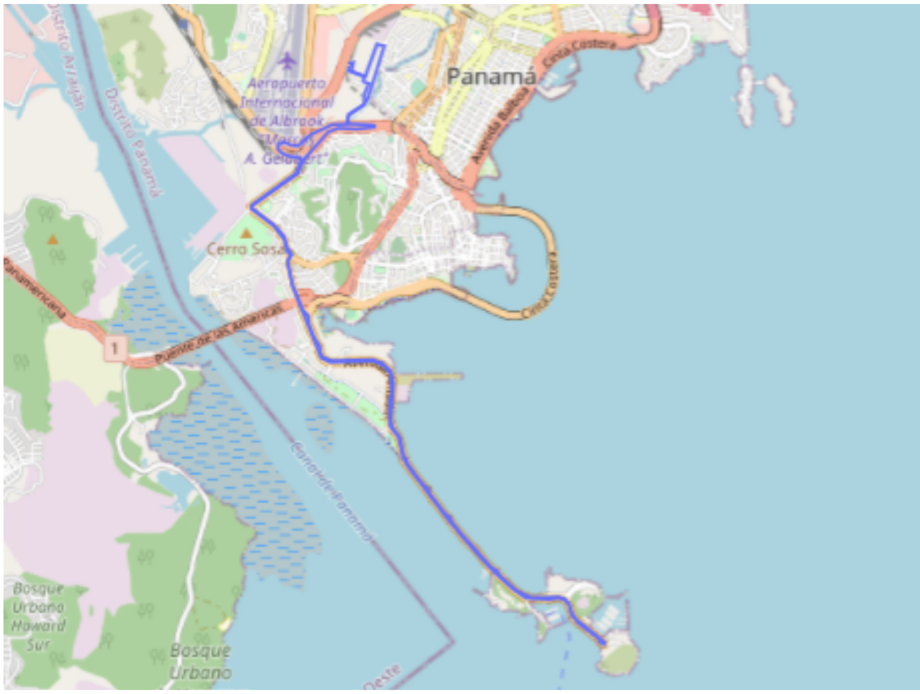
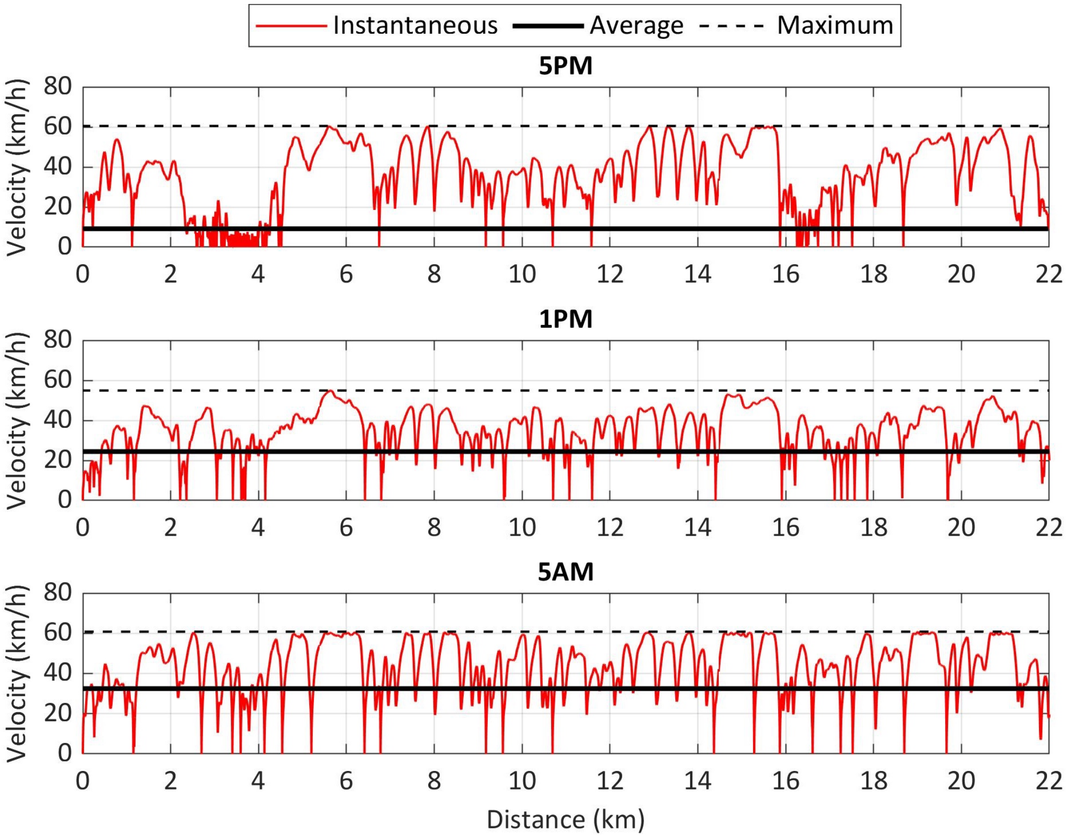


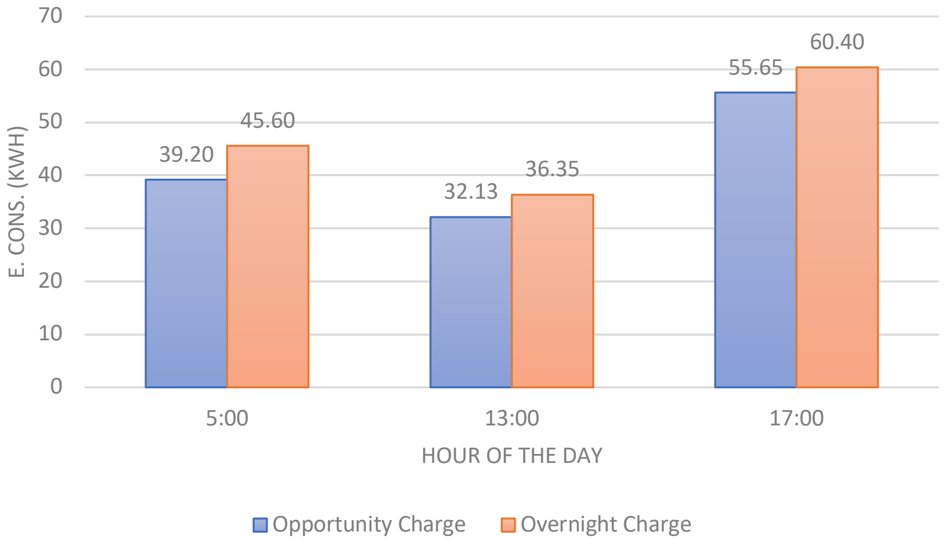
Figure 6. Velocity profiles for the three cases selected.



For the analysis of energy consumption, one cycle of the route is simulated using both buses with the different payloads and HVAC demand.

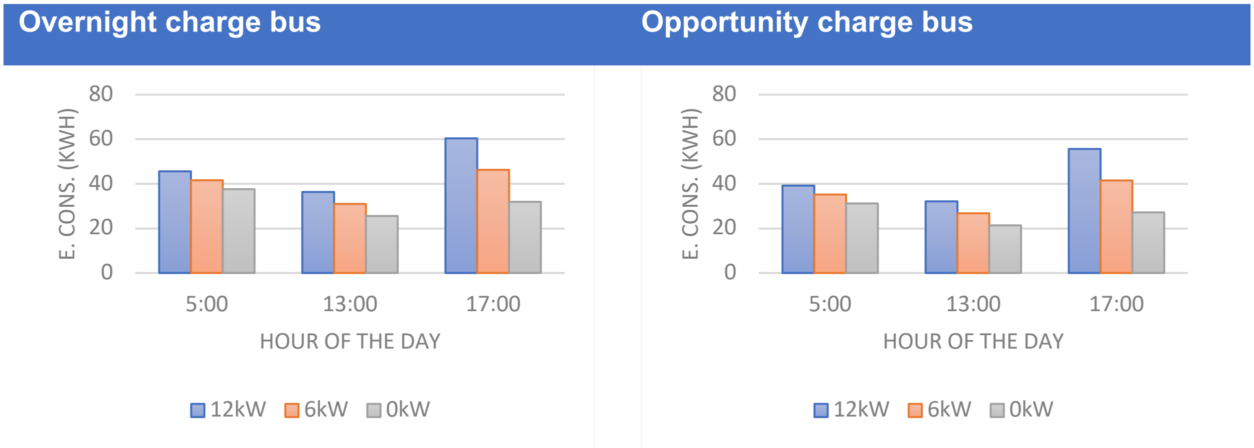
Figure 7 shows the energy consumption of both buses using the maximum passenger load and a 12-kW power demand of the HVAC, which suggests higher efficiency for the opportunity charge bus selected for this study. Also, the 5 AM driving behavior produces a higher consumption than that of the 1 PM. This is more evident in Figure 8, which shows the traction consumption (HVAC Off) in the gray bars, where the 5 AM has the highest consumption, even when it has the most favorable road and traffic conditions. This highlights the importance of creating awareness about driving behavior as a means to increase the efficiency of the bus.

Figure 7. Energy consumption comparison. Overnight charge bus vs Opportunity charge bus.



Since precise information regarding the operation of the air conditioning unit and its consumption was not available, three conditions were analyzed based on technical specifications of similar HVAC units. Figure 8 shows the impact of HVAC use in the energy consumption of the bus using constant power loads of 12 kW, 6 kW and 0 kW. The 5 PM case is the most affected by traffic congestion, which increases the driving time and the impact of HVAC in the total energy consumption, which is doubled when 12 kW is assumed. This highlights the importance of providing the right operational conditions to electrify transportation systems in an efficient way.

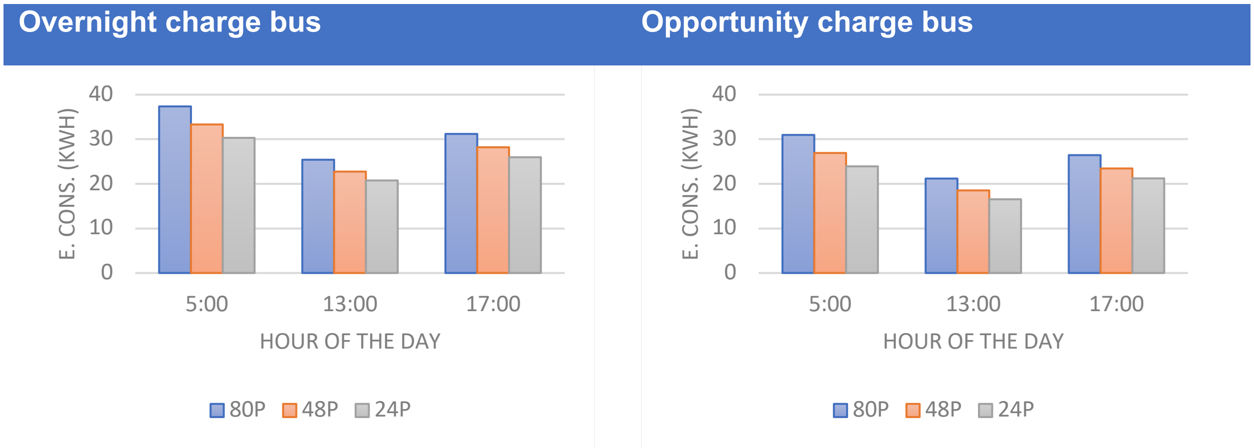
Figure 8. HVAC effect on energy consumption.



Passenger occupation also has a significant impact on the traction consumption, as shown in Figure 9. Passenger loads of 100%, 60%, and 30% of the total passenger capacity were considered, assuming an average passenger weight of 75 kg. To show the passenger effect, it was assumed that the HVAC unit was off. While HVAC consumption will tend to increase with passenger occupation, that effect was not included here, as it would unnecessarily (for the purpose of this analysis) complicate the modeling. The impact of passenger occupation can determine the number of cycles that the buses can complete with one charge, especially in the case of the overnight charging where a couple of atypical cycles with higher demand may considerably reduce the daily range. The opportunity charge bus should be designed for the worst-case cycle scenario and will better manage high and sustained passenger demand.

To keep the analysis focused on the technology and design of charging strategies, the congestion problem will be ignored for this route, to evaluate the performance of both buses during a complete day. So, for this route, the 1 PM case is used as a representative case for the overnight charge bus, which should be as close as possible to the average cycle consumption. Three scenarios are considered for the overnight charge bus, showing the effect of passenger occupation, namely 80, 48, and 24 passengers. Meanwhile, the 5 AM case will be considered as the worst-case scenario for the opportunity charge bus. A summary of the results obtained is presented in Table 3.

Figure 9. Passenger occupation effect on energy consumption



Overnight charge bus

Opportunity charge bus

Table 3. Performance summary

Test		Energy (kWh)	Avg. Vel. (km/h)	Efficiency (kWh/km)	Range (km)	
					Initial	End of life
Opportunity charge bus	Worst case scenario	39.20	32.47	1.77	25	18
Overnight charge bus	1 PM - 80 P scenario	36.35	24.42	1.63	170	127
	1 PM - 48 P scenario	33.69	24.42	1.51	184	138
	1 PM - 24 P scenario	31.70	24.42	1.42	195	146

The projected range for the case of the overnight charge bus, is between 170 km and 195 km[6]. Thus, the bus could complete 7 or 8 consecutive cycles in this route, depending on the passenger occupation. Furthermore, considering the battery degradation as defined before, the number of

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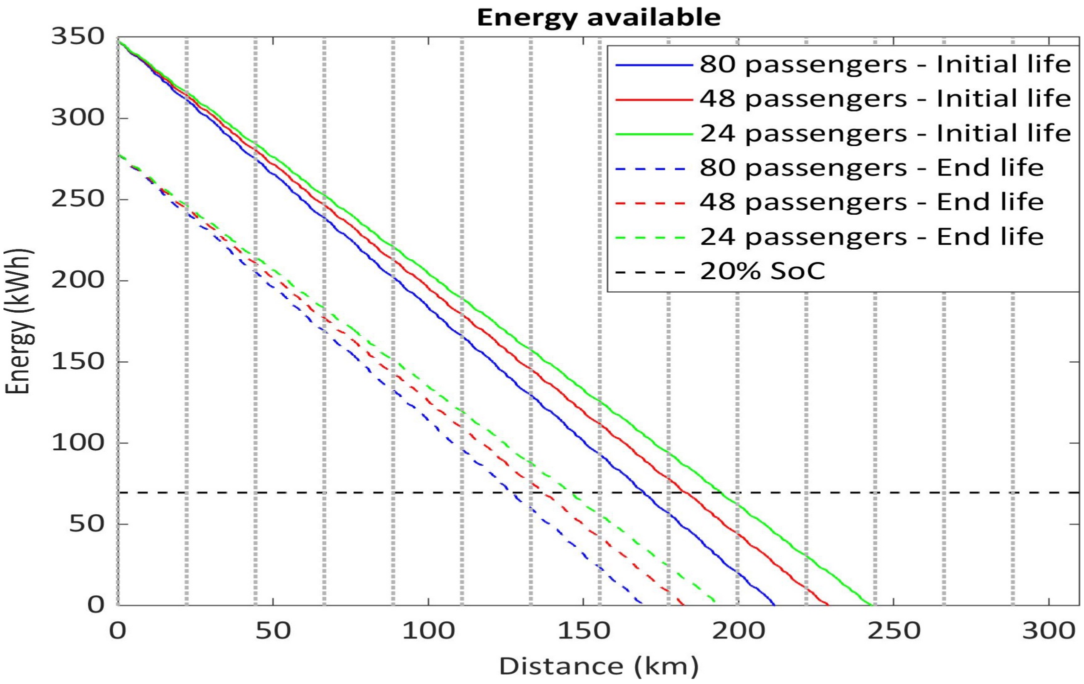
[6] Range estimations assume the bus maintains a minimum SoC of 20% at all times.

cycles that the bus could complete with one charge will decrease over the years of operation. By the end of the battery life cycle, the estimated range of the bus will allow the bus to complete 5 or 6 cycles.

Figure 10 shows the discharge evolution with respect to the distance traveled by bus 1W0002U. Vertical lines represent one complete cycle of the route. This bus should complete 14 cycles during the day, which would not be possible using the overnight charge bus. Moreover, if the operation remains as it is now, none of the buses operated by MiBus on this service route could be effectively replaced by the overnight charge bus.

Figure 10. Energy consumption throughout the day (overnight charge bus).



