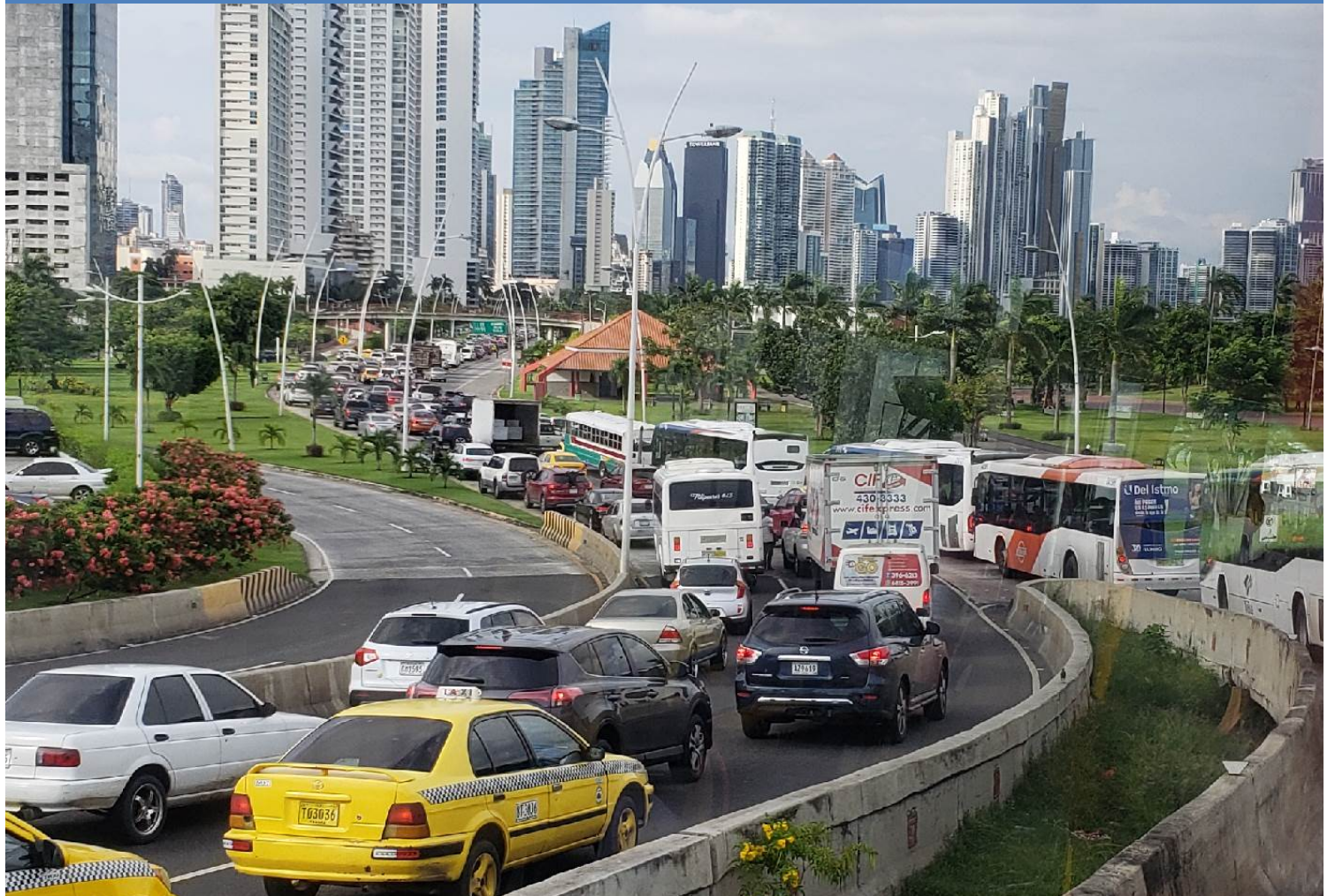




Accelerating the Transition to Sustainable Mobility and Low Carbon Emissions in Panama City



Deliverable 2.2: Final Report

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

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Table of Contents

Table of Contents	4
List of Tables	5
List of Figures	6
1. Introduction	9
2. K7 Electric Bus pilot test in Panama	9
2.1 Pilot test results	9
2.2 Electric bus specifications and operating conditions	11
2.3 Electric Bus energy consumption analysis	14
2.4 Conclusion: K7 BYD Electric Bus Pilot Test	18
3. Prominent routes for successful electrification	19
3.1 Deliverable 2.1 Summary: Routes selection, GPS data collection and driving cycle generation	19
3.2 Electric bus modelling	21
3.3 Electric Bus energy consumption analysis	22
3.4 Operation conditions in Panama City	24
3.4.1 Bus commercial speeds	24
3.4.2 Passengers transported	25
3.4.3 Ambient temperature & Air conditioning intensity	26
3.4.4 Route characteristic distances	28
3.5 Preliminary identification of electrifiable routes	30
4. Projection of fuel/energy consumption of available low emission bus technologies	34
4.1 Fuel consumption of diesel Euro III buses in Panamá City	34
4.1.1 Diesel bus computational modeling	34
4.1.2 Simulation results	35
4.2 Fuel consumption for Euro VI buses: Diesel & natural gas	36

5.	Environmental impact of the different bus technologies.....	38
5.1	Carbon footprint of each evaluated technology.....	38
5.1.1	Electricity carbon footprint.....	39
5.1.2	Diesel and CNG carbon footprint	40
5.1.3	GHG emission of the different evaluated bus technologies.....	41
5.2	Air quality emissions of Euro III and Euro VI technologies.....	42
5.3	Potential of emissions reduction of each evaluated technology.....	43
6.	Summary	44

List of Tables

Table 1.	Parameters of the BYD K7 electric bus being tested in the historical center of Panama City. Specifications of the air conditioning equipment are included.	12
Table 2.	BYD K7 electric bus model specific energy consumption results under the four created driving cycles for both best- (50 pax & 15kW), and worst-case (25 pax & 6kW) scenarios of passenger load and air conditioning power demand.....	14
Table 3.	Characteristic parameters of each created driving cycle for circular routes: mean speed, mean positive acceleration, mean positive and negative slope, idle relation, stops per kilometer and average percentage error compared to real routes parameters shown in Table 3 and Table 4, Deliverable 2.1.....	21
Table 4.	Characteristic parameters of each created driving cycle for two-way routes: mean speed, mean positive acceleration, mean positive and negative slope, idle relation, stops per kilometer and average percentage error compared to real routes parameters shown in Table 3 and Table 4, Deliverable 2.1.....	21
Table 5.	Characteristic of a slow charge (overnight), fast charge (opportunity) electric 12-meter buses.	22
Table 6.	Operation parameters of each circular route for both vehicle types, rapid charge (RC) and slow charge (SC).....	30
Table 7.	Operation parameters of each two way route for both vehicle types. rapid charge (RC) and slow charge (SC). The letter “G” beside the names stands for go, and letter “R” for return.	30
Table 8.	Volvo B290R Euro III bus’s specifications used to create the bus’s computational model.....	34
Table 9.	Direct and indirect GHG emissions related to each technology per kWh of fuel or electricity consumed.....	41