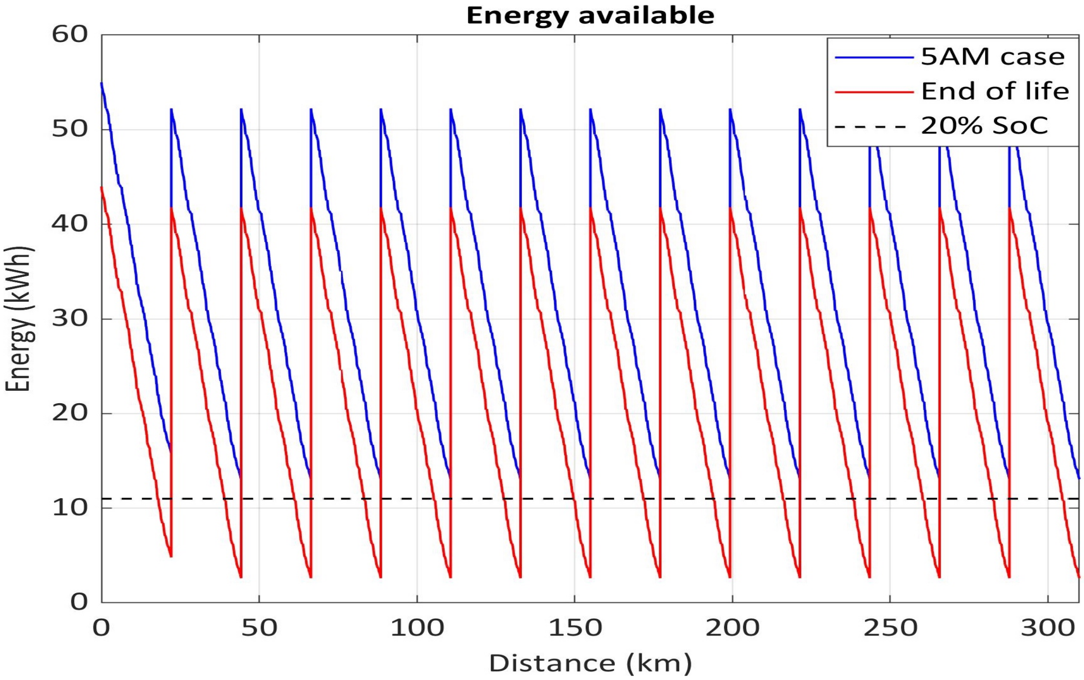
For the case of the opportunity charging bus, the estimated range of operation for the worst-case scenario is 25 km, which is sufficient to complete one cycle. Assuming that overhead fast charging infrastructure can be installed at the terminal, the battery can be recharged (to approximately 95% SoC) once a cycle and would be able to serve this route. Assuming the bus charger delivers 350 kW, the battery is charged within a window of a few minutes.

As mentioned above, the range of operation between charge events will decrease as the battery degrades over time and loses part of its energy capacity. The simulation results suggest that, with the battery size assumed for the analysis, the opportunity charge bus would not be able to meet the requirements of this route after couple of years in operation. Therefore, a bigger battery could be required for this route. It should be noted, if driving behavior is relaxed, energy consumption could be reduced, and the range of operation can be improved.

Another tactic for this strategy is that the bus could operate for a couple of years on this route and eventually be assigned to a route with lower energy requirements, thus extending the battery lifetime. While this tactic is available regardless of the battery size and it can support a longer-term investment strategy, it should be expected that a bus can serve a given route for a minimum of 4-5 years.

Alternatively, routes could be given access to more than one charging point. This would allow charging for a short period of time, which will reduce the range limitation even with such a small battery. As discussed later, these additional charging points should be located optimally in such a way that buses from other routes could use it. The depth of discharge (DoD) is also an important component of a charging strategy, with implications on battery life cycle and operating costs. Depth of discharge, and by association charging times, should be integrated into the planning route operations. MiBus should consider that the battery life cycle is inversely proportional to the DoD.

Figure 11. Energy consumption throughout the day (opportunity charge bus).

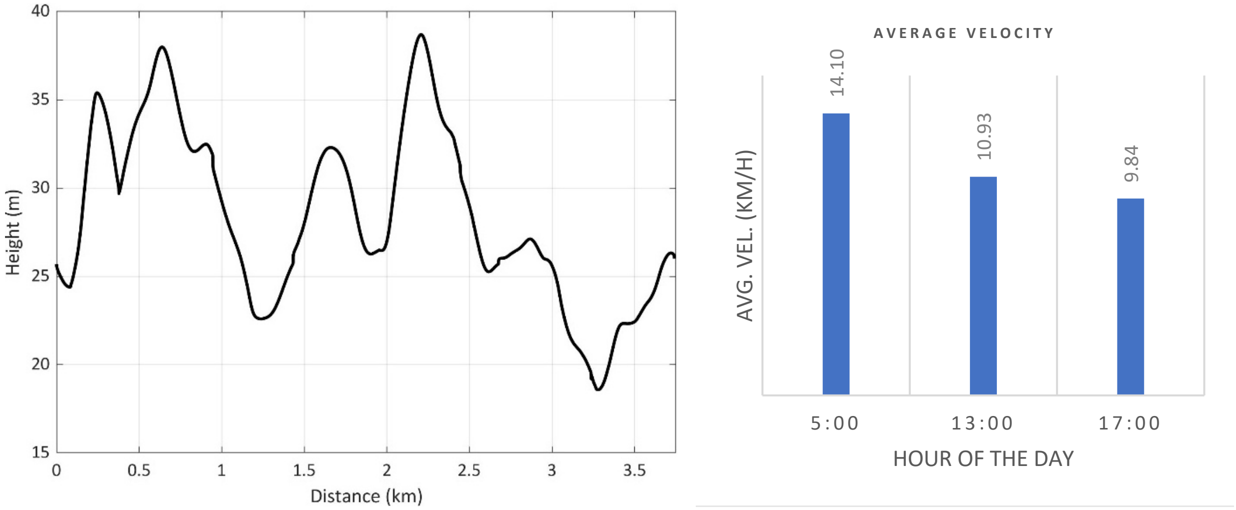


Route C888

The route C888 is a circular route with 3.9 km length, and a topographical profile shown in Figure 12 (a). The average velocity for the driving cycles selected is shown in Figure 12 (b). For this route, the tendency remains as expected and the fastest cycle occurs in the 5 AM case while the slowest is the 5 PM case.

Figure 13 shows the map of the route obtained from LOGIOS’s technical analysis platform.

Figure 12. Topographical profile and average velocity of the Route C888.



(a) (b)

Figure 13. Map of route C888

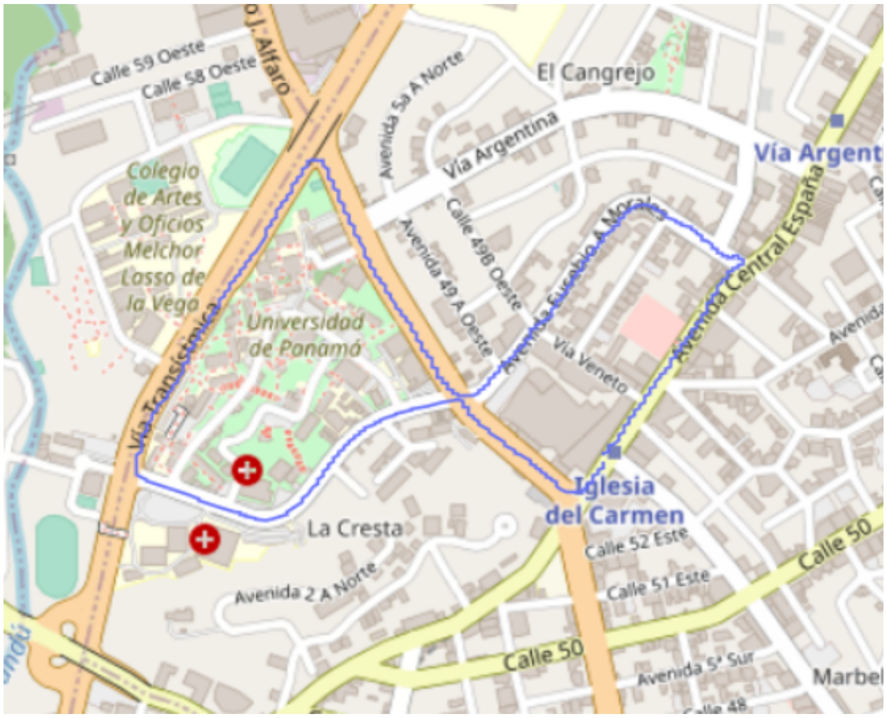


Figure 14 shows the velocity profiles of each case. The maximum velocity is considerably lower than the previous route, reaching values around 40 km/h. Furthermore, the 5 AM case has the lowest number stops and the highest average velocity, which will reduce both the traction and HVAC consumption. On the contrary, the 5 PM case has the highest number of stops and the lowest average velocity, which increases the energy consumption. This is evident in Figure 15.

Figure 15 shows the energy consumption of both buses, which shows higher efficiency in the opportunity charge bus, as expected. The energy consumption in the 1 PM case is higher than the one at 5 AM, different from the previous route. It must be noticed that traction consumption is similar for the three cases, as shown Figure 16 (gray bars), and the consumption difference is more related to the HVAC consumption. For this route, the impact of the traffic is lower than in the previous route and the energy consumption variation during the day is considerably lower. Moreover, HVAC consumption still is representative and reaches around 30% to 40% of the total energy consumed in the 5 PM case.

Figure 14. Velocity profiles for the three cases selected.

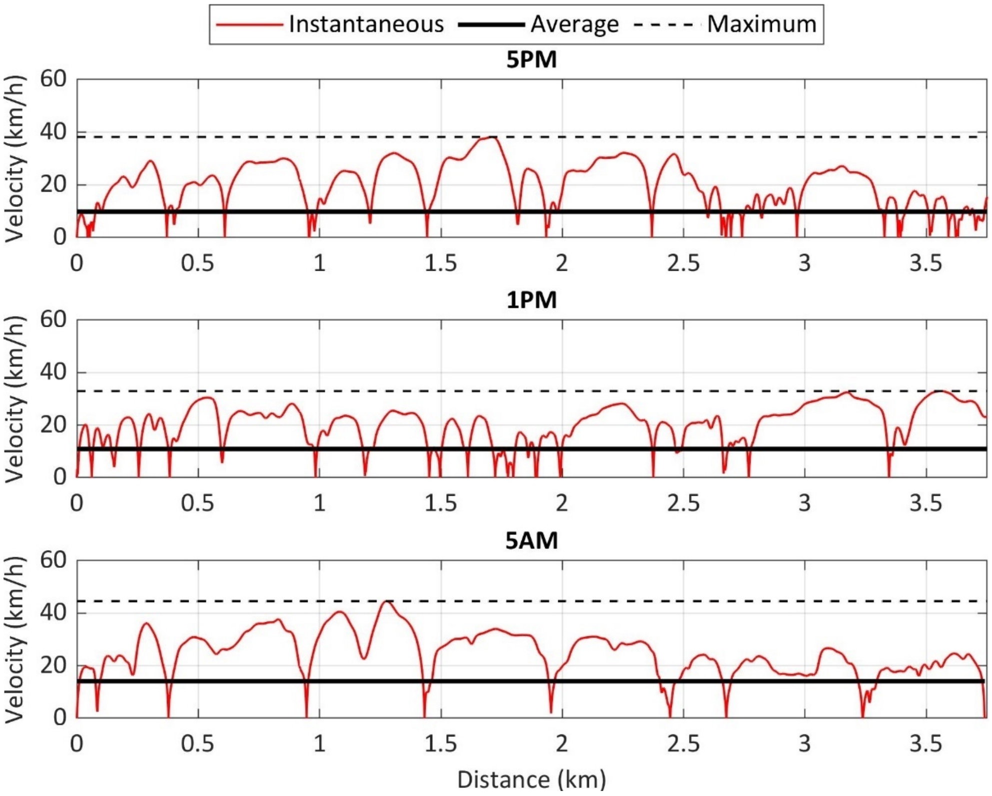


Figure 15. Energy consumption comparison. Overnight charge bus vs Opportunity charge bus.

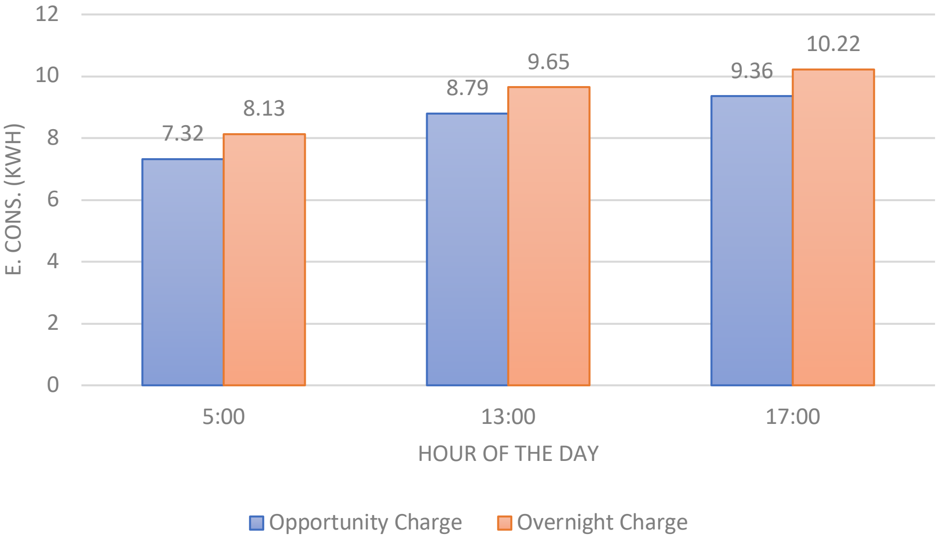
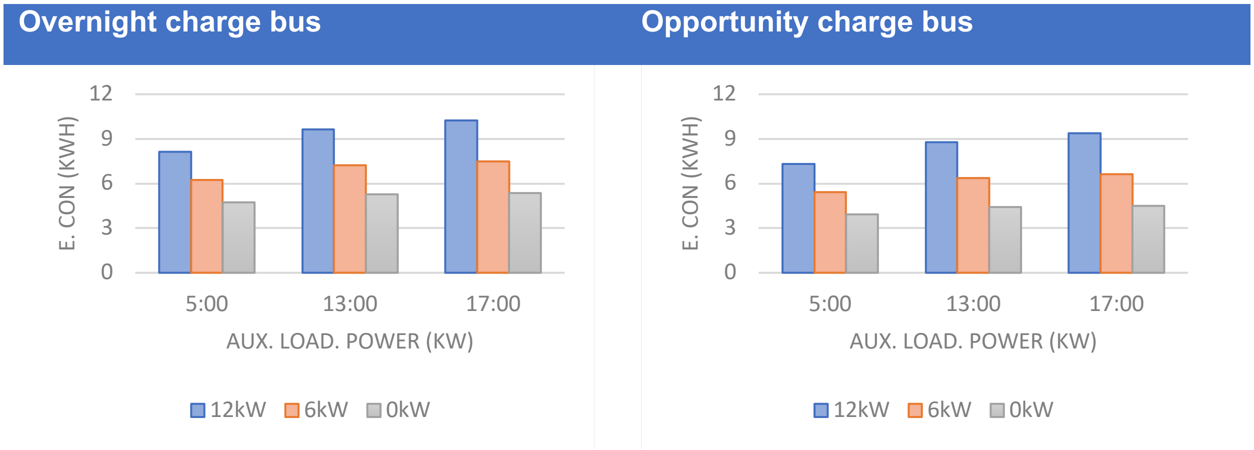


Figure 16. HVAC effect on energy consumption.



Overnight charge bus

Opportunity charge bus

The passenger occupation effect on traction consumption is shown in Figure 17. Passenger loads of 100%, 60%, and 30% of the total passenger capacity were considered assuming an average passenger weight of 75 kg. Moreover, to show the passenger effect, it was assumed that the HVAC was Off. LOGIOS is aware of the impact that passenger occupation will have on the HVAC consumption, but this effect was not included in the modeling, to avoid excessive complexity.

For this route, the 1 PM case will be considered as a representative case for the overnight charge bus and the 5 PM case will be considered for the opportunity charge bus. A summary of the results obtained is presented in Table 4. Three scenarios are considered for the overnight charge bus, showing the effect of passenger occupation in the bus (80, 48, and 24 passengers).

Figure 17. Passenger occupation effect on energy consumption.

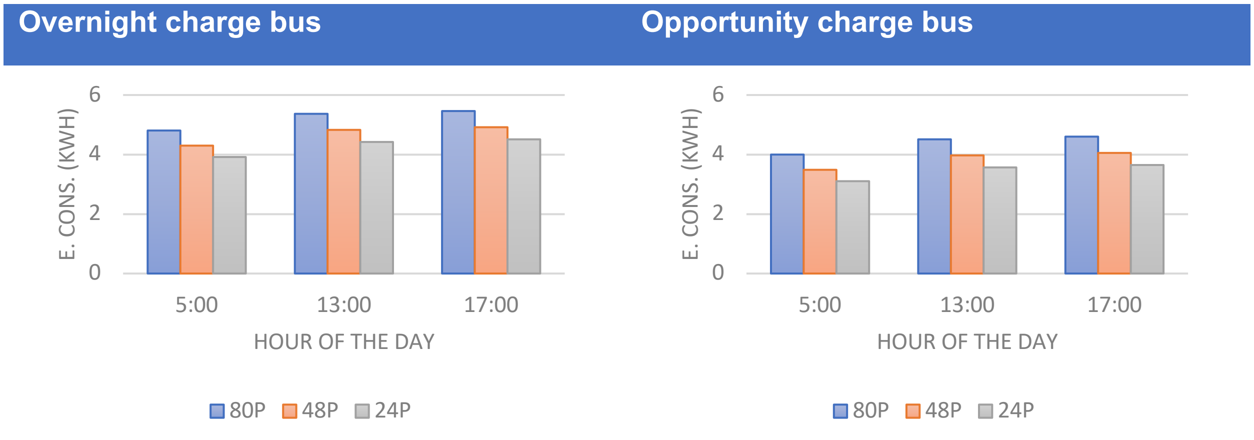


Table 4. Bus performance summary

	Test	Energy (kWh)	Avg. Vel. (km/h)	Efficiency (kWh/km)	Range (km)	
					Initial	End of life
Opportunity charge bus	Worst case scenario	9.36	9.84	2.40	18	13
Overnight charge bus	1 PM - 80 P scenario	9.65	10.93	2.47	112	84
	1 PM - 48 P scenario	9.11	10.93	2.34	119	89
	1 PM - 24 P scenario	8.7	10.93	2.23	124	93

The estimated range for the overnight charge bus goes from 112 km to 124 km depending on the passenger demand, and it could complete around 28 or 31 consecutive cycles in this route before reaching 20% of the SoC of the battery. Furthermore, the bus range will decrease to 84-93 km by the end of the battery's life cycle, which means that the bus could complete 21 to 23 consecutive cycles in this route. Another way to see this is that the DoD of the battery could be reduced, and its life cycle would be extended. Figure 18 shows the estimated depth of discharge for the operation of bus 4DG001U, which completes 19 cycles per day. Assuming that the buses are used exclusively in this route (and not repurposed to serve other routes at different times in the day) an overnight charge bus can replace all diesel for this route considering the mileage per day reported by MiBus.