Table 10. Direct and indirect GHG emissions related to each technology per kWh of fuel or electricity consumed.....	43
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List of Figures

Figure 1 Data sheets of the BYD K7 daily operation on the 24/08/2018, filled out by the bus driver along the route.	10
Figure 2. K7 electric bus specific energy consumption as function of trip mean speed. Each data point represents the mean energy consumption of the bus over a full roundtrip over the designated bus route (Source: MiBus (blue points) and Logios (red points)).	11
Figure 3. AUTONOMIE computational model of an electric bus powertrain. Each block is adapted to fit the specifications of the K7 electric bus.	13
Figure 4. Driving cycles created using GPS data collected by LOGIOS on board of the BYD K7 electric bus used for the pilot test in the historical downtown of Panamá City. Each cycle has a different mean speed, shown by the red lines, representing different driving conditions.	13
Figure 5. Simulation results plotted over the specific energy consumption estimated from MiBus data of the BYD K7 pilot test.	15
Figure 6. Daily mean specific energy consumption of the BYD K7 electric bus for a total of 45 operation days, calculated by LOGIOS using data collected by MiBus, and simulation results under best- and worst-case scenarios of operation are included.	16
Figure 7 Bus Energy consumption operating at varying mean speeds and in 4 different conditions of load, slope and air conditioning.	17
Figure 8. Routes selected by LOGIOS and MiBus for the study of electrification viability. A detail of the electric bus pilot test route is included.....	19
Figure 9. Representative driving cycles of the 8 surveyed routes, including variable speed, slope profiles and mean speed values. For two-way routes, the letter “G” beside the name stands for “Go”, and means the bus is departing from terminal. Letter “R” stands for “Return”, meaning the bus is returning to terminal.	20
Figure 10. Slow charge electric bus specific energy consumption as a function of the different representative driving cycles mean speed.	23
Figure 11. Fast charge electric bus specific energy consumption as a function of the different representative driving cycles mean speed.....	23
Figure 12. Mean speed of the different surveyed bus routes during the different periods of the day.....	25
Figure 13. Number of passengers and bus occupancy factor as a function of the time of day for the VECMC return route.....	26

Figure 14. Peak and Mean number of passengers and bus occupancy factor for the different evaluated bus routes.	26
Figure 15. Panama City average temperature and number of passengers in a given bus route as a function of the time of day ¹	27
Figure 16. Proposed air conditioning system hourly power requirement as a function of the time of day, along with the mean power capacity throughout the entire day.....	28
Figure 17. daily distance covered over the different bus routes as a function of their daily mean speed. Primary routes, secondary routes and the specific routes surveyed by LOGIOS are identified.....	29
Figure 18. Round trip distance covered over the different bus routes as a function of their minimum mean speed. Primary routes, secondary routes and the specific routes surveyed by LOGIOS are identified.	29
Figure 19. Operational range for both slow charging and fast charging e buses as a function of the representative driving profile mean speed.	31
Figure 20. Slow charge electric bus operational range compared to the daily distance covered over the different bus routes as a function of their daily mean speed. Primary routes, secondary routes and the specific routes surveyed by LOGIOS are identified.	32
Figure 21. Fast charge electric bus operational range compared to the round-trip distance covered over the different bus routes as a function of their minimum driving profile mean speed. Primary routes, secondary routes and the specific routes surveyed by LOGIOS are identified.....	32
Figure 22. Powertrain architecture of a conventional bus. Each block is adapted to fit the specifications of the Volvo B290R bus.....	35
Figure 23. Fuel consumption as a function of mean speed for a Euro III diesel bus under Panama city operating conditions compared to results generated by the HBEFA with and without positive slope conditions.....	36
Figure 24. Fuel consumption, in liters equivalent of diesel, as a function of mean speed for Euro III, Euro VI Diesel and Euro VI CNG buses under Panama operating conditions. The original results of HBEFA for a Diesel E VI bus are shown in dashed lines to illustrate the increase projected in consumption due to Panama Operating conditions.	37
Figure 25. Vehicle and fuel life-cycle illustration. When assessing the carbon footprint of a technology, both the vehicle and the fuel's life cycles must be appraised.....	38
Figure 26. GHG emissions due to electricity generation. Each box represents a process and in it are displayed its efficiency and the accumulative GHG (or CO ₂ eq.) emissions until that point. The blue percentages represent the relative weight of each type of generation in the electric matrix. Information was provided by Panama's Energy Ministry and modeled using GREET.	40

Figure 27. Carbon footprint of each evaluated technology per kilometer, as a function of mean speed. Diesel Euro VI and CNG Euro VI results are almost identical, so the lines overlap..... 41

Figure 28. Air quality emissions of diesel Euro III buses compared to Euro VI buses. The solid lines correspond to NOx emissions (left axis), and the dash-dot ones to PM emissions (right axis)..... 42

1. Introduction

This report builds upon the results presented in the previous one (D2.1). It integrates field data, representative of the real operating conditions of public transport buses in Panama City, with advanced technology modeling tools. The central objective of this is to produce state-of-the-art projections of the performance, efficiency and environmental outlook of different bus technologies under real day-to-day local operating conditions.

The report undertakes the evaluation of both diesel and CNG Euro VI buses, as well as configurations of fully electric vehicles. Due to their relative novelty and their range and charging time restrictions, the latter require a more detailed and precise analysis to define an optimum relation between vehicle configuration, operational conditions, charging strategy, and deployment feasibility.

The report also covers a detailed evaluation of the performance of the electric bus that started operations in the Historic City Center as part of a pilot program.

2. K7 Electric Bus pilot test in Panama

In the interest of establishing a clear path towards a sustainable public transport system for Panama City, local officials launched an electric bus pilot test on August 2018. It consists in operating a 9-meter BYD K7 electric bus on a new route confined within the Historic City Center. As part of the current project Terms of Reference, LOGIOS has conducted the monitoring and analysis of the electric bus performance under the designated operating conditions.

The work presented in this report picks up from the results exhibited in Deliverable 2.1 detailing the operation and the bus driving profile, to conduct further analysis on the energy consumption of the bus and that of its different components. This will enable a better understanding of the high energy consumption and low mileage achieved by the vehicle under the operating conditions on the aforementioned route.

The following section presents and discusses data sets recorded by MiBus personnel together with additional information gathered and produced by LOGIOS. Results are compared to those obtained by computational model representative of the K7 electric bus running under characteristic driving cycles produced with the collected GPS data on the pilot test route. Part of the reason for this process is to validate the computational models and the produced driving cycles. The validated model is used to produce simulations, which yield a variety of results, including the energy consumption of the bus as a whole and that of its specific components. The decomposition of energy consumption will help explain the factors driving the high energy consumption that the BYD K7 has shown during the pilot. On average, this energy consumption exceeds by about 100% the energy consumption detailed in the bus technical specifications.

2.1 Pilot test results

As mentioned above, the electric bus pilot test is operating in the historical city center of Panama. The bus services a route of 4.8 kilometers, starting with a 2-hour service shift in

the morning, followed by a charging event and a 4-hours service shift in the afternoon, after which the bus returns to the depot for an overnight charge.

As shown **Figure 1**, during the pilot MiBus personnel recorded, for every roundtrip done by the electric bus, the date, type of trip, start time, end time, accumulated distance, state of charge of the battery pack at the beginning and at the end of the trip.

DIARIO DE CONSUMO						
Fecha	Recorrido	Tipo de Recorrido	Hora	% Carga	Millas	Observaciones
27/8/18	Inicio	VACIO	5:59	99.9	201.96	
	Fin	VACIO	6:08	89.9	202.01	
	Inicio	C. Mercad	6:09	89.9	202.01	
	Fin	C. Mercad	6:25	84.4	202.04	
	Inicio	C. Mercad	6:26	84.4	202.04	
	Fin	C. Mercad	6:45	80.0	202.07	
	Inicio	C. Mercad	6:46	80.0	202.07	
	Fin	C. Mercad	7:07	74.7	202.09	
	Inicio	C. Mercad	7:08	74.7	202.09	
	Fin	C. Mercad	7:34	68.8	202.13	
	Inicio	C. Mercad	7:37	68.8	202.13	
	Fin	C. Mercad	7:59	63.2	202.16	
	Inicio	C. Mercad	8:02	63.2	202.16	
	Fin	C. Mercad	8:27	57.7	202.18	
	Inicio	C. Mercad	8:29	57.7	202.18	
	Fin	C. Mercad	8:49	53.1	202.21	
	Inicio	VACIO	8:50	53.1	202.21	
	Fin	VACIO	8:59	50.3	202.24	
	Inicio	VACIO	13:16	96	20225	
	Fin	"	13:35	89.3	20228	
	Inicio	Comercio	13:40	89.3	20228	
	Fin	"	14:05	82.6	20231	
	Inicio	"	14:16	82.5	20231	
	Fin	"	14:50	74.2	20234	
	Inicio	"	14:50	"	20234	
	Fin	"	15:20	67.4	20237	
	Inicio	"	15:35	"	"	
	Fin	"	15:56	60.9	20239	
	Inicio	"	16:00	"	"	
	Fin	"	16:35	52.00	20242	
	Inicio	"	16:35	52.00	20242	
	Fin	"	17:05	45.9	20245	
	Inicio	"	17:10	"	"	
	Fin	"				

Figure 1 Data sheets of the BYD K7 daily operation on the 24/08/2018, filled out by the bus driver along the route.

Using this information and the specifications of the K7 electric bus provided by the supplier (BYD), the average energy consumption and mean operational speed of the vehicle for every roundtrip performed was calculated.

The *Mean Speed* of the electric bus on a given trip (*MSp*) can be calculated as:

$$MSp = \frac{AD_E - AD_S}{T_E - T_S},$$

where, AD_S is the accumulated distance at the start of a trip, AD_E is the accumulated distance at the end of a trip and T_S and T_E are the times at the start and end of the trip, respectively. The *Mean Energy Consumption* of the bus during that same trip (*MEC*), can be estimated as:

$$MEC = (SOC_S - SOC_E) * BPNEC,$$

where SOC_S and SOC_E are the *State of Charge* of the battery pack at the start and end of the trip, respectively, and $BPNEC$ is the electric bus *Battery Pack Nominal Energy Capacity*. Finally, the *Specific Energy Consumption* of the bus during a trip (*SEC*) can be calculated as:

$SEC = MEC / (AD_E - AD_S)$ For the purpose of calculating specific energy consumption under real operating conditions, only the commercial trips of the electric bus were taken into consideration, while empty trips made from the bus depot to the start point of the route were discarded.

Results are presented in **Figure 2**. Each data point represents the specific energy consumption of the electric bus as a function of its mean speed over a given round trip. Blue points are calculated based on data provided by MiBus, whilst red points are calculated using the GPS data compiled by LOGIOS over six weeks of fieldwork. The light blue curve depicts the average specific energy consumption of the overall data pool as a function of bus mean speed. This chart shows that the specific energy consumption for the BYD K7 electric bus can vary significantly from a low of 1.1 kWh/km to a high of 5.6 kWh/km depending on the operating conditions.

Furthermore, the collected data shows that the SEC of the bus grows rapidly as mean speeds decrease, similarly to what would happen with other vehicle platforms, although at a slower rate. Also, for a given mean speed the spread in SEC from the mean value is generally in excess of 50%. This puts into evidence that, in addition to the average speed of the trip, the aggressiveness of the driving profile and external factors such as ambient temperature and number of passengers have a considerable impact on the bus energy consumption, and therefore on its mileage.

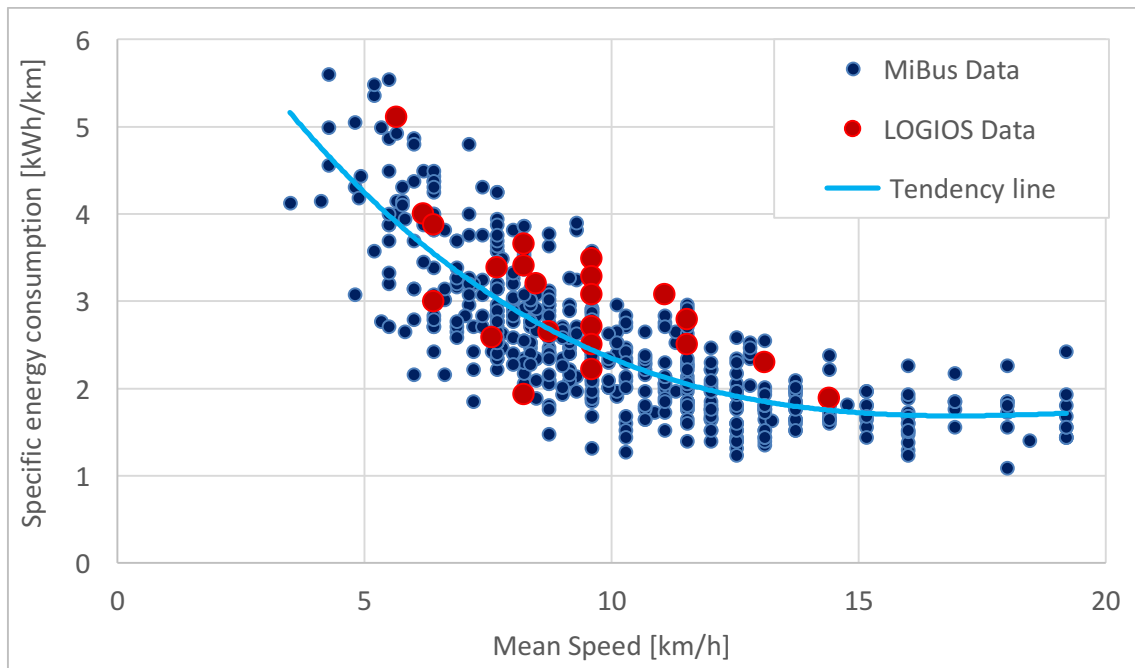


Figure 2. K7 electric bus specific energy consumption as function of trip mean speed. Each data point represents the mean energy consumption of the bus over a full roundtrip over the designated bus route (Source: MiBus (blue points) and Logios (red points)).