On the other hand, the estimated range of operation for the opportunity charge bus is 18 km, and 4 cycles could be completed before reaching 20% of SoC. Moreover, if the bus can recharge until 95% of SoC after it finishes each cycle, the bus could run 24 hours of service. Something interesting for this short route is that an opportunity charging bus could offer some flexibility in the charging events, and the bus could run up to 3 or 4 consecutive cycles before it stops for recharge. This could help to manage better the timing for charging, selecting periods of the day with that are more favorable for MiBus operation, as shown in Section 3.

Figure 19 shows the discharging-charging events of the bus 4DG001U, which should complete 19 cycles per day. Initial and end of life operation are presented to observe the differences in the DoD.

Figure 18. Energy consumption throughout the day (overnight charge bus)

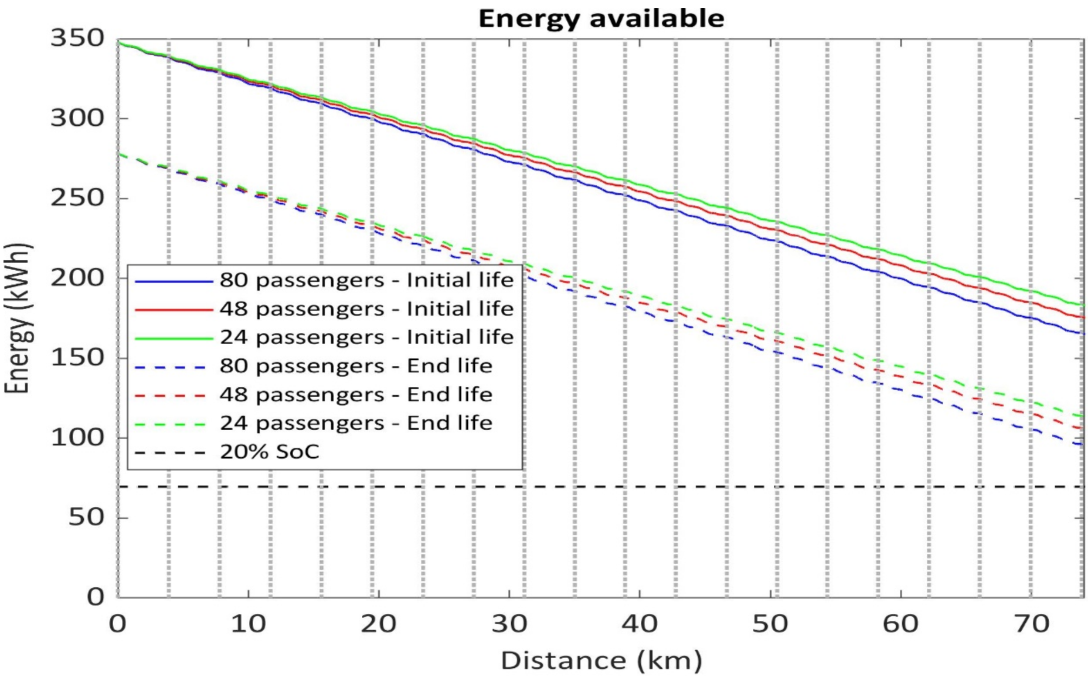
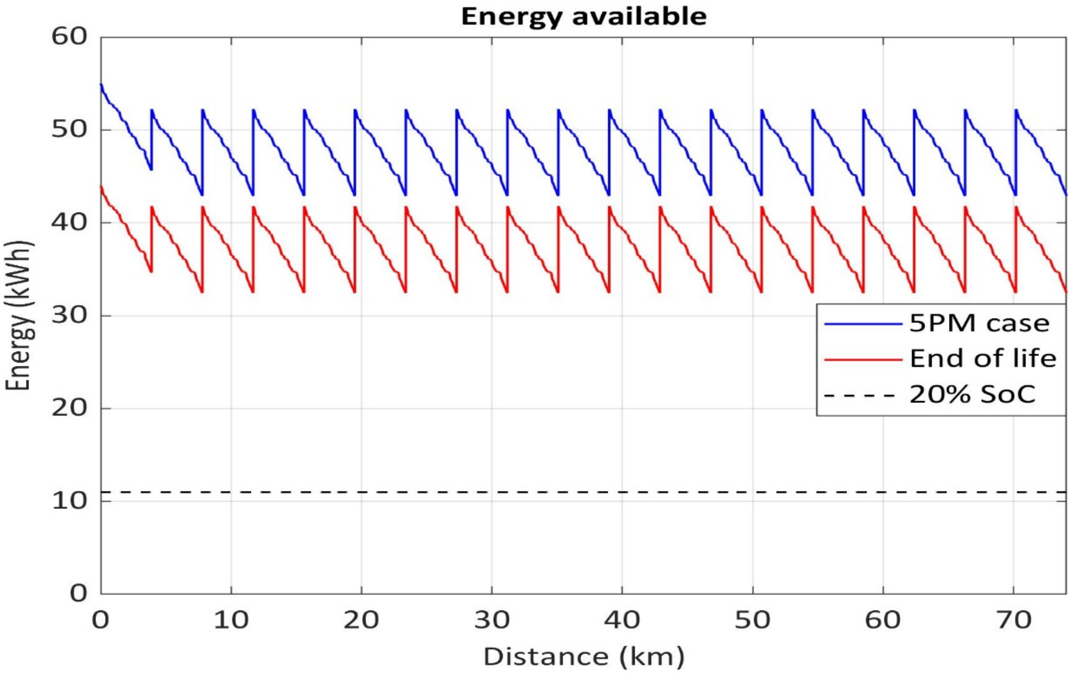


Figure 19. Energy consumption throughout the day (Opportunity charge bus).



Route C898

The route C898 is a circular route, with a length of 8.7 km, and a topographical profile as shown in Figure 20(a). The average velocity for the driving cycles selected is shown in Figure 20(b), which shows a similar behavior than in the previous routes. Figure 21 shows the map of the route obtained from LOGIOS's technical analysis platform.

Figure 20. Topographical profile and average velocity of the Route C898.

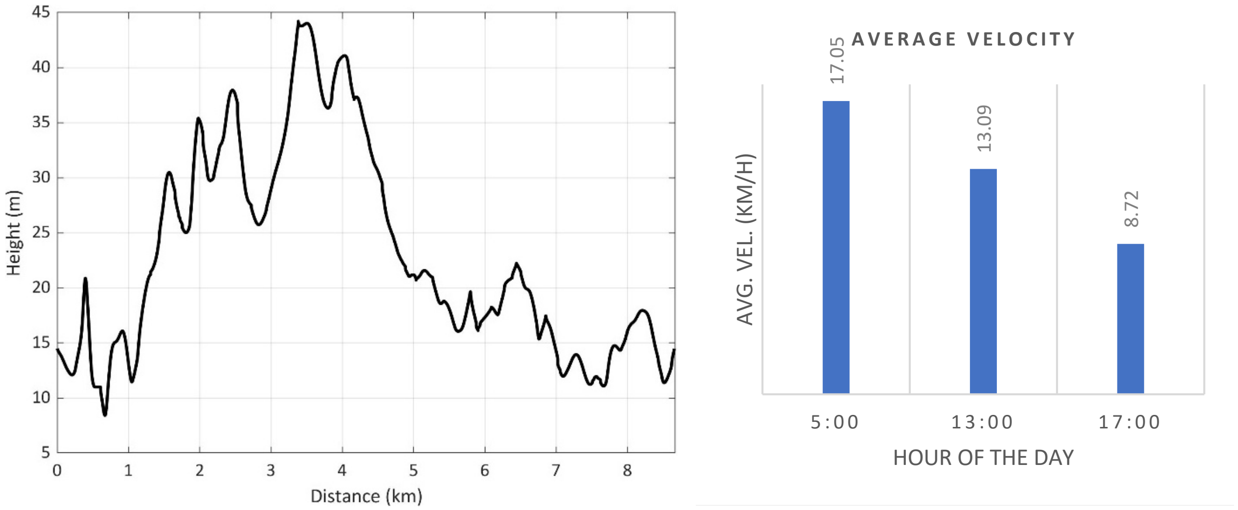


Figure 21. Map of route C898

Figure 22 shows the velocity profiles of the selected moments of the day. The tendency remains the same as in the routes analyzed below, showing that maximum velocity is higher for the 5 AM case, while its number of stops is the lowest. The other two cases have similar maximum velocities and number of stops, but traffic congestion affects the most the 5 PM case.

Figure 23 shows the energy consumption of both buses, which shows higher efficiency in the opportunity charge bus, as expected. Also, the consumption tendency for the selected cases is evident. The gray bars in Figure 24 shows that the traction consumption is similar for the three cases. This situation is ideal to predict better the effect of other factors such as traffic and HVAC on energy consumption. Figure 24 shows the effect of the HVAC consumption, and the effect of the traffic congestion is noticeable, especially for the 5PM case, where the HVAC increases energy consumption by 46% to 96%, depending on the HVAC power demand.

Figure 22. Velocity profiles for the three cases selected.

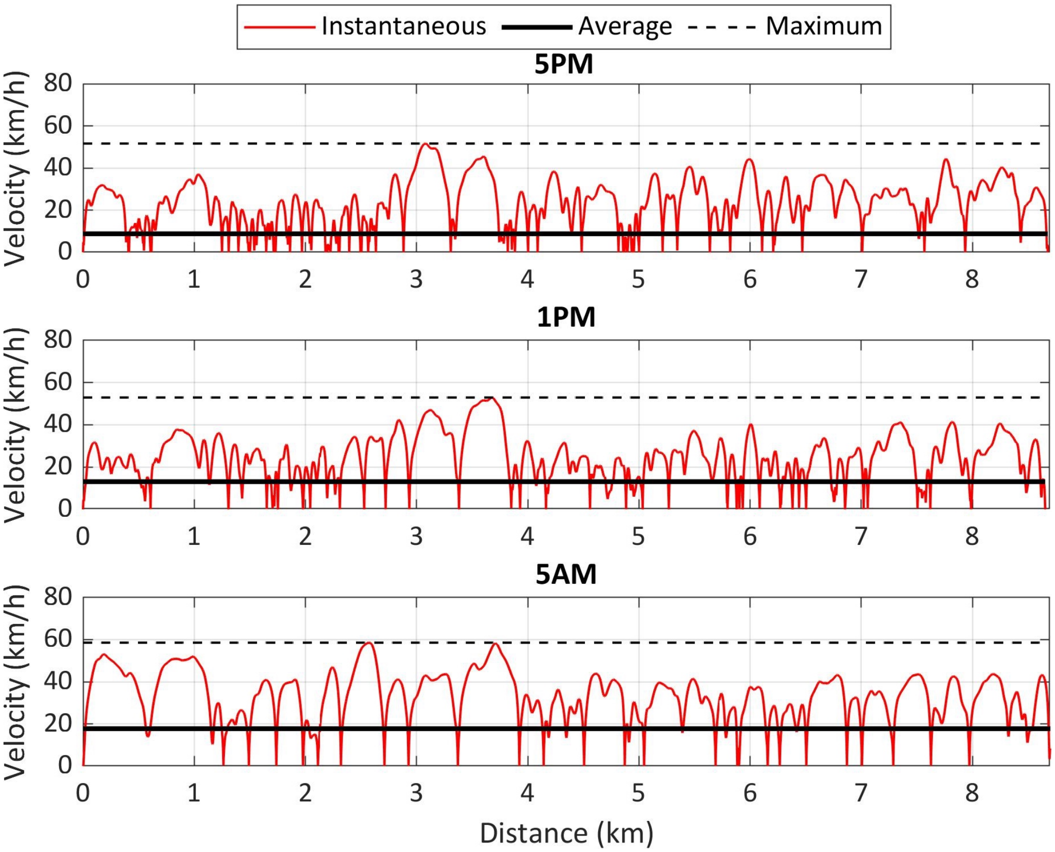


Figure 23. Energy consumption comparison. Overnight charge bus vs Opportunity charge bus.

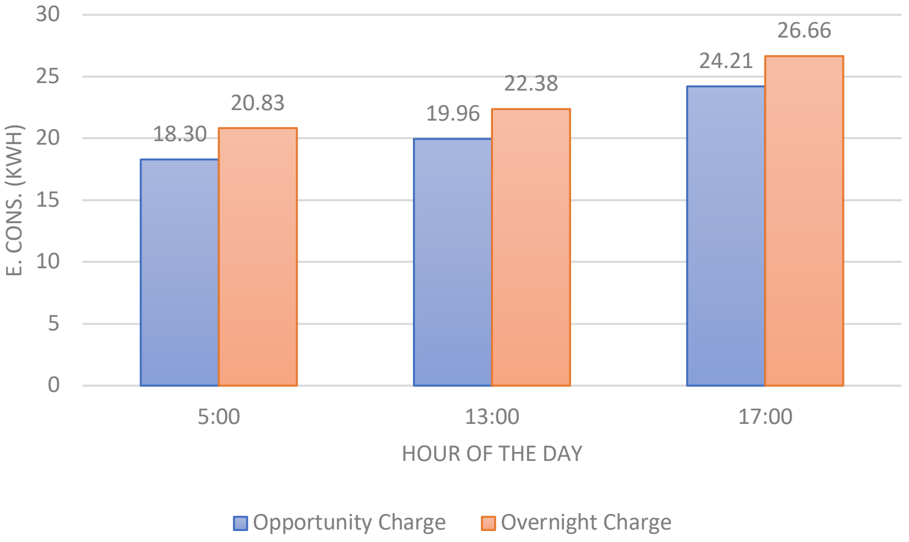
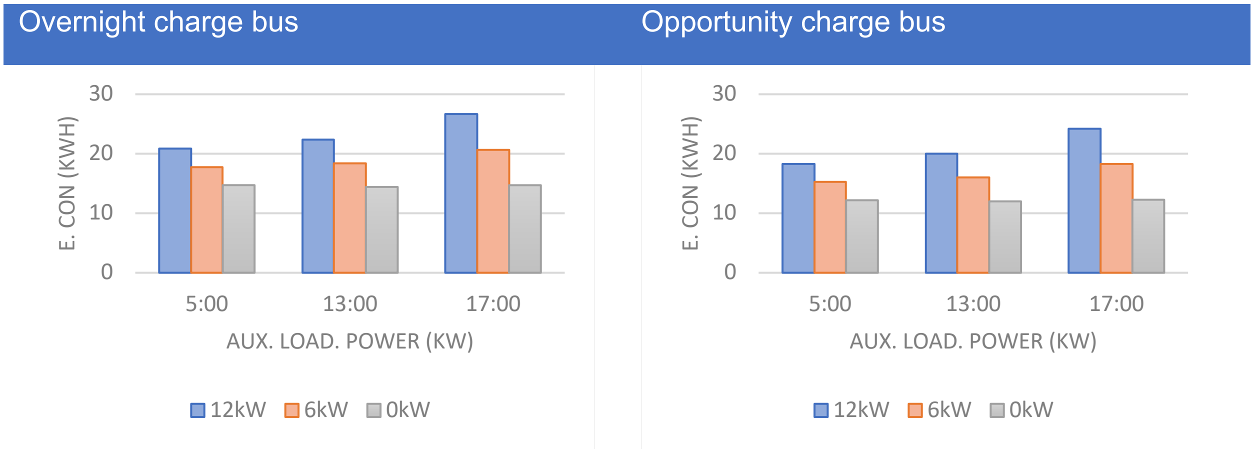


Figure 24. HVAC effect on energy consumption.

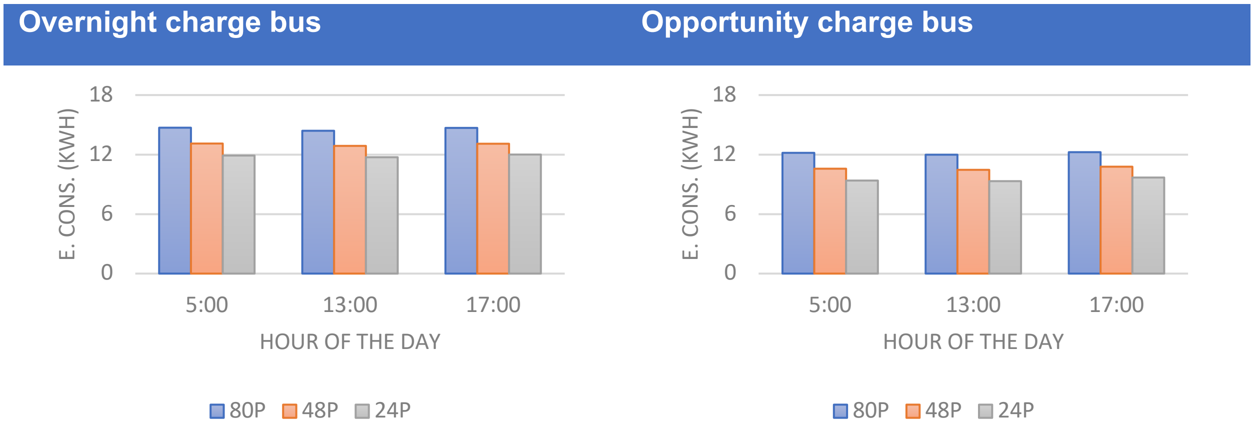


Overnight charge bus

Opportunity charge bus

The passenger occupation effect on traction consumption is shown in Figure 25. Passenger loads of 100%, 60%, and 30% of the total passenger capacity were considered assuming an average passenger weight of 75 kg. Moreover, to show the passenger effect, it was assumed that the HVAC was Off. Although the impact of passenger is lower than the one of the HVAC system, traction consumption increases around 25% to 28% when passenger demand increases from 30% to 100%. LOGIOS is aware of the impact that passenger occupation will have on the HVAC consumption, but this effect was not included in the modeling, to avoid excessive complexity.