2.2 Electric bus specifications and operating conditions

The GPS data collected on board the BYD K7 bus covers a wide range of operating conditions. This is essential to understand the real performance of the bus. To do this a variety of representative driving cycles were constructed using the collected data and used as inputs of a proprietary computational model of the tested bus to estimate the latter's

energy consumption and that of its individual components over a range of operating conditions.

The specific parameters of the BYD K7 electric bus are shown in **Table 1**. These are used to build the computational model of the vehicle on the simulation platform AUTONOMIE (www.autonomie.net). The powertrain configuration of the vehicle is shown in **Figure 3**. Each block of the model is specified based on the specific parameters of the evaluated vehicle.

Table 1. Parameters of the BYD K7 electric bus being tested in the historical center of Panama City. Specifications of the air conditioning equipment are included.

BYD K7			
Chassis			
Length [m]			9.36
Curb weight [kg]			10,200
Max. cargo	[kg]		3,300
(Equivalent to)			(44 passengers)
Motor			
Top speed [km/h]			90
Max. gradeability [%]			17
Max. Power [kW]			2x90
Max. Torque [Nm]			2x400
Battery Pack			
Battery capacity [kWh]			196
Declared range [km]			216
Charging Power [kW]			80
Charging time [hrs]			2-3
Air Conditioning			
Brand and model			Valeo, REVO-E Global
Compressor nominal voltage [V]			600
Compressor maximum current [A]			22
Compressor nominal current [A]			9
Ventilation system nominal voltage [V]			24
Ventilation system maximum current [A]			85
Ventilation system nominal current [A]			55
Air conditioning maximum power [kW]			15
Air conditioning nominal power [kW]			6

Once the model has been developed, operational inputs must be defined. These inputs include driving profile, passengers transported, route topography, and ambient conditions.



Figure 3. AUTONOMIE computational model of an electric bus powertrain. Each block is adapted to fit the specifications of the K7 electric bus.

As described in the report presented for Deliverable 2.1, the driving conditions of the operation are established using the GPS data that LOGIOS collected on board of the bus. These data is filtered, processed, and categorized to generate statistically-based driving cycles that represent real-world operating conditions of the bus.

Figure 4 shows four representative driving cycles of the operation, each of an overall mean speed (5, 9, 12 and 15 km/h). Together, these cover most of the mean speed spectrum under which the electric bus is currently operating, as well as short and long micro-cycle durations, average idling times, low and high speeds and a wide range of acceleration rates.

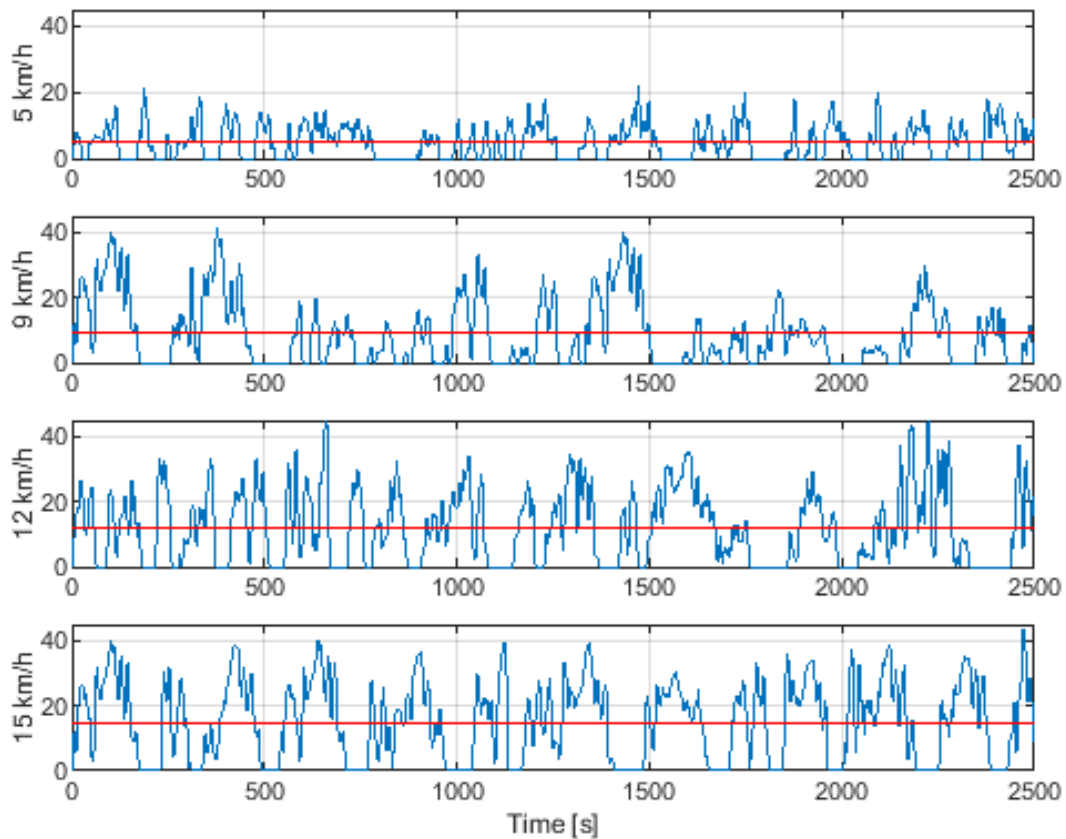


Figure 4. Driving cycles created using GPS data collected by LOGIOS on board of the BYD K7 electric bus used for the pilot test in the historical downtown of Panamá City. Each cycle has a different mean speed, shown by the red lines, representing different driving conditions.

Other external variables such as ambient temperature and passenger load also vary over the daily operation. To analyze the entire range of energy demand for the electric bus operation, worst-case and best-case scenarios are defined for each proposed driving cycle.

The worst-case scenario assumes that the air conditioning (AC) system is operating at maximum power (15 kW), and that the bus is hauling its maximum load (50 passengers). On the other hand, for the best-case scenarios it is assumed that the bus AC system is operating at its nominal capacity (6kW) and that the bus is transporting 25 passengers.

The presented driving cycles, together with the aforementioned scenarios are used to replicate the different working conditions to which the electric bus is subject to during its daily operation. This will be used to simulate the operation and further the gain insight into the reasons why the registered energy consumption is considerably higher than originally expected.

2.3 Electric Bus energy consumption analysis

The model of the bus is run using the four created driving cycles, each under both the best- and worst-case scenarios, described in the preceding section, giving a total of eight simulation runs.

Table 2 shows the specific energy consumption results obtained by the bus model under the different vehicle operating conditions.

Table 2. BYD K7 electric bus model specific energy consumption results under the four created driving cycles for both best- (50 pax & 15kW), and worst-case (25 pax & 6kW) scenarios of passenger load and air conditioning power demand.

Scenario	Mean Speed			
	5.5 km/h	9 km/h	12 km/h	15 km/h
Best-case [kWh/km]	2.87	2.05	1.64	1.34
Worst-case [kWh/km]	4.75	3.17	2.51	2.24

Overall, results show that for a given mean speed the passenger load and AC power requirement have an important impact on the SEC of the vehicle, with differences between scenarios ranging from 50% to more than 100% depending on the mean speed. This highlights the critical importance of fully understanding the characteristics of the operation to adequately estimate the potential energy consumption of an alternative technology bus operating in a given service.

Figure 5 plots the values of SEC obtained by the bus model (**Table 2**) over those calculated using the recorded data provided by MiBus (**Figure 2**). The model results show good correlation with the field recorded. More so, the percentage deviation from the tendency value line for both the worst- and best-case scenarios remains almost constant along the entire mean speed range.

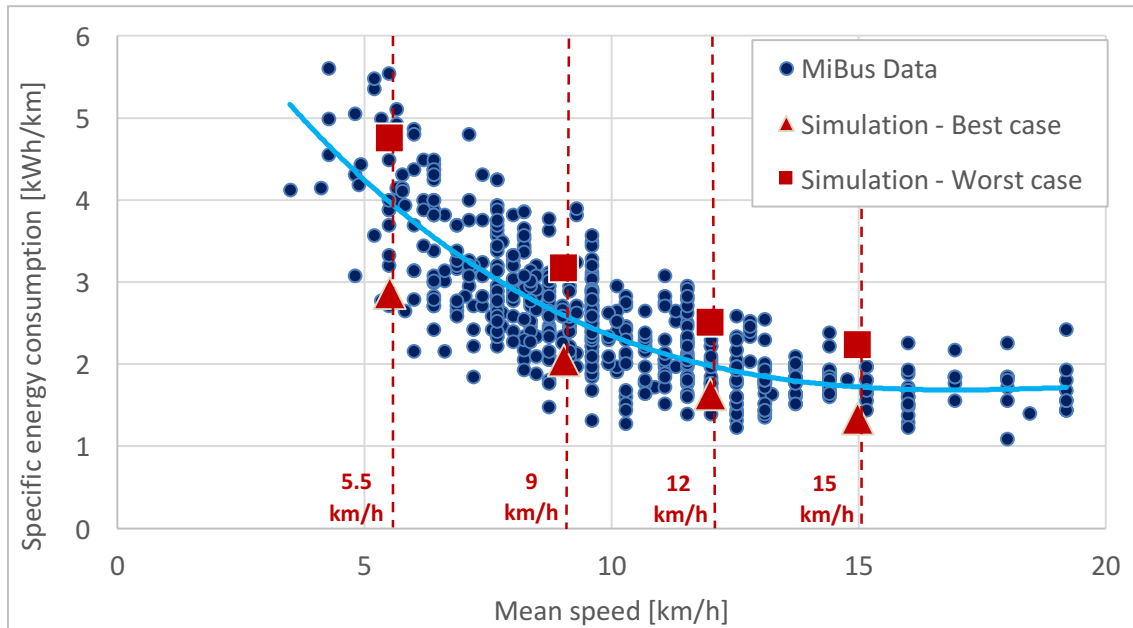


Figure 5. Simulation results plotted over the specific energy consumption estimated from MiBus data of the BYD K7 pilot test

Results presented in **Figure 5** show that the developed model is an accurate representation of the BYD K7 electric bus. The figure also shows that some of the recorded data points fall above and below the estimated best- and worst-case scenario results. The reason for this is that each driving cycle is built as a combination of micro-cycles of different trips which, together, characterize the average operation of the electric bus at a given mean speed. Therefore, the presented simulation energy consumption results, while calculated for the conditions of passenger load and AC demand described above, are intended to reflect representative driving conditions. Consequently, several recorded trips are both more and less aggressive, resulting in values of SEC in excess and defect of the results for the worst- and best-case scenarios, respectively. For example, as shown in **Figure 5**, for a mean speed of 5.5 km/h the maximum SEC registered is 5.5 kWh/km, while simulation results show a maximum consumption of 4.8 kWh/km for that same mean speed.

If the daily operation is considered, rather than each individual trip, the daily average specific energy consumption can be calculated. This enables the estimation of mileage, or range, of the K7 electric bus per charging event under the average daily operating conditions. **Figure 6** shows the daily mean SEC of the K7 electric bus over each of the 45 days of recorded operation. As expected, when averaged over a day, both the SEC and mean speed variations are smaller. More importantly **Figure 6** shows that simulation results for both the worst- and best-case scenarios correlate very closely with real operation results, with all recorded points fitting smoothly between the presented projections. This proves that the developed model and constructed driving cycles are a very accurate representation of both the bus and its operating conditions.

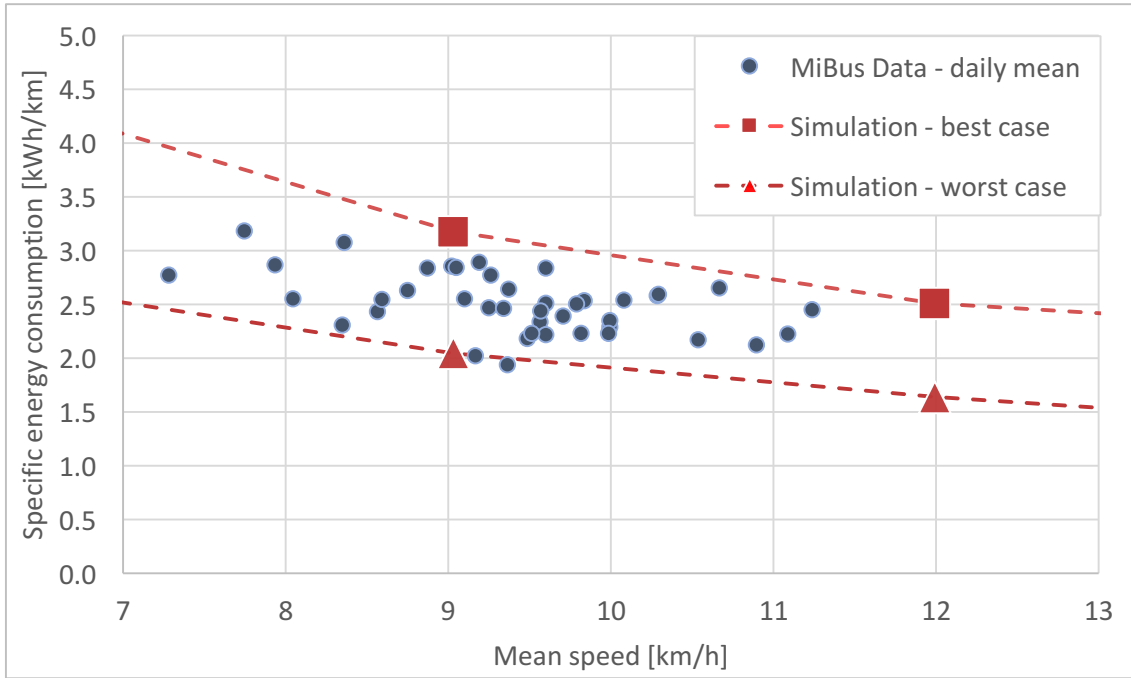


Figure 6. Daily mean specific energy consumption of the BYD K7 electric bus for a total of 45 operation days, calculated by LOGIOS using data collected by MiBus, and simulation results under best- and worst-case scenarios of operation are included.