Figure 25. Passenger occupation effect on energy consumption.



Overnight charge bus

Opportunity charge bus

For this route, the 1 PM case will be considered as a representative case for the overnight charge bus and the 5 PM case will be considered for the opportunity charge bus. A summary of the results obtained is presented in Table 5. Three scenarios are considered for the overnight charge bus, showing the effect of passenger occupation in the bus (80, 48, and 24 passengers).

Table 5. Performance summary

Test		Energy (kWh)	Avg. Vel. (km/h)	Efficiency (kWh/km)	Range (km)	
					Initial	End of life
Opportunity charge bus	Worst case scenario	24.21	8.72	2.78	15	11
Overnight charge bus	1 PM - 80 P scenario	22.38	13.09	2.57	108	81
	1 PM - 48 P scenario	20.85	13.09	2.40	116	87
	1 PM - 24 P scenario	19.71	13.09	2.27	122	92

The estimated range for the overnight charge bus goes from 108 km to 122 km, and the bus could complete around 12 to 14 consecutive cycles before reaching 20% of the SoC of the battery. Furthermore, the bus will lose around 30 km of range by the end of the battery's life cycle, which means that the bus could complete 9 to 10 consecutive cycles in this route. Figure 26 shows the current cycles that the bus 0I3002H currently performs in a day of operation. The bus considered in this study could not cover the expected daily range for the current buses, which is between 163 km and 181 km.

On the other hand, the estimated range of the opportunity charge bus for this route is 15 km, and no more than one cycle could be completed per charge. However, the bus could run 24 hours of service if the same charging infrastructure discussed before is assumed here. The estimated charging time will be around 4 minutes, depending on the final SoC at the end of each cycle.

Figure 27 shows the discharging-charging events of the bus 0I3002H, which completes 21 cycles in one day. Initial and end-of-life operation are presented, to show the differences in the DoD. It is important to notice is that the opportunity charge bus could have a lower consumption at different times in the day, which could offer some flexibility to program the charging events. For instance, if the energy consumption of the 1 PM case is considered, the range of operation increases to 19 km, which would be enough to complete 2 cycles. This discussion will be expanded in Section 3.

Figure 26. Energy consumption throughout the day (overnight charge bus).

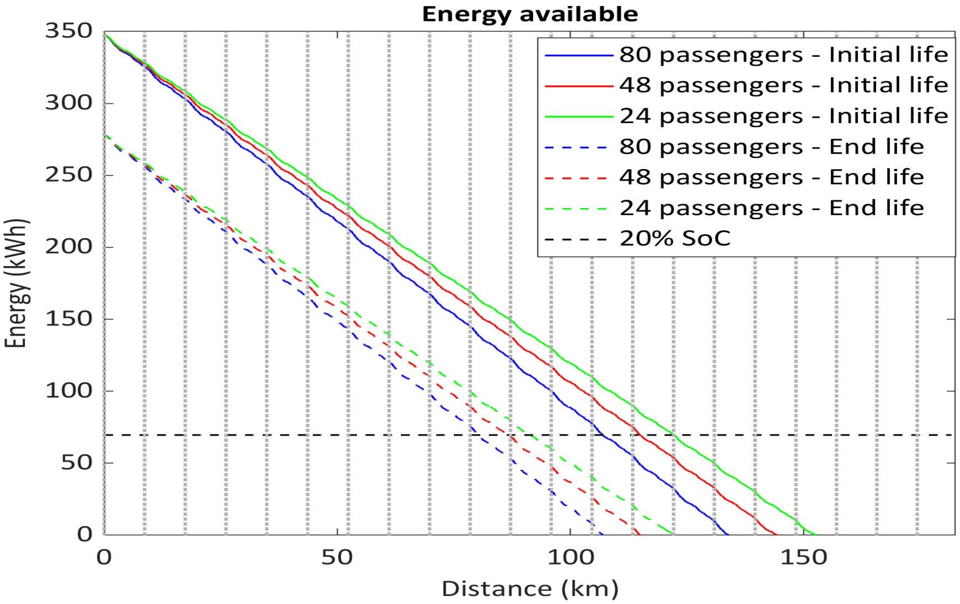
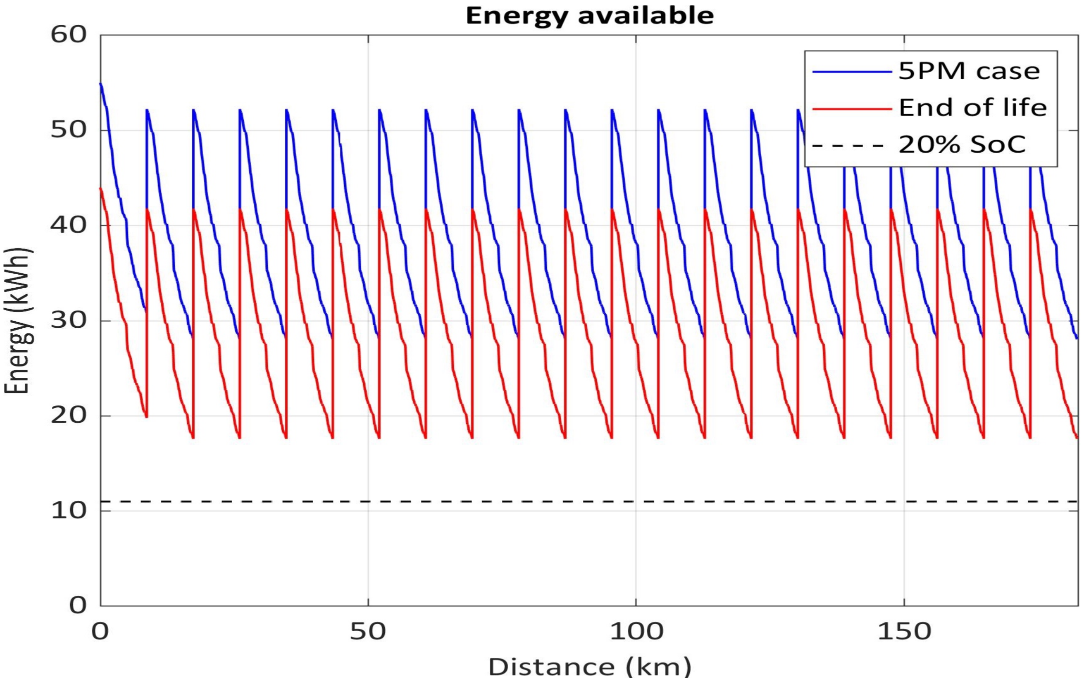


Figure 27. Energy consumption throughout the day (opportunity charge bus).



Route C938

The route C938 is a circular route with 20.7 km length, and a topographical profile shown in Figure 28 (a). The average velocity for the driving cycles selected is shown in Figure 28 (b), following the expected tendency, where the 5 AM case is the fastest and the 5 PM the slowest. Figure 29 shows the map of the route, obtained from LOGIOS's technical analysis platform.

Figure 28. Topographical profile and average velocity of the Route C938.

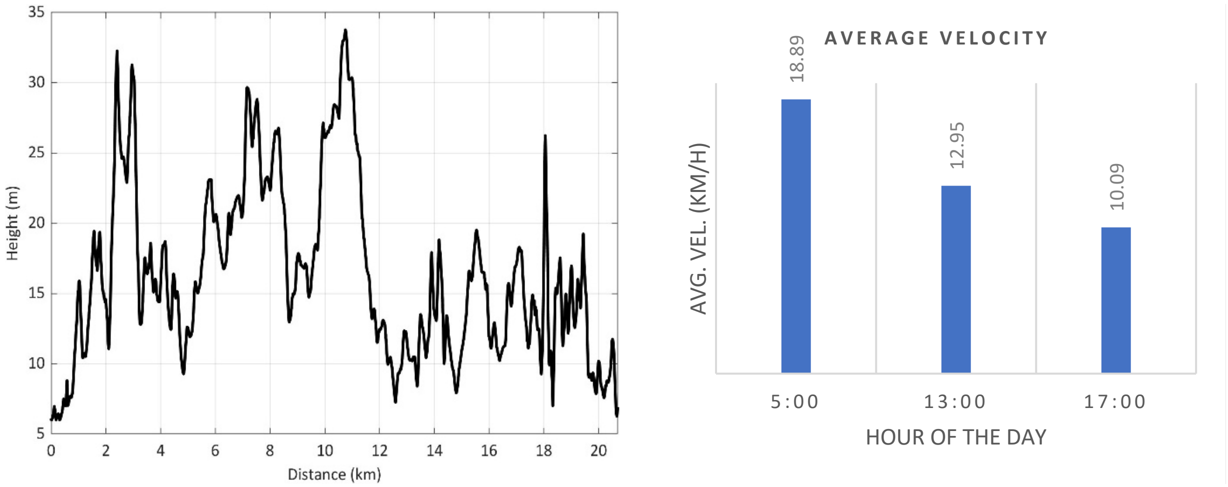


Figure 30 shows the velocity profiles of each case, where the 5 AM case is the one with the more aggressive acceleration to higher velocities. Furthermore, the number of stops during the day is not that different as in other routes. This has an impact on energy consumption, and it can be observed in the gray bars presented in Figure 32, where the 5 AM case has the highest traction consumption.

Figure 29. Map of route C938

Figure 31 shows the energy consumption of both buses, which shows higher efficiency in the opportunity charge bus, as expected. The energy consumption in the 5 AM and 1 PM cases is quite similar. In Figure 32, the gray bars show that the 5 AM case has the highest traction consumption and the lowest impact of the HVAC. On the other hand, the traffic congestion affects more the 1 PM and 5 PM cases, and the total energy consumption is higher due to the HVAC consumption.

Figure 30. Velocity profiles for the three cases selected.

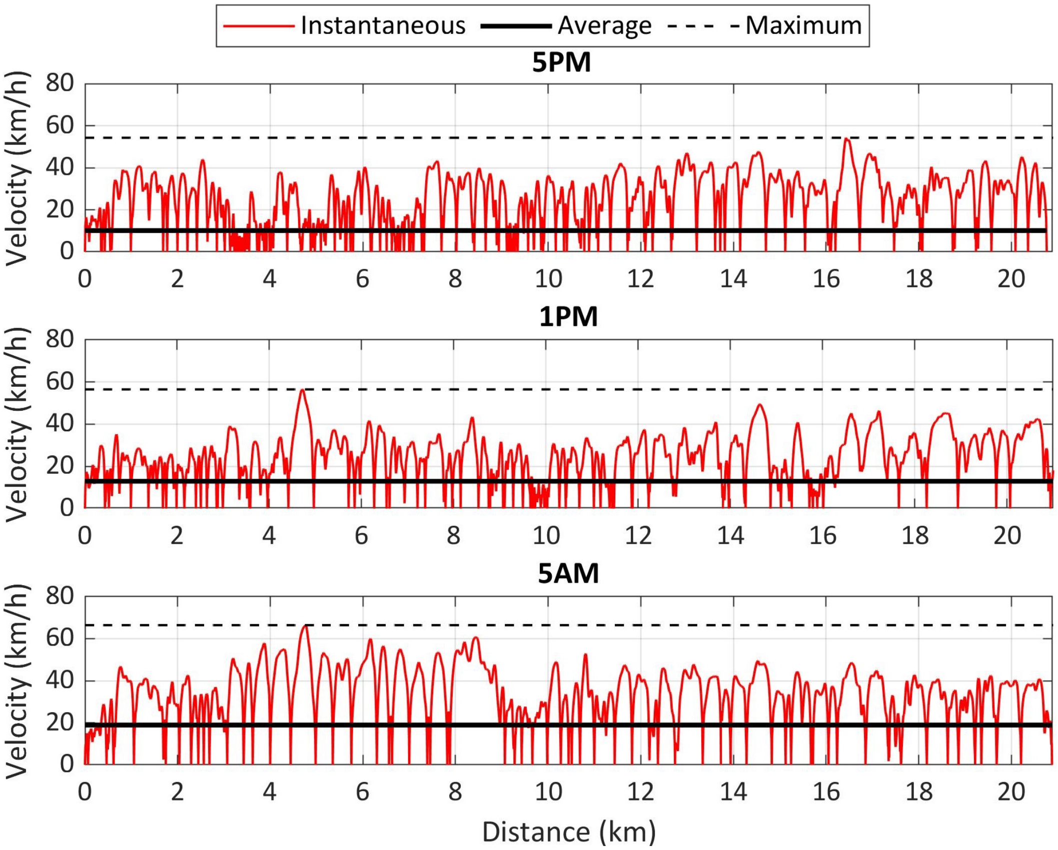


Figure 31. Energy consumption comparison. Overnight charge bus vs Opportunity charge bus.

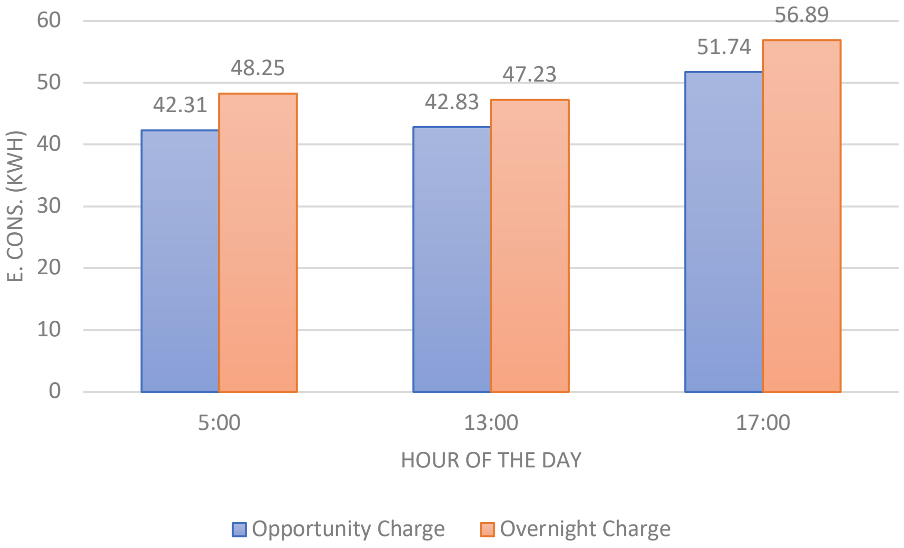
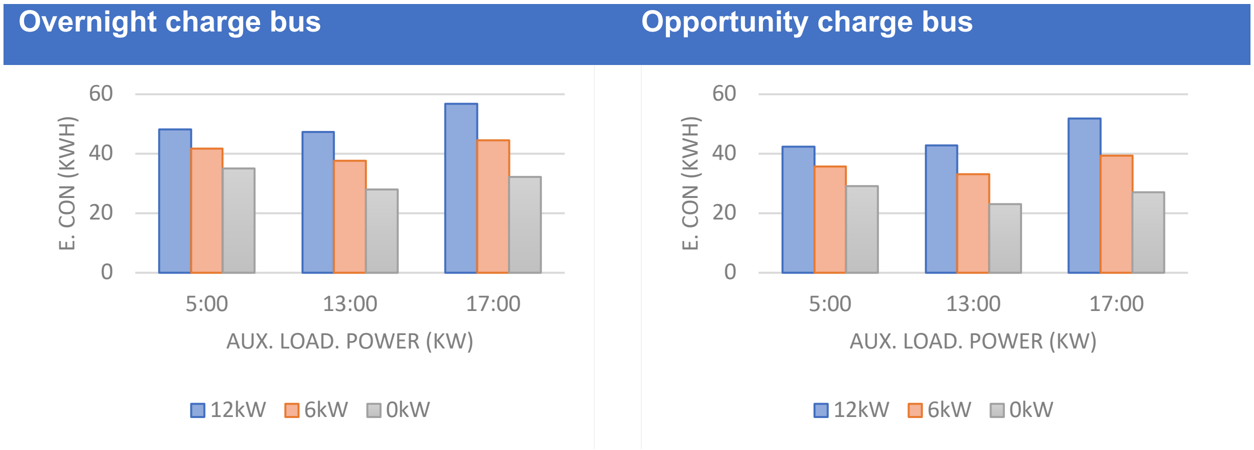
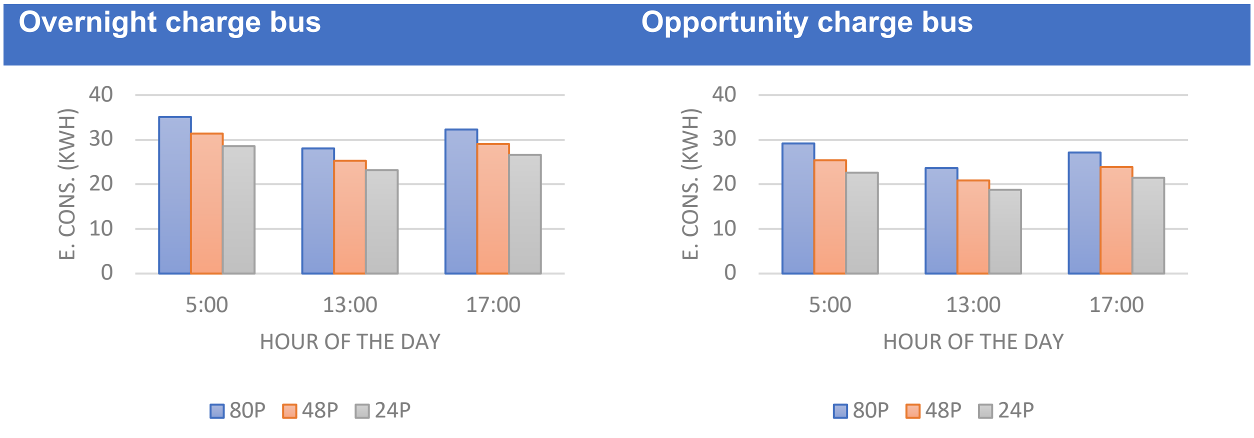


Figure 32. HVAC effect on energy consumption.



The passenger occupation effect on traction consumption is shown in Figure 33. Passenger loads of 100%, 60%, and 30% of the total passenger capacity were considered assuming an average passenger weight of 75 kg. Moreover, to show the passenger effect, it was assumed that the HVAC was Off. In this route, the impact of the passenger demand is similar to the previous cases, increasing the traction consumption around 27% when the passenger demand increases from 30% to 100%. LOGIOS is aware of the impact that passenger occupation will have on the HVAC consumption, but this effect was not included in the modeling, to avoid excessive complexity.

Figure 33. Passenger occupation effect on energy consumption.



For this route, the 1 PM case will be considered as a representative case for the overnight charge bus and the 1 PM case will be considered for the opportunity charge bus. A summary of the results obtained is presented in Table 6. Three scenarios are considered for the overnight charge bus, showing the effect of passenger occupation in the bus (80, 48, and 24 passengers).

Table 6. Performance summary

Test		Energy (kWh)	Avg. Vel. (km/h)	Efficiency (kWh/km)	Range (km)	
					Initial	End of life
Opportunity charge bus	Worst case scenario	42.83	12.95	2.07	21	16
Overnight charge bus	1 PM - 80 P scenario	47.23	12.95	2.28	122	91
	1 PM - 48 P scenario	44.46	12.95	2.15	129	97
	1 PM - 24 P scenario	42.37	12.95	2.05	136	102

The estimated range for the overnight charge bus goes from 122 km to 136 km (depending on the passenger demand), and the bus would complete between 5 and 6 consecutive cycles before reaching 20% of the SoC of the battery. Furthermore, the bus range will decrease around 35 km by the end of the battery's life cycle, which means that the bus could complete 5 consecutive cycles in this route, which will be enough to directly replace some of the diesel buses, only if the electric buses are used exclusively in this route and not repurposed to serve other routes at different times in the day.

Figure 34 shows the cycles that bus 4DP008U would perform in a day of operation, according to the mileage per day reported by MiBus. The overnight charge bus could cover the expected daily range for the current buses, which is around 82.8 km or 4 cycles.

On the other hand, the worst-case scenario for the opportunity charge will be the 1 PM case. This is due to the large impact that the traffic has on the 5 PM case. Therefore, the estimated range for this bus would be 21 km before the SoC reaches 20%. Even so, the DoD is at the limit, and the battery will always be discharged below 20% of the SoC, which will affect its lifecycle. Furthermore, by the end of the battery's lifetime, this bus could not complete this route in every cycle of the day. Figure 35 shows the discharging-charging events of bus 4DP008U, which should complete 4 cycles per day. Initial and end of life operation are presented to observe the differences in the DoD. To use an opportunity charging bus in this route, the capacity of the battery should be increased, and the traffic issue should be improved. Another consideration could be having an extra charging point in the middle of the route. This extra charging point should be optimally located considering other lines that can be electrified using the same charging point, as will be discussed in Section 3.

Figure 34. Energy consumption throughout the day (overnight charge bus).

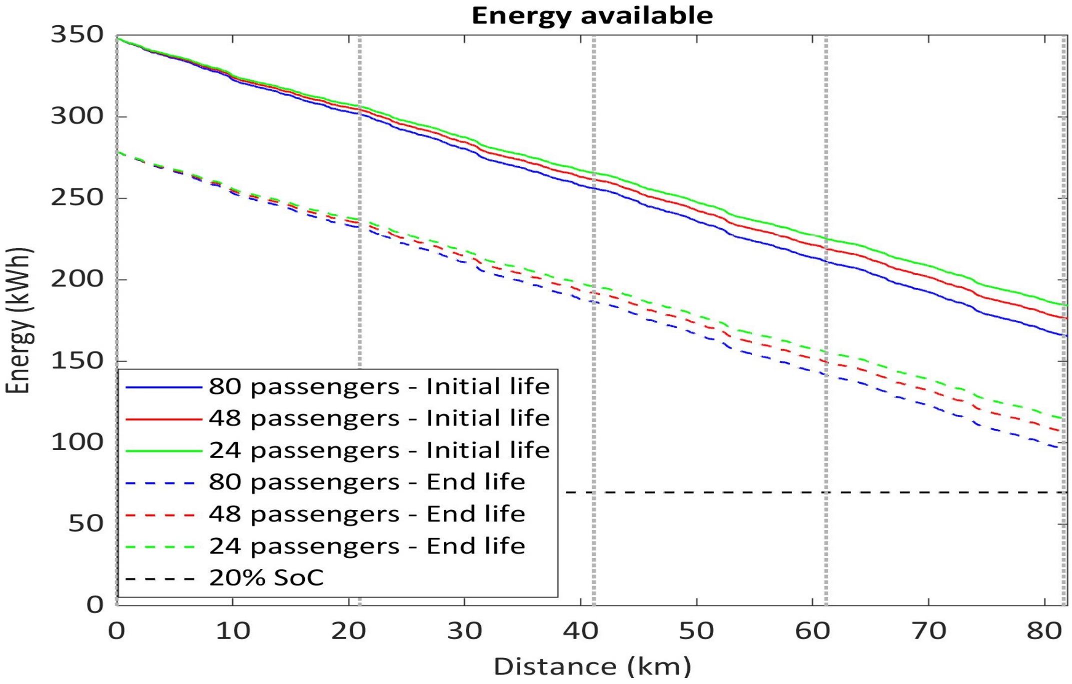
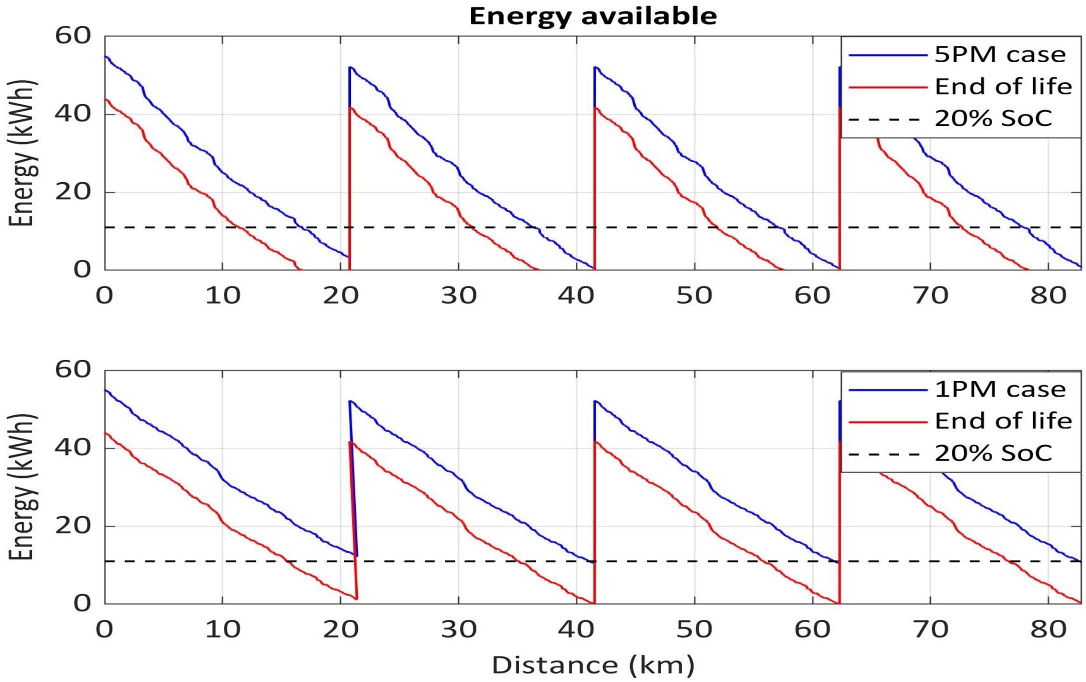


Figure 35. Energy consumption throughout the day (opportunity charge bus).



Route C968

The route C968 is a circular route, with 6 km length, and a topographical profile shown in Figure 36 (a). The average velocity for the driving cycles selected are also shown in Figure 36 (b). The tendency of the average velocity is similar, with an important difference between the 5 AM and 5 PM cases. Furthermore, the numbers in the average velocity seem a bit low compared with the previous routes. These low velocities can be explained when the time evolution of velocity is examined, see Figure 39.

Figure 37 shows the map of the route obtained from LOGIOS's technical analysis platform.

Figure 38 shows the velocity evolution with respect to the distance, which shows the 1 PM as the more aggressive case. This will have an impact in the traction consumption. Furthermore, the buses in this route make an unusual stop around kilometer 3. This behavior is shown in Figure 39, and the stop window referred here is highlighted in blue for each case. Moreover, the stop time window is different for each of the cases investigated, making it difficult to predict the effect of this stop in energy consumption. Also, it is important to know what the HVAC and other auxiliaries' consumption during these long stops is.

Figure 36. Topographical profile and average velocity of the Route C968

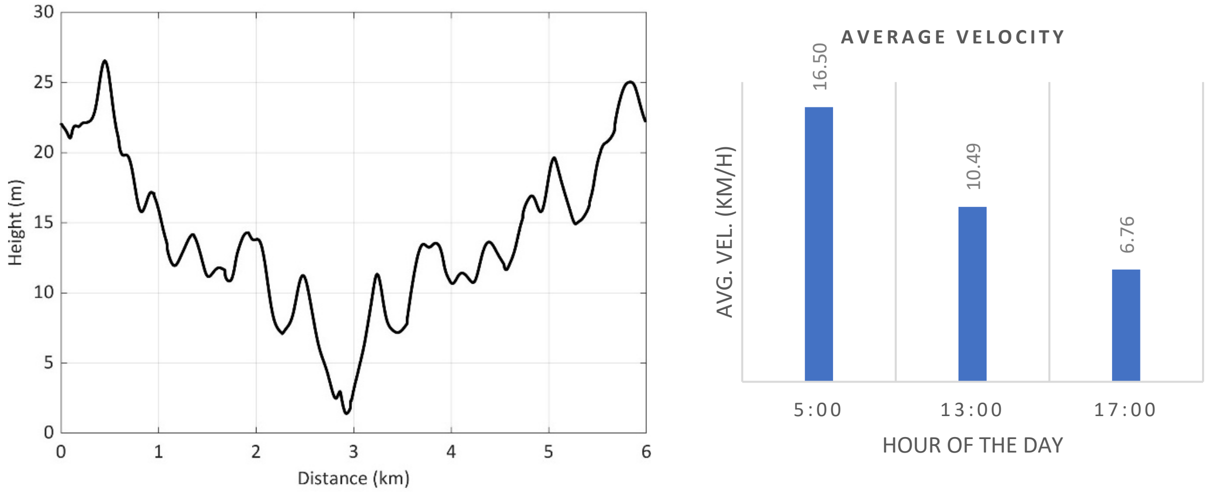


Figure 37. Map of route C968

Figure 38. Velocity profiles for the three cases selected.

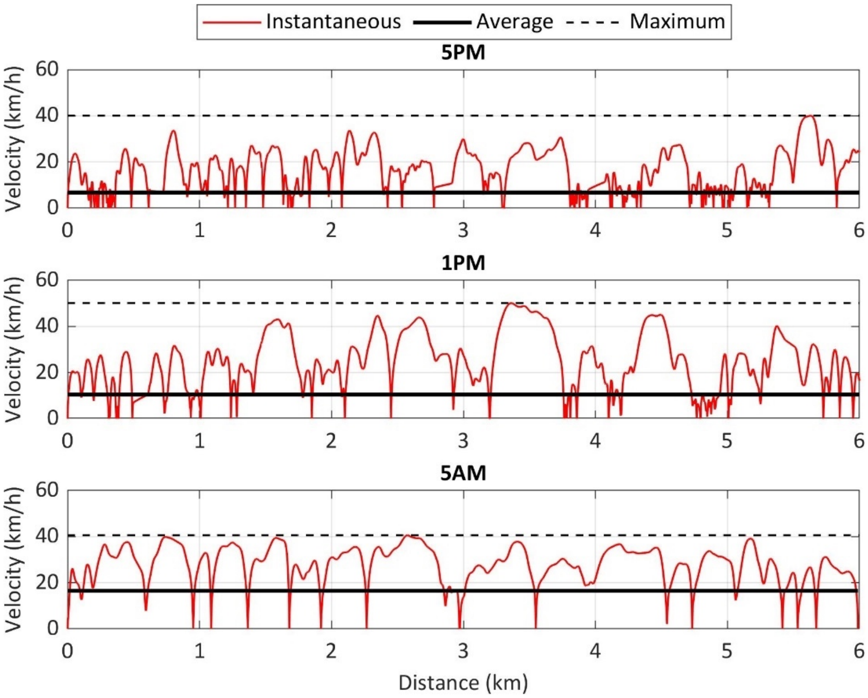


Figure 39. Velocity evolution in time for the three cases selected.

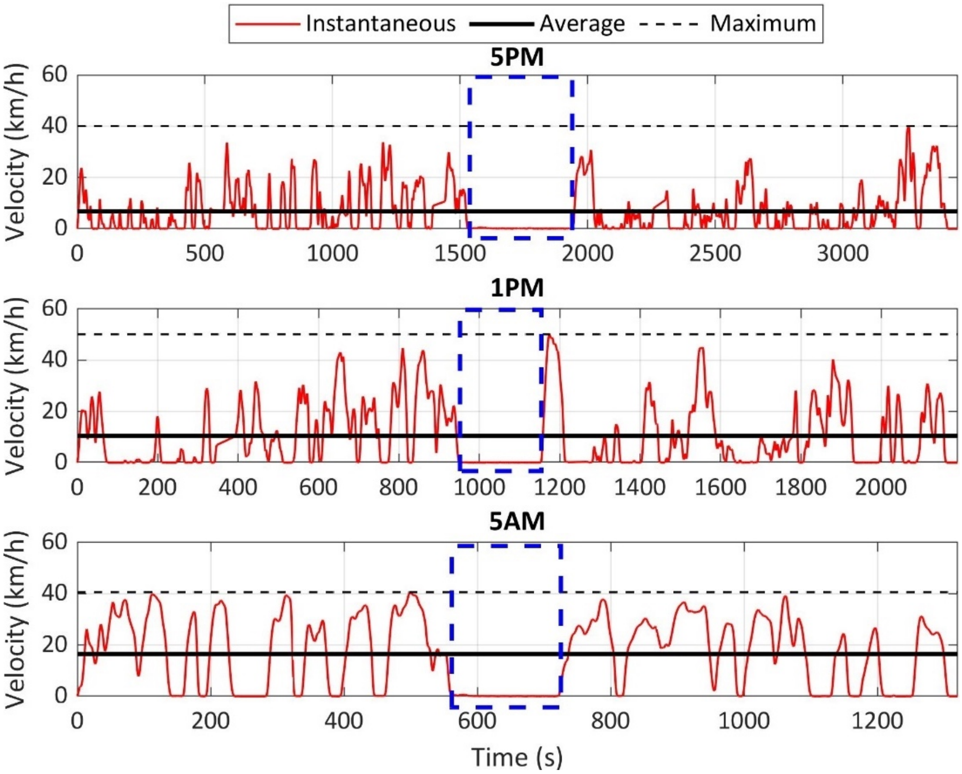


Figure 40 shows the energy consumption of both buses, which shows higher efficiency in the opportunity charge bus, as expected. Also, the worst-case scenario is the 5 PM case, and the average consumption is close the 1 PM case. Figure 41 shows the effect of the HVAC on energy consumption. As expected, the HVAC has a higher effect in the 5PM case, increasing from 70% to 150% the energy consumption with respect to the traction consumption. This high impact on the consumption could be reduced if the HVAC is handled differently when the bus stops for long periods of time as the one highlighted in Figure 39.

Figure 40. Energy consumption comparison. Overnight charge bus vs Opportunity charge bus.