Having established the energy consumption of the K7 electric bus under the different operating conditions for the selected service routes, it is possible to calculate its range using the following equation:

$$Rg = \frac{BC[kWh]}{SEC[kWh/km]} * 0.8,$$

where Rg represents the operation range of the electric bus [kilometers per full charge event] and BC is the nominal energy capacity of the battery pack. The 0.8 factor reflects our assumption that the battery's SOC will be kept over 20% at all times, in order to preserve battery life and ensure performance capabilities. Thus the usable portion of the energy in a given battery pack is assumed to be 80% of its nominal capacity.

Applying the above, the range of the K7 electric bus in operating conditions prevailing in the pilot test, is between 50 and 80 kilometers. These values are only 25% to 40% of the manufacturer declared range of 216 km, which would imply a consumption of 0.91 kWh/km assuming the use of the entire battery capacity.

To understand the reasons for such a large discrepancy between empirical and nominal range, the bus model is used to evaluate the energy balance of the vehicle and identify a) contributions of the different bus components to energy consumption, and b) impact of operating conditions on these contributions. This is done by running the model for each of the four proposed driving cycles (Figure 4), whilst varying the passenger load, slope condition and AC requirements. Results are presented in Figure 7.

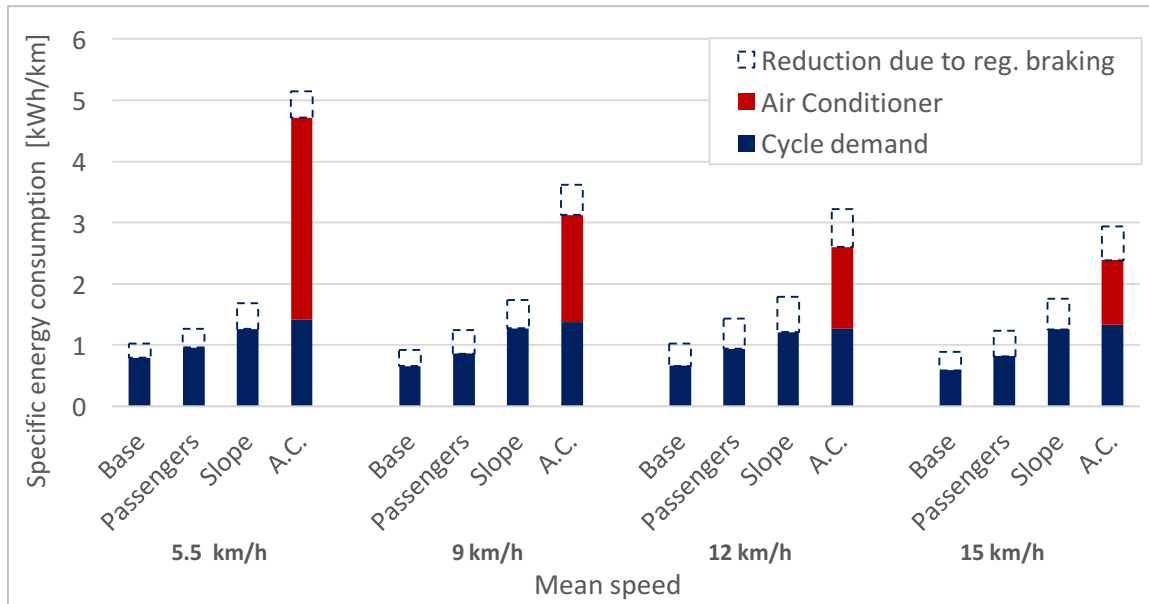


Figure 7 Bus Energy consumption operating at varying mean speeds and in 4 different conditions of load, slope and air conditioning.

The **Base** case consists of a simulation with no passengers, no slope and no AC. For the **Passengers** case, a full load of 50 passengers was added. On top of this, for the **Slope** case the slope of the routes was added to the cycles. Finally, the **A.C.** case takes in all the previous loads and adds the load of an AC working at maximum capacity (15 kW). The figure shows that for the base case the vehicle's SEC is considerably lower than that recorded over the pilot test and is close to efficiencies reported by the manufacturer. It can be seen that the energy consumption is not very different across the four driving cycles.

When adding the effect of passengers (full load) and, subsequently, road slope (sometimes referred to as *road grade*), the net SEC is increased by 20% and 30%, respectively. This is due to various reasons, probably the most intuitive of which is the increase in the energy required to overcome the friction force proportional to weight. The additional passenger mass also increases the energy required by the vehicle during acceleration events, effect which is intensified when the vehicle travels uphill. On the other hand, the additional kinetic and potential energy due to the added mass and slope is also available during braking, increasing the potential capacity of the regenerative braking system. However, in practice, not all this energy can be stored back into the batteries. There is a loss of power as the kinetic energy is transformed and makes its way back through the powertrain (see Figure 3), starting with inefficient braking behaviors, transmission losses, generator inefficiencies, and limitations on the current that can be injected into the battery. All of these factors limit energy recovery resulting in net energy losses.

Finally, the intensive use of AC results in an abrupt increase of the net specific energy consumption of the bus for all evaluated driving profiles, with the impact being worse as the mean speed of the vehicle is reduced. The power demand of this equipment, which can be of up to 15 kW (see Table 1), represents an energy demand of up to 15 kWh/h. Therefore, as the vehicle speed is reduced the impact per km is increased (i.e. the SEC increases). Under the evaluated range of mean speeds, the energy demand due to the use of the AC system may range from 1 to 3 kWh/km, plus battery and power system inefficiencies.

2.4 Conclusion: K7 BYD Electric Bus Pilot Test

Overall the results of our evaluation of the pilot test show that the energy consumption of the bus under the specific service conditions was in far excess of what was expected. Whilst the bus was advertised to have a range of 210 km per full charge, under real operating conditions it could only cover on average around 75 km per charge. Given that it is recommended that the minimum SOC of the battery pack does not drop below 20%, the actual operational range under the conditions of this route would drop to about 62 km.

The detailed analysis of the vehicle energy consumption yields a number of key findings, which are summarize next. The driving profile performed by the bus drivers is not aggressive and results in a base energy consumption of around 0.8 kWh/km when averaged over the entire mean speed range of the operation. It was observed that the net vehicle energy consumption does not change significantly across the four generated driving profiles. As expected, increasing the number of passengers affects negatively the vehicle energy consumption, and this effect is magnified as the slope conditions of the route are included in the analysis. The combined addition of passenger load and road slope results in a net average SEC over the mean speed spectrum of 1.35 kWh/km, which almost 50% lower than the 2.5 kWh/km recorded by MiBus drivers over the pilot trail. Results show that the biggest impact on the bus energy consumption comes from the use of the AC system, which can consume up to 3 kWh/km when the bus operates at 5 km/h. Overall, the AC system doubled the expected bus energy consumption per kilometer. Ultimately, results demonstrate the critical importance of understanding the real operating conditions of a public transport service to establish reliable projections of vehicle efficiency and range.

3. Prominent routes for successful electrification

This section presents a viability analysis for the introduction of electric buses into the public transport system of Panama City. As described in detail throughout Deliverable 2.1, in collaboration with MiBus a group of 8 different bus routes, were selected and analyzed. Together, these cover most of the operating conditions of the bus transport system of Panama City. The operation of each line was monitored using a GPS, over both peak and valley operation times. The collected data was then used to generate representative driving cycles of each operation.

In the current section, the developed driving cycles, together with statistical data of the system and ambient conditions will be used to model different bus platforms, to evaluate the performance and viability of introducing both fast charging and slow charging electric buses into Panama's public transport system.

3.1 Deliverable 2.1 Summary: Routes selection, GPS data collection and driving cycle generation

LOGIOS spent several weeks in Panama City collecting field data of the current bus operation. Bus routes, which were preselected in collaboration with MiBus, were surveyed using GPS equipment, in order to establish the true driving profile of each route and use the recorded information to create representative driving cycles of each operation. **Figure 8** shows a map of the city and the surveyed routes. In total 85 hours and 1,300 kilometers of useful filtered data was collected.

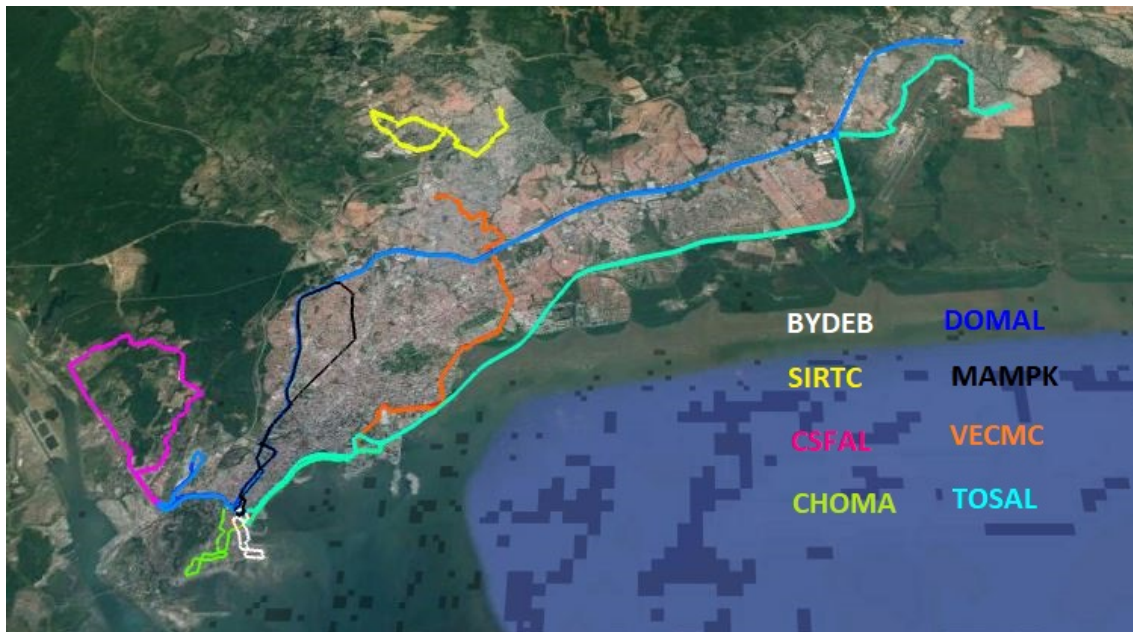


Figure 8. Routes selected by LOGIOS and MiBus for the study of electrification viability. A detail of the electric bus pilot test route is included.

The processed, filtered and categorized GPS data was subsequently used to generate representative driving cycles of each bus route. **Figure 9** shows the driving cycle, slope profile and mean speed of each surveyed bus route.