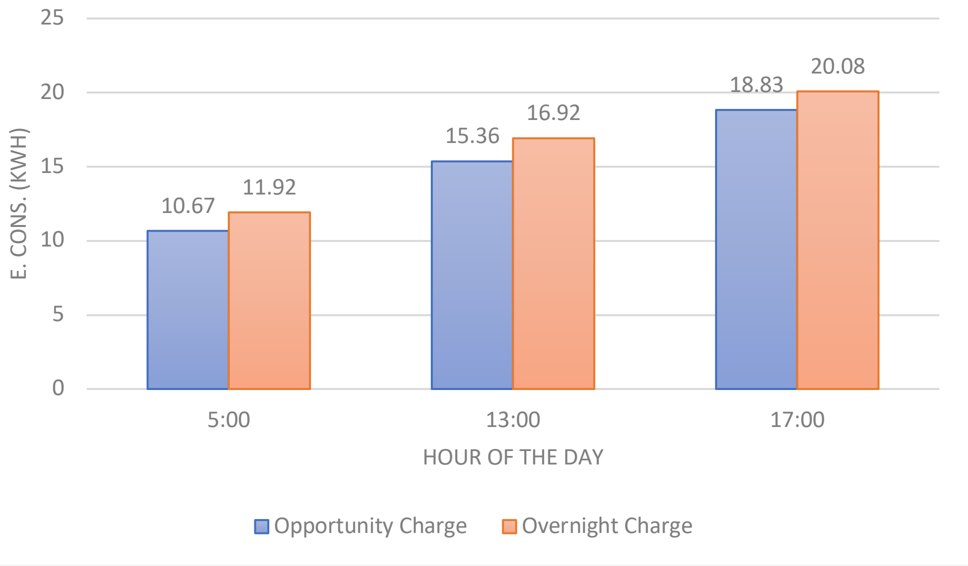
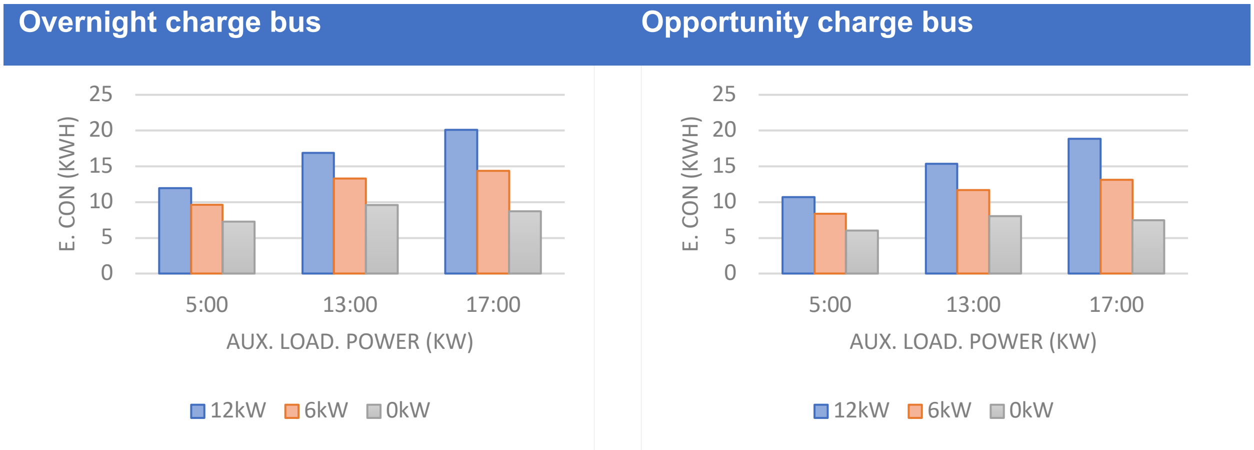


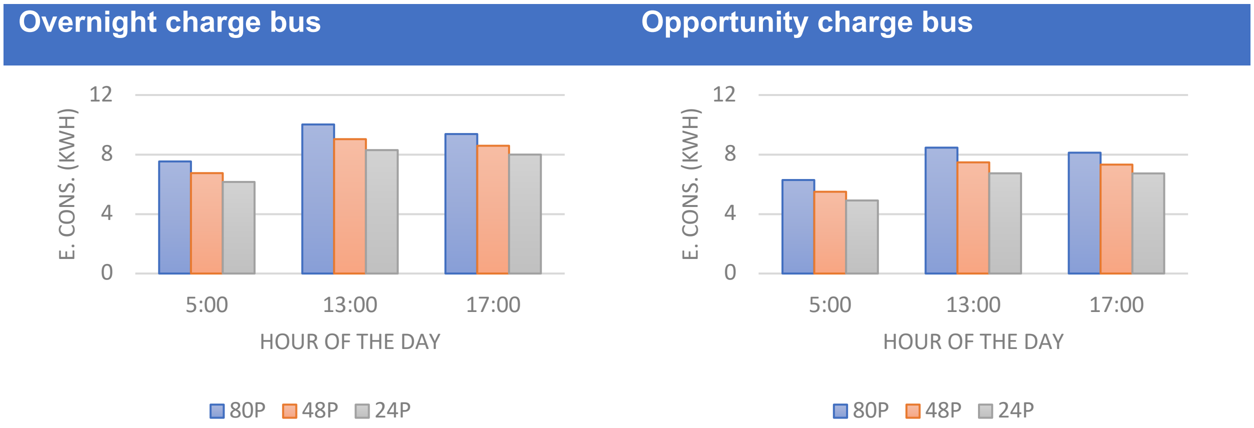
Figure 41. HVAC effect on energy consumption.


Overnight charge bus

Opportunity charge bus

The passenger occupation effect on traction consumption is shown in Figure 42. Passenger loads of 100%, 60%, and 30% of the total passenger capacity were considered assuming an average passenger weight of 75 kg. The impact in this route is similar, increasing around 25% of the traction consumption when the passenger demand rises from 30% to 100%. Moreover, to show the passenger effect, it was assumed that the HVAC was Off. LOGIOS is aware of the impact that passenger occupation will have on the HVAC consumption, but this effect was not included in the modeling, to avoid excessive complexity.

Figure 42. Passenger occupation effect on energy consumption.



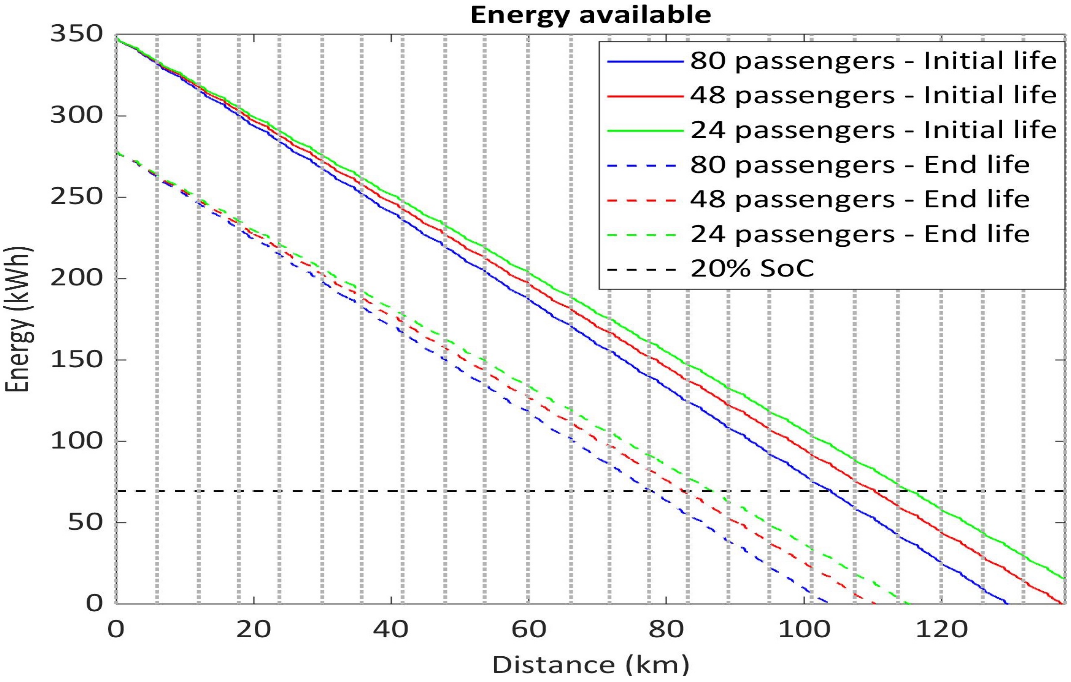
For this route, the 1 PM case will be considered as a representative case for the overnight charge bus and the 5 PM case will be considered for the opportunity charge bus. A summary of the results obtained is presented in Table 7. Three scenarios are considered for the overnight charge bus, showing the effect of passenger occupation in the bus (80, 48, and 24 passengers).

Table 7. Performance summary.

Test		Energy (kWh)	Avg. Vel. (km/h)	Efficiency (kWh/km)	Range (km)	
					Initial	End of life
Opportunity charge bus	Worst case scenario	18.83	6.76	3.12	14	10
Overnight charge bus	1 PM - 80 P scenario	16.92	10.49	2.81	99	74
	1 PM - 48 P scenario	15.93	10.49	2.64	105	79
	1 PM - 24 P scenario	15.19	10.49	2.52	110	82

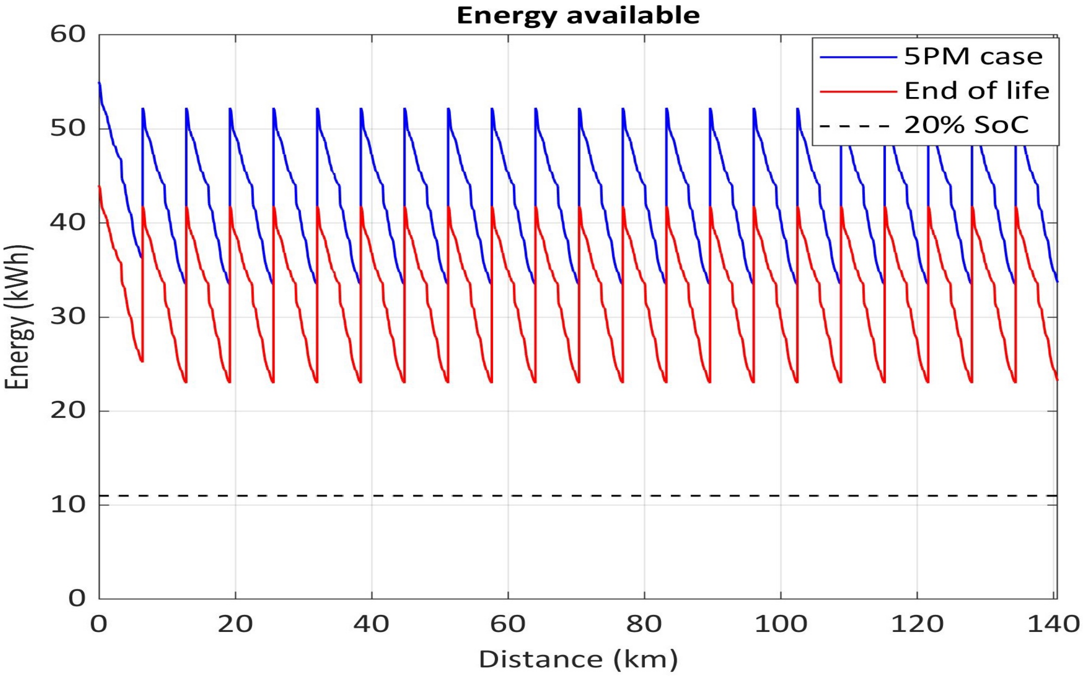
The estimated range for the overnight charge bus goes from 99 km to 110 km, and the bus could complete up to 16 consecutive cycles before reaching 20% of the SoC of the battery. Furthermore, the bus range will decrease to 74-82 km by the end of the battery's life cycle, which means that the bus could complete up to 13 consecutive cycles in this route. Figure 43 shows the current cycles that bus 0MY001H currently performs in a day of operation, which could not be completed by the overnight charge bus considered here. Moreover, the current operation of bus 0MY004H requires a range of operation of 102 km, which is close to the case presented here. Perhaps, an improvement in the HVAC consumption, especially during this unusual stop highlighted in Figure 39, will have a positive impact on the performance of the bus, and make it feasible to replace the buses in this route.

Figure 43. Energy consumption throughout the day (overnight charge bus).



On the other hand, the estimated range of operation of the opportunity charge bus is 14 km before the SoC reaches 20%. Therefore, this bus could complete two consecutive cycles for this route. If the HVAC is used in a more efficiently when the bus stops for a long time, the range of operation could be improved. Also, if traffic congestion is reduced, the range could increase to similar values as the 1 PM case (17 km). Furthermore, by the end of the battery's lifetime, the range of operation is reduced to 10 km, allowing only one cycle per charge. Moreover, a small improvement in the operation time for the worst-case scenario would permit the bus to complete two consecutive cycles. It should be remarked that this scenario would allow MiBus to have some flexibility programming the charging events during the day of operation. Figure 44 shows the discharging-charging events of bus 0MY001H completing 23 cycles in the worst-case scenario. Initial and end of life operation are presented to observe the differences in the DoD.

Figure 44. Energy consumption throughout the day (opportunity charge bus).



Route E489 - I & R

The route E489 is a Go (I) and Return (R) route, with a total length of 12.1 km (5.7 km going + 6.4 km returning), and a topographical profile shown in Figure 45 for both Go and Return paths. The average velocity for the driving cycles selected is shown in Figure 46. For the Go-path, the average velocities do not follow the usual tendency as in the other routes assessed in this report. The main difference is that the 1 PM case is the fastest. However, in the Return-path this behavior changes, and the 5 AM case is the fastest. This has an impact on traction consumption when the three cases as analyzed. Furthermore, the Return-path seems to be more affected by traffic congestion, and the average velocities are lower than in the Go-path.

Figure 45. Topographical profile of the route E489, Go and Return tracks.

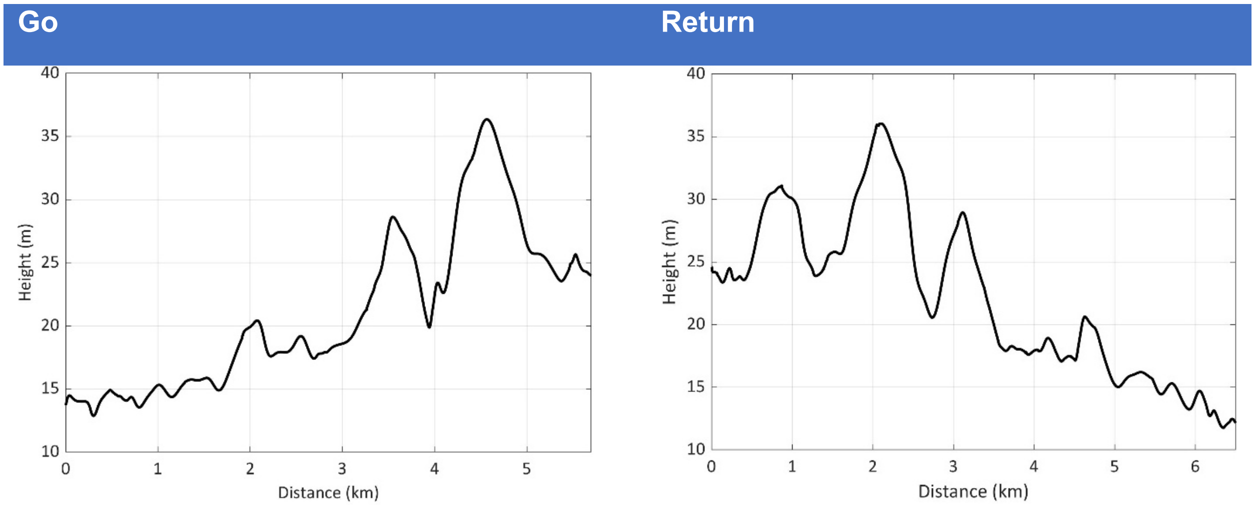


Figure 46. Average velocities of the route E489, Go and Return tracks.

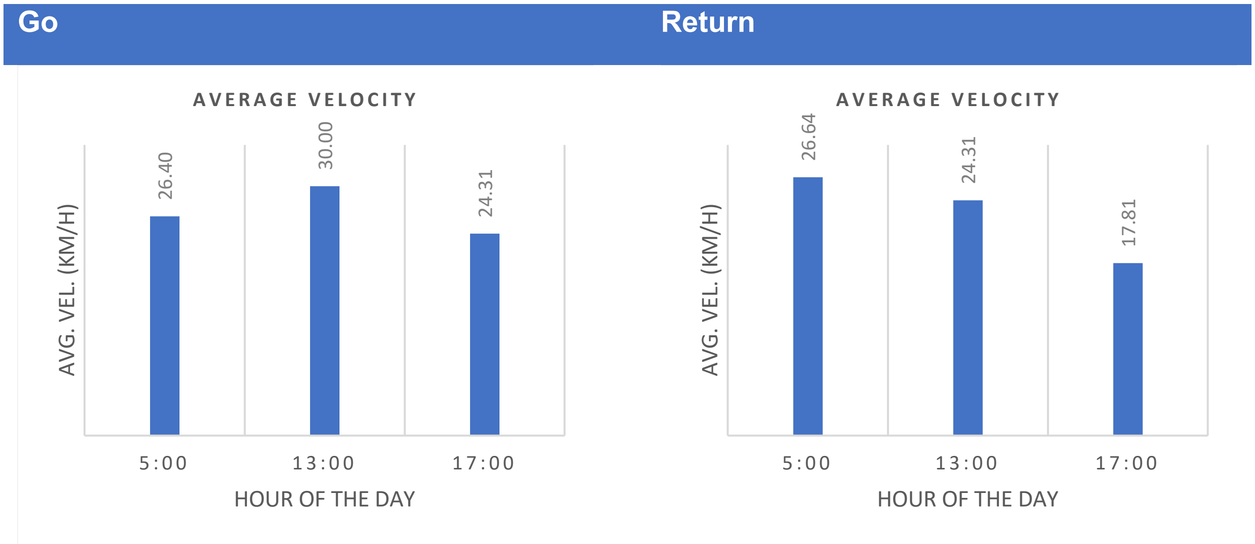
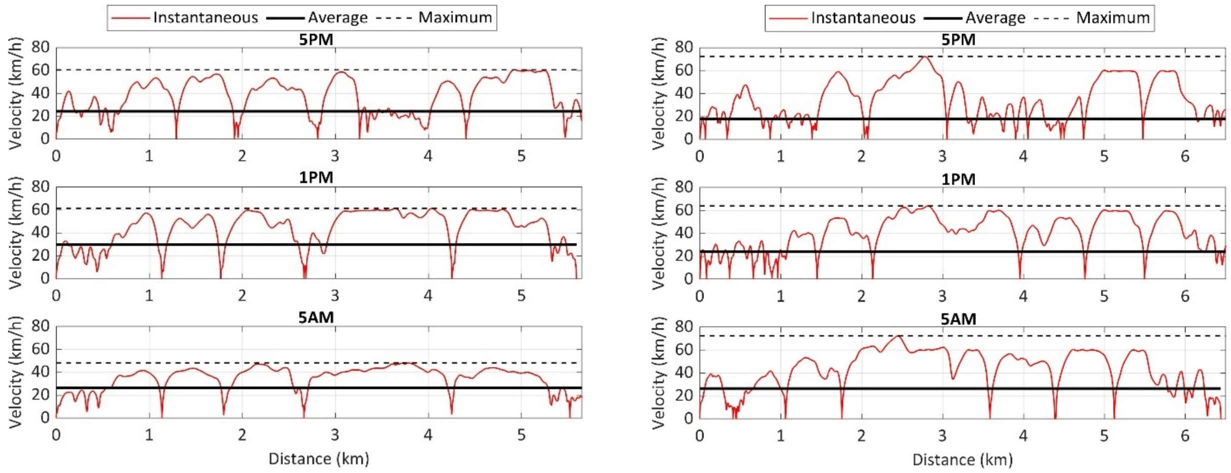


Figure 47 show the velocity evolution with respect to distance. The maximum velocities reached in the Return-path are always higher. This has an impact on the traction consumption, which is more evident in the 5 AM case, where the Return-path consumption is around 50% higher than the Go-path. This, once again, remarks on the effect of the driving behavior on energy consumption, and the importance of having smoother driving cycles that allow predicting better the energy consumption per cycle.

Figure 47. Velocity profiles for the three cases selected.


Go

Return

Figure 48 shows the energy consumption of the buses, which shows higher efficiency in the opportunity charge bus, both for the Go and Return-path. In the Go-path, the driving behavior are softer in the 5 AM case, which makes the traction consumption considerably higher in the 1 PM and 5 PM cases (45% to 60%). On the other hand, in the Return-path, the driving behavior are not so different for the three cases analyzed, and the traction consumption variation is around 10% with respect to the higher values.

Figure 49 and

Figure 50 show the effect of the HVAC. The impact is higher in the Return-path, and the 5 PM case is the more affected one, increasing around 3.8 kWh. In the Go-path, the effect of the HVAC is lower, and the incremental energy is around 2 kWh for each case.

Figure 48. Energy consumption comparison. Overnight charge bus vs Opportunity charge bus.

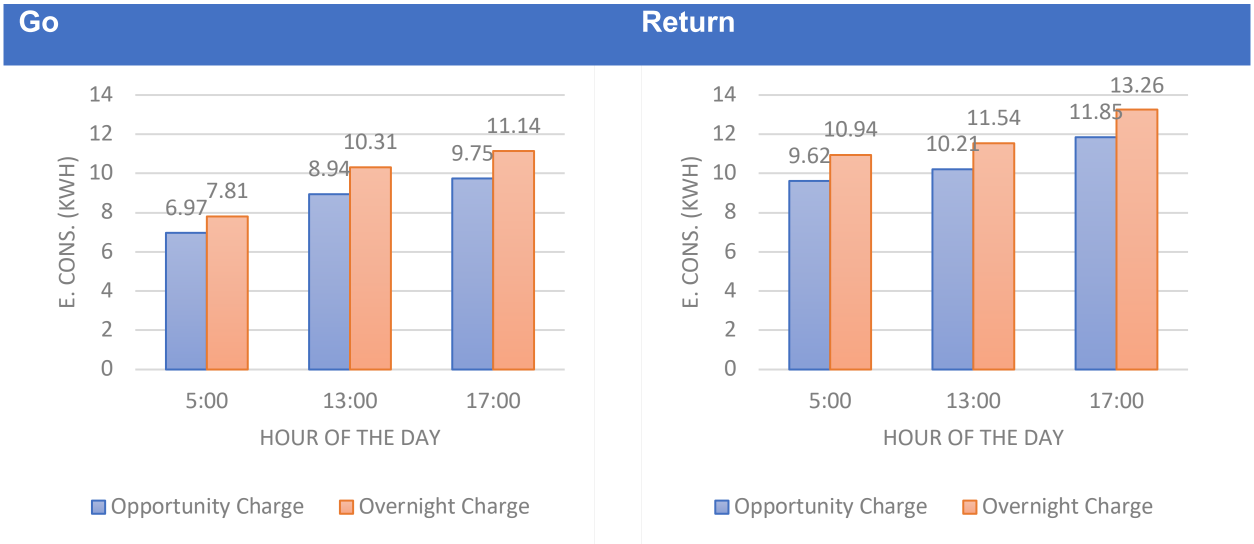


Figure 49. HVAC effect on energy consumption (GO).

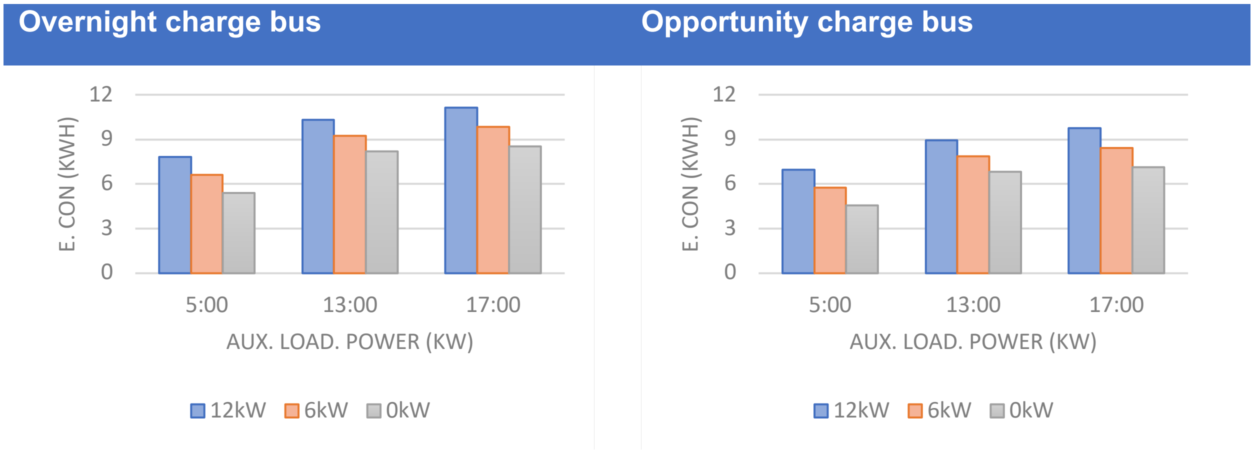
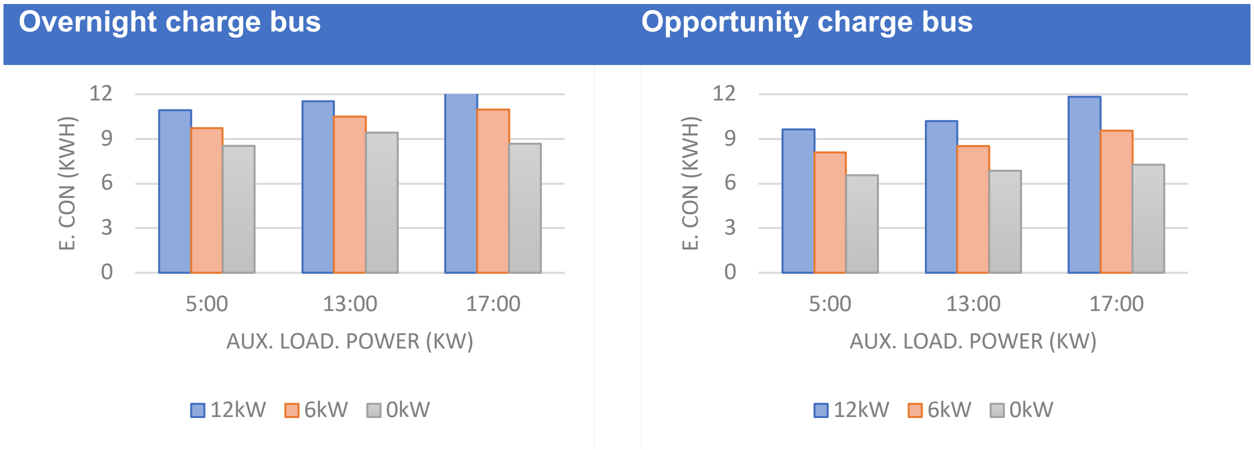


Figure 50. HVAC effect on energy consumption (RETURN).


Overnight charge bus

Opportunity charge bus

The passenger occupation effect on traction consumption is shown in Figure 51 and

Figure 52. Passenger loads of 100%, 60%, and 30% of the total passenger capacity were considered assuming an average passenger weight of 75 kg. Moreover, to show the passenger effect, it was assumed that the HVAC was Off. LOGIOS is aware of the impact that passenger occupation will have on the HVAC consumption, but this effect was not included in the modeling, to avoid excessive complexity.

Figure 51. Passenger occupation effect on energy consumption (GO).

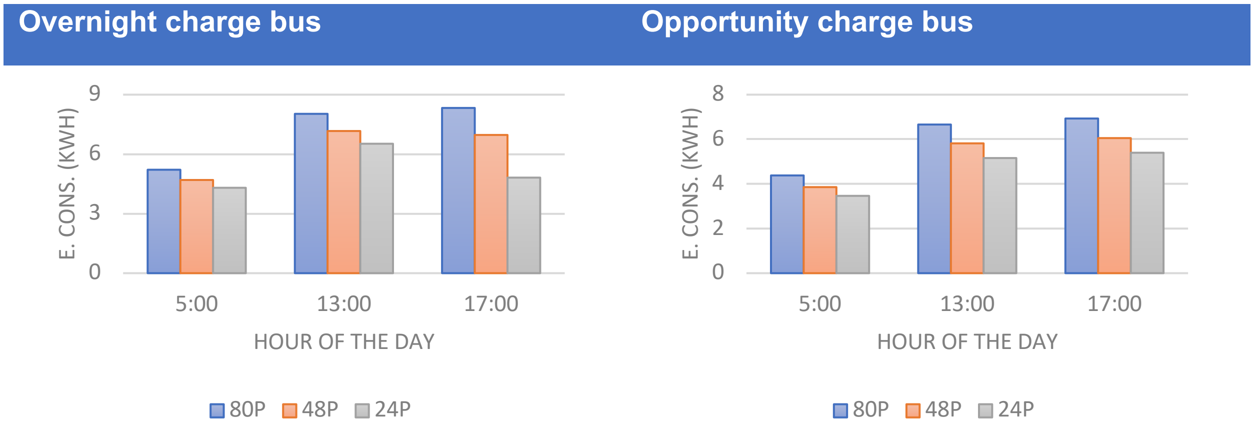
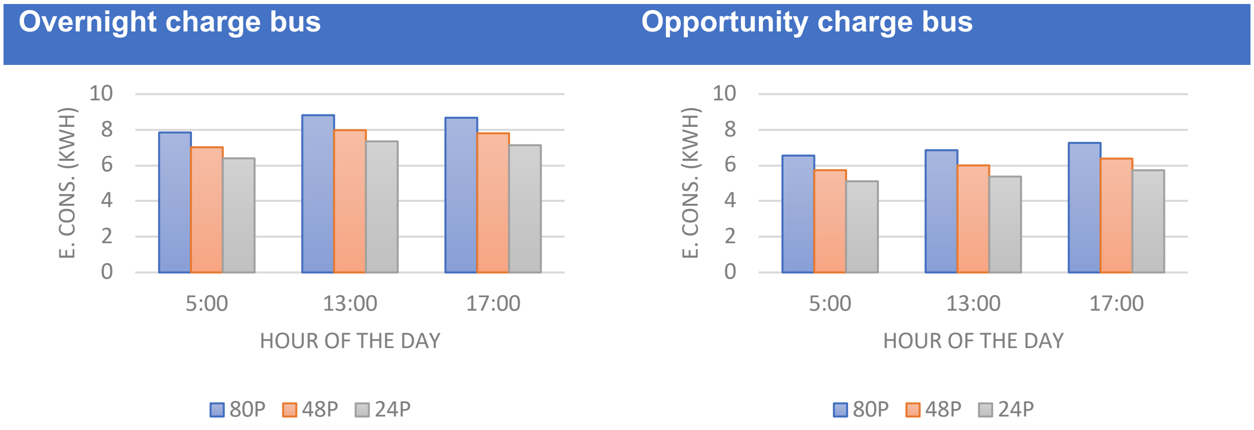


Figure 52. Passenger occupation effect on energy consumption (RETURN).



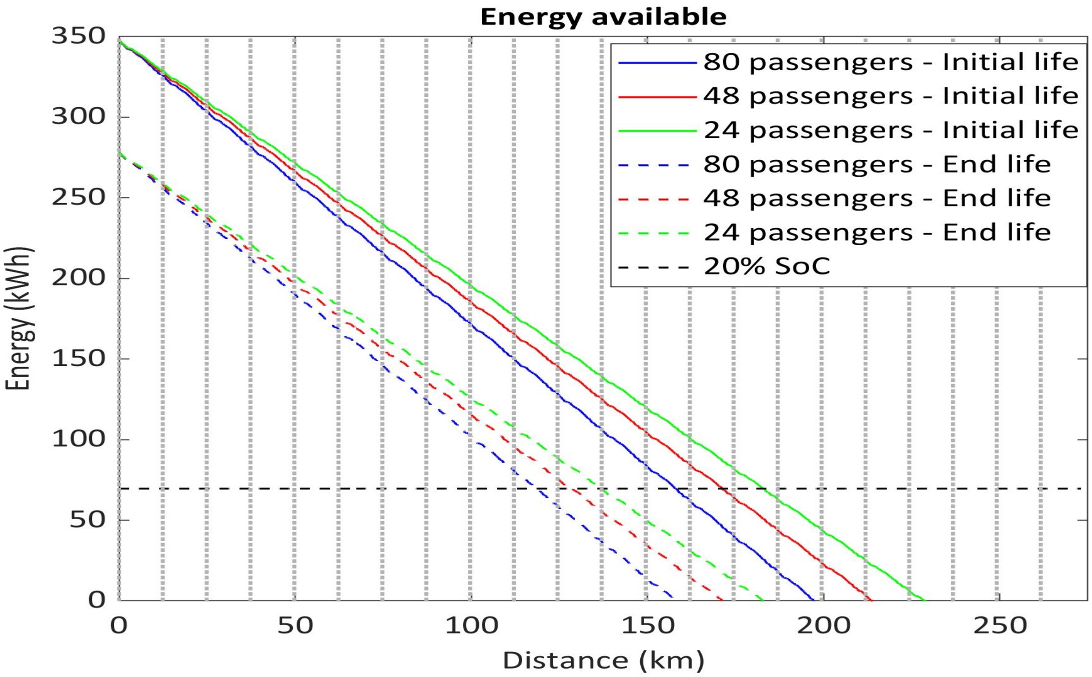
For both paths, Go and Return, the 1 PM case will be considered as a representative case for the overnight charge bus, and the 5 PM case will be considered for the opportunity charge bus. A summary of the results obtained is presented in Table 8.

Table 8. Performance summary.

Test		Energy (kWh) Go + Return	Efficiency (kWh/km)	Range (km)	
				Initial	End of life
Opportunity charge bus	Worst case scenario	21.59	1.73	25	19
Overnight charge bus	1 PM - 80 P scenario	20.48	1.64	169	127
	1 PM - 48 P scenario	18.80	1.50	185	138
	1 PM - 24 P scenario	17.51	1.40	198	149

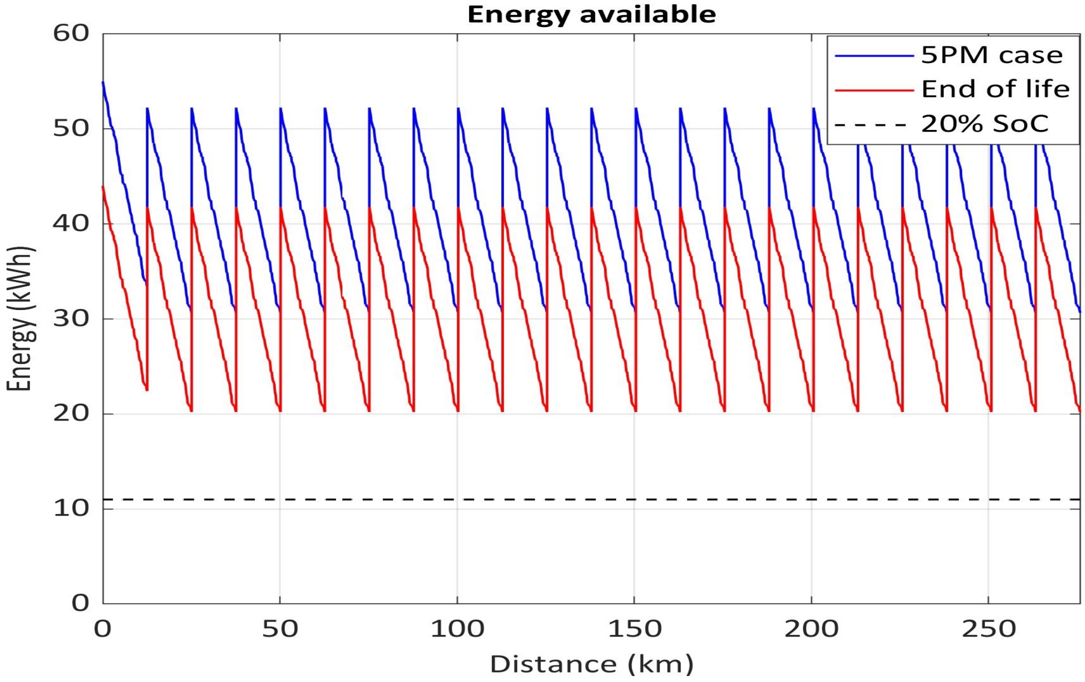
The estimated range of the overnight charge bus goes from 169 km to 198 km, and the bus would complete between 13 to 16 consecutive cycles (Go + Return) before reaching 20% of the SoC of the battery. Furthermore, the bus will lose around 45 km of its range by the end of the battery's life cycle, which means that the bus could complete around 9 to 12 consecutive cycles in this route (depending on the passenger demand). Figure 53 shows the cycles that the bus 0S2003D currently performs in a day of operation. The overnight charge bus considered here cannot cover the expected daily range for the current buses used in this route, except for the bus 0S2004D, which covers 8 complete cycles (Go + Return).

Figure 53. Energy consumption throughout the day (overnight charge bus).



The estimated range of operation of the opportunity charging bus is 25 km before the SoC reaches 20%. Therefore, this bus could complete two cycles (Go + Return) for this route. Furthermore, the end of life range decreases to 19 km, allowing just one complete cycle in the worst-case scenario. This means that in more optimistic scenarios such as the 5 AM, this bus could offer more flexibility, even by the end of the battery cycle life. Figure 54 shows the discharging-charging events of bus 0S2003D, which currently completes 22 cycles per day (Go + Return). Initial and end of life operation are presented to observe the differences in the DoD.

Figure 54. Energy consumption throughout the day (Opportunity charge bus).



2.3 Energy consumption conclusions

LOGIOS modeling and simulation software was used to assess the performance of two electric buses with different charging technologies. The buses considered are representative of commercially available buses, one that can operate with an overnight charging method, and another that can operate with an opportunity charging method. The most noticeable differences between the buses and charging methods were highlighted, showing the suitability of each technological option for each route, based on the current operation information provided by MiBus.

The analysis of the seven routes confirms and quantifies the high impact that the driving behavior/conditions have on traction consumption. Conditions with rapid accelerations translate into higher energy consumption, and possibly into lower performance. Energy consumption is also affected by traffic conditions in Panama City. It is observed that average velocities drop considerably at certain hours during the day and that such drop varies across routes. Three scenarios were created for the operation of the HVAC system, defined as high, medium, and none. The load from the HVAC system can be considerable, depending on a complex interaction between ambient temperature and other factors. This load can have a great impact on per-kilometer energy consumption when velocity is low. It is found that reductions in average velocity translate into 50% to 105% increments in energy consumption in some of the routes.

It is not realistic to expect the technology to perform efficiently and demonstrate viability under all and any operational conditions. Thus, the preceding discussion points to action areas for Panama, namely:

a. For MiBus, the education and training of drivers, to foster awareness about their role in the decarbonization of the transport system, and
b. For the municipal and national governments, the implementation of regulations and measures to improve driving conditions along bus routes.

Not only could these steps increase the viability of electric buses for more routes, but they would also reduce the amount of capital needed for fleet transformation.

Finally, passenger demand is an important variable that affects both traction and HVAC consumption. The impact of passenger load on HVAC load was not included in the model, to avoid excessive complexity. While bigger numbers of passengers will increase traction consumption, it is observed that increases in passenger capacity from 30% to 100% leads to traction consumption increments in the order of 20% to 25%. This suggests that energy consumption is more sensitive to HVAC load than to passenger load. This is a positive result because one of the metrics of the success of fleet electrification programs should be that ridership increases. Success looks like a fleet of electric buses that displace emissions from fossil fuels both by switching to zero emission technologies and by inducing travelers to switch modes from the automobile to public transportation.

3. Discussion of charging strategies

A charging strategy can be defined as the set of integrated practices adopted in order to supply electrical energy to the buses. The selection of a charging strategy involves the optimization of this set of practices, with a given set of economic and social objectives in mind. In the definition of a charging strategy, LOGIOS considers the following key practices:

- The charging method

- The rating of the charging equipment
- The location of the charging assets
- The timing of charging events
- The duration of charging events
- The power demand of charging events
- The scalability of the charging solution
- The rate of utilization of the charging assets

The next two subsections are concerned with the discussion of charging strategies, both for overnight charging and opportunity charging, in the context of the routes selected by MiBus in Panama City.

3.1 Overnight charging strategy

The planning of the charging events in the overnight charging strategy is usually straightforward. The buses are charged outside of service hours, typically during the night. The operator needs to allocate a certain time for the charging of these units, which will be determined based on the following:

- The rate at which the equipment can supply energy to the bus. This, in turn, predominantly depends on:
    - The rated power of the charging equipment;
    - The maximum current recommended by the battery supplier (to manage cell temperature and preserve battery life)
    - The gradual reduction in (tapering) of charging current, which depends on the instantaneous state of charge, and on the particular battery technology,
- The state of charge of the battery when the bus arrives at the charging site, and
- The capacity of the battery, which will decrease as the battery ages.

The charging schedules for overnight charging buses are not very flexible, and this can impose tighter constraints on vehicle range. For this reason, careful planning is needed so that the onboard energy storage system, accounting for battery degradation, is adequately tailored to the energy requirements of the particular route. This makes the direct, 1-to-1, replacement of conventional buses with overnight charging buses more difficult and, in general, a riskier investment. For instance, the analysis shows that, assuming that the buses are used exclusively in the analyzed routes (and not repurposed to serve other routes at different times in the day), some of the diesel buses serving routes C888, C938, and E489 could be replaced with overnight charge buses. It was also found that the overnight bus may be able to meet the current requirements of route C968, though only if the average power consumption of the HVAC system is kept under 6 kW and average passenger demand is under 60%.

Certainly, for buses whose daily distance is longer than the range of the overnight charge electric bus, investors have the option to procure bus models with longer ranges, which most likely involve bigger batteries. It should be pointed out, however, that the marginal increase in route length that can be served by adding one unit of battery capacity is significantly lower for overnight buses than for overhead charge buses.

Though not recommended, another strategy to cope with the challenges above described may be, in some cases, to integrate charging events during the day. Routes are served by a number of bus units during the day, although not all of them are operational at all times. Bus frequency is typically higher during peak hours, at which time all buses assigned to that route are required. During off-peak hours, bus units that are not needed for a particular route are either allocated to different route or sent to depot. A scenario is then conceivable, in which the electric bus is scheduled to operate only during peak hours and sent to charge during the period of lower demand between peaks. From an economic and financial standpoint, however, this type of scenario tends to be suboptimal, as it limits the capacity of the rolling asset to generate savings in operating costs. Furthermore, increasing the number of charging events per daily cycle of operation will negatively affect battery lifetime.

The sizing of charging infrastructure (number of pieces of equipment and their power rating) for overnight charging will depend directly on the number of electric buses stationed in a given depot, the time available for their charging, and the capacity of the distribution system at the site of the depot. Alternatively, the same decision problem can be framed in terms of the size of the fleet, as follows: the sizing of the electric bus fleet stationed in a depot will depend directly on ability to charge them within the time available, given constraints in the distribution system at the site.

The large power demand required at the depot to charge several buses simultaneously is the question that requires the most attention in the development of a charging strategy for overnight charging buses. It is critical to develop an energy supply plan that not only is economically viable but that is also scalable. Conversations with the electric utilities serving Panama City suggest that there should be no problems with access to power, even in depots located in the city.

The integration with the grid via demand response and auxiliary services is a critical element in an overnight charging strategy for the near term. This integration essentially involves the management of charging so that it reacts to price signals can create win-win situations for the bus operator, investors, and electric utility. A somewhat related question is that of the selection of the depot where these buses would be stationed. This choice can have implications on the price of electricity and impacts on the grid. This issue is discussed to some extent in a separate report.

3.2 Opportunity charging strategy

Bus fleet operators, and particularly their planning and operations divisions, are used to fleets with one single type of bus technology, that can be assigned to any one of the routes in their service. While this expectation is not appropriate for a fleet of electric buses, the technology solution that can closest meet it is the overhead (or opportunity) charge bus. This section discusses charging strategies for this type of electric bus.

The design of an opportunity charging strategy is an order of magnitude more complex than that for overnight charge buses. This complexity is however the key to unlock a host of potential efficiencies that may increase the bankability of the project or, alternatively, the return on the use of public money.

In the most basic form of an opportunity charging strategy, overhead charging infrastructure is installed at the one site along the route, and the bus charges for a few minutes every time it arrives at it, to then continue on to the next route cycle. This simple description includes several parameters that are, to varying degrees, under the control of the operator. The selection of these parameters, with the goal of maximizing the efficiency of the operation and, more broadly, the investment, constitutes the *charging strategy*. Each of these parameters are discussed separately next.

Onboard energy storage system: Investors cannot, unfortunately, specify the size of the battery for each bus in a procurement contract. They instead need to select from the menu of commercially available models. This is particularly true in the Latin America market. The key considerations in selecting the size of the battery were discussed above. The size of the battery is important in deciding how much charge the bus needs every time it comes to terminal. The battery is expected to have more *excess* capacity during the earlier part of its life, which allows more flexibility in deciding on the depth of charge. The choice of battery size is based on maximizing project bankability rather than on the charging strategy. Thus, for the purpose of defining a charging strategy, battery size is taken as given exogenously.

Overhead charging infrastructure: The amount of power that the equipment can deliver will determine the electrical current in the battery, and ultimately the amount of time needed to charge the battery. As discussed earlier in the report, opportunity charge buses are typically fitted with LTO batteries, which are capable of taking very high amperage. For this reason, the choice of nominal power for the charging equipment is the decision factor for a desired rate of charge. Higher nominal power reduces charging times, but this has to be balanced with any potential constraints in power supply at the site (and cost and financing of upgrades to the distribution system) and the demand charges that may apply (overhead charging will typically take place during peak or semi-peak hours). For some applications, it may be necessary (or efficient) to locate more than one charging station along a given route. MiBus should consider locating charging infrastructure at points where utilization can be maximized, namely at route intersection points. For the set of routes that MiBus selected for the initial deployment of electric buses, routes C982 and C938 intersect around Zona Paga 5 de Mayo, which invites the evaluation of that site for the installation of overhead charging infrastructure.

Charging time: The amount of time used in a charge event can be an input or an output of the charging strategy. In the more general case, the time will be dictated by the charging power and the energy requirements. For the analyses included in this report, charging time is taken as an *output*. The charging power and the energy withdrawn at a charging event can in turn be determined by other factors. For example, in a smart charging environment, the charging power and energy uptake can be moderated so as to react to price signals. In a different scenario, charging time may be an *input* to the charging strategy. This will be the case when the frequency of buses arriving to charge imposes restrictions on the time available for each charge, in which case time may determine the power rating needed for the charging infrastructure that will be installed.

Energy uptake: The amount of energy withdrawn in a charging event is primarily an input, but it can also be an output. The bus will have a minimum energy requirement to complete the following cycle; this sets the lower limit for the amount of energy to be delivered by the charging station. In a smart charging environment, the system will produce a fairly robust estimation of this energy requirement. A naïve charging strategy could assume that at every charging event the battery would be fully charged. Such strategy would be as impractical (it does not take into account the tapering of charging amperage) as unnecessary (the battery will typically have excess capacity and be able to complete a cycle with less than 80% of the capacity) as inefficient (it would ignore the interaction of potential value streams that can be obtained from the modulation of the energy uptake). As just mentioned, the modulation of energy uptake can produce several value streams that the bus operator should consider.[7] One of particular interest is the impact of the variation in state of charge on the life of the battery.

In the analyses presented earlier, it was assumed that each route has access to only one charging station, which is located at the route terminal. The results showed that electric buses under an opportunity charge strategy could operate seamlessly throughout the day in routes C888, C898, C968, and E489, *even in a worst-case scenario* with high HVAC power demand, highest passenger load, and most challenging driving cycle. The most demanding cycles for routes C850 and C938 could not be served with opportunity charge buses with the assumed battery size (3 times smaller than that assumed for the overnight charge bus). In these cases, the addition of one charging point would enable the electric buses to run the entire operational day. These decisions must however be made on a case-by-case basis, with due consideration to the factors discussed above, as well as conditions on the ground. For example, one natural potential location for a charging station along route C938 is Zona Paga 5 de Mayo. Meanwhile, for route C850, one

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[7] It is important to understand the alignment of interests among the players in a system of electric bus charging. Specifically, the charging strategy can have an impact on the grid, an impact on the life of the battery, etc. The misalignment of interests can create a principal-agent situation.

station could be located at the terminal in Metro Albrook, but the location for a second charging point is not immediately obvious. Should that station be located in Isla Perico, it would have a low utilization rate, which would negatively affect the economics of the project.

Finally, an interesting alternative to increase the returns on investments in overhead charging infrastructure, is to collocate charging stations for other modes of electric mobility, such as electric taxis, personal electric vehicles, and electric scooters. These other vehicles would need to use different charging equipment, but they would benefit from possible economies of scale on site construction and electrical grid upgrades. Access to charging stations is one of the key challenges to the adoption of electric vehicles in dense urban areas, and this concept could offer a solution in some cases.

3.3 Flash Charging

For completeness, this section includes a mention to a third approach to charging advanced by ABB – Hitachi Power Grids, known as *flash charging*. Figure 55 presents a summary of the two approaches to electric bus charging described thus far, along with flash charging.

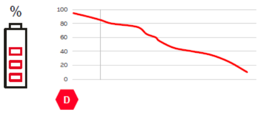
Flash charging is aimed at supporting battery electric buses autonomy without sacrificing weight to batteries nor sacrificing the bus schedule to charging. This may be especially applicable to longer bus routes or buses with shorter operational headway. In such cases the energy demand can be very high, and a compromise may be needed between operational time with passengers and charging time. Addressing this may lead to increased number of chargers and larger fleet sizes. To tackle these challenges the Flash charging approach was developed. This concept enables the vehicle to charge at any point along the route, be it short bus stops or longer stops at line terminals. This is achieved by allowing the power electronics already on board the vehicle to act as the charger and works like regenerative breaking which occurs any time the bus is not accelerating.

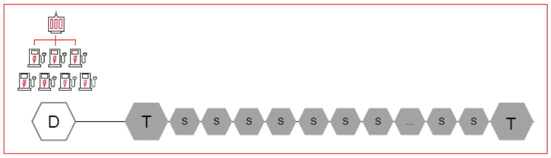
Figure 55. Electric Bus Charging Strategies and Infrastructure Implications (Source: Courtesy of ABB – Hitachi Power Grids)

D depot T terminal S stops

Overnight 50kW-150kW (plug) **Opportunity and Flash-charging** 150kW-600kW (pantograph)

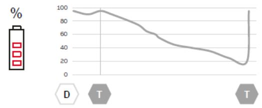
Overnight charging at depot

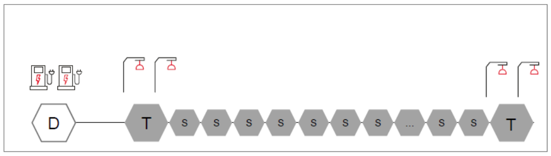




- Significant footprint required
- HV or MV substation needed
- Large batteries
- Long downtime to recharge
- Usually small e-buses
- Usually charging via plug
- Interoperable with all bus OEMs

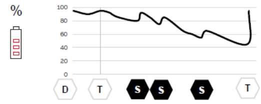
Opportunity charging at terminals

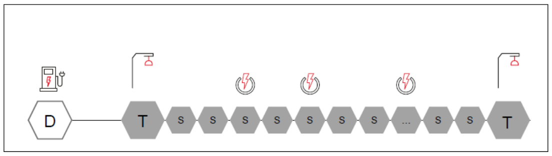




- Space needed at terminals
- Typically 12m or 18 e-buses
- Available on PantoUp
- Available on PantoDown (OppCharge)
- Interoperable with few bus OEMs

Flash-charging at some stops





- Light and spread infrastructure
- Light batteries
- No downtime to recharge
- High frequency/capacity lines
- Best suited to big e-buses and Bus Rapid Transit (BRT)

Grid-eMotion™ Fleet

Grid-eMotion™ Flash

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