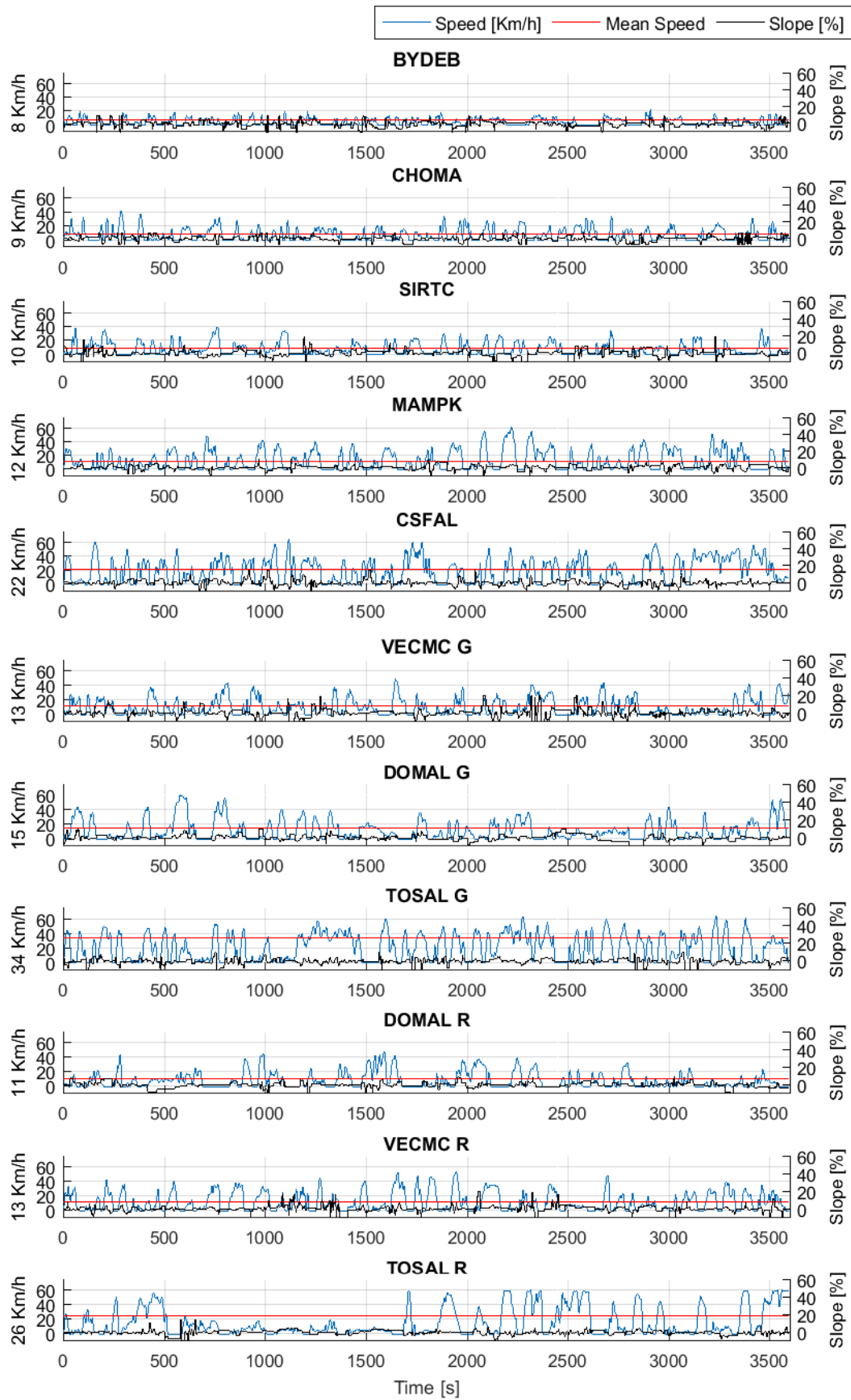


Figure 9. Representative driving cycles of the 8 surveyed routes, including variable speed, slope profiles and mean speed values. For two-way routes, the letter “G” beside the name stands for “Go”, and means the bus is departing from terminal. Letter “R” stands for “Return”, meaning the bus is returning to terminal.

To ensure that the created driving cycles are representative of the collected data pool of each route, characteristic parameters such as mean speed, mean positive acceleration, mean positive and negative slope, idle relation and stops per kilometer are scrutinized safeguarding that values of the proposed driving cycles and those of the route data pool have discrepancies of no more than 5%. Results of the parameters compared and overall average error for each cycle are shown on [Table 3](#) and [Table 4](#). As it can be seen the resemblance between the cycles created and the original data is adequate since none of the cycles exceed a 3% average error.

Table 3. Characteristic parameters of each created driving cycle for circular routes: mean speed, mean positive acceleration, mean positive and negative slope, idle relation, stops per kilometer and average percentage error compared to real routes parameters shown in [Table 3](#) and [Table 4, Deliverable 2.1](#).

	BYDEB	CSFAL	SIRTC	CHOMA	MAMPK
Trip	Round	Round	Round	Round	Round
Mean Speed [km/h]	7.6	22	10.2	9.2	12.2
Mean Pos. Ac. [Km/h*s]	1.0	1.5	1.2	1.3	1.4
Mean Pos. Grade [%]	2.2%	1.9%	2.5%	1.6%	2.0%
Mean Neg. Grade [%]	-2.3%	-2.0%	-2.6%	-1.6%	-1.9%
Idle Time	31%	23%	33%	30%	30%
Stop [1/Km]	5.1	1.8	4.6	5.3	3.5
Average Error [%]	2%	2%	2%	2%	3%

Table 4. Characteristic parameters of each created driving cycle for two-way routes: mean speed, mean positive acceleration, mean positive and negative slope, idle relation, stops per kilometer and average percentage error compared to real routes parameters shown in [Table 3](#) and [Table 4, Deliverable 2.1](#).

Trip	DOMAL		TOSAL		VECMC	
	Go	Return	Go	Return	Go	Return
Mean Speed [km/h]	15.3	11.3	33.9	26.5	12.9	12.6
Mean Pos. Ac. [Km/h*s]	1.3	1.1	1.1	1.0	1.3	1.3
Mean Pos. Grade [%]	2.0	1.9%	1.4%	1.3%	2.4%	2.4%
Mean Neg. Grade [%]	-1.8	-2.0%	-1.4%	-1.3%	-2.5%	-2.2%
Idle Time	28%	34%	16%	22%	28%	26%
Stop [1/Km]	2.6	3.8	0.8	1.1	4.3	4.3
Average Error [%]	3%	3%	3%	3%	3%	3%

3.2 Electric bus modelling

As done for the evaluation of the specific energy consumption results presented for the BYD K7 electric bus, vehicle models are used to evaluate the performance and energy consumption of a given bus operating under a given set of operating conditions.

Electric buses can be categorized according to the type of battery with which they are equipped. There are mainly two categories: fast-charging and slow-charging buses. In the case of 12-meter buses, a slow charging system operates with chargers of between 70-200 kW. On the other hand, fast charge buses can take charging events of 350 kW and above.

Slow-charging buses have battery packs of greater energy capacity (approximately 300 kWh), generally of lithium iron phosphate cells. This allows them to have an autonomy of between 100 and 200 km per day, depending on the battery capacity and operating conditions to which the bus is subject to. However, they require between 3 and 5 hours to charge, so they must be out of operation for extended periods of time. Charging is generally

done at night when the demand for public transport service is low. Fast-charging buses, on the other hand, have batteries of lower capacity (up to 150 kWh), generally of lithium titanium oxide. These provide a lower autonomy per charging event, between 50 and 100 km depending on the battery capacity and operating conditions of the bus, but can be recharged in 5 to 15 minutes, approximately. This allows the vehicles to be charged during the bus driver resting periods, so they could, in theory, operate 24 hours a day.

Table 4 shows the characteristic of two popular 12 m electric buses. The first is a slow charging bus equipped with a 324 kWh Lithium Iron Phosphate battery pack. This would be the equivalent of scaling up the K7 bus used in the pilot test. The second is a fast charging bus equipped with an 88 kWh Lithium Titanium Oxide battery pack.

Table 5. Characteristic of a slow charge (overnight), fast charge (opportunity) electric 12-meter buses.

12m Electric Buses		
	Slow Charging	Rapid Charging
Chassis		
Drag Coefficient	0,65	0,8
Frontal Area [m2]	6,6	6,5
Curb weight [kg]	14500	12900
Fraction of weight in front axle [%]	0,36	0,4
Battery Pack		
Nominal Energy [kWh]	324	88
Nominal Tension [V]	600	550
Maximum capacity [Ah]	540	160
Maximum discharge current [A]	400	480
Maximum charge current [A]	250	640
Nominal charging power[kW]	80	360
Motor		
Nominal Power [kW]	2x110	100
Maximum Power [kW]	2x150	200
Minimum admitted Tension [V]	500	300
Maximum admitted Current [A]	430	220
Reduction Gear / Final Drive		
Total reduction	21,8	6,14
Efficiency	91%	95%
Air Conditioning		
Nominal Power [kW]		6
Maximum Power [kW]		15

LOGIOS has developed experimentally validated computational models of each of the electric vehicles depicted in **Table 5**. Using these models and the representative driving cycles of each bus route presented in **Figure 9**, the specific energy consumption and mileage of the two vehicles will be assessed under the different operating conditions.

3.3 Electric Bus energy consumption analysis

To be consistent with results presents for the K7 bus, first the impact of driving cycle mean speed on the vehicle energy consumption is evaluated. As it can be seen on **Table 3**, all the assesses bus routes present different mean speeds of operation, with values spanning from 7.5 to 30 km/h. Therefore, running the computational models of each bus over the

constructed driving cycles will allow to evaluate the impact of mean speed on each of the buses specific energy consumption. Results are presented on [Figure 10](#) and [Figure 11](#) for the slow charging and fast charging buses, respectively.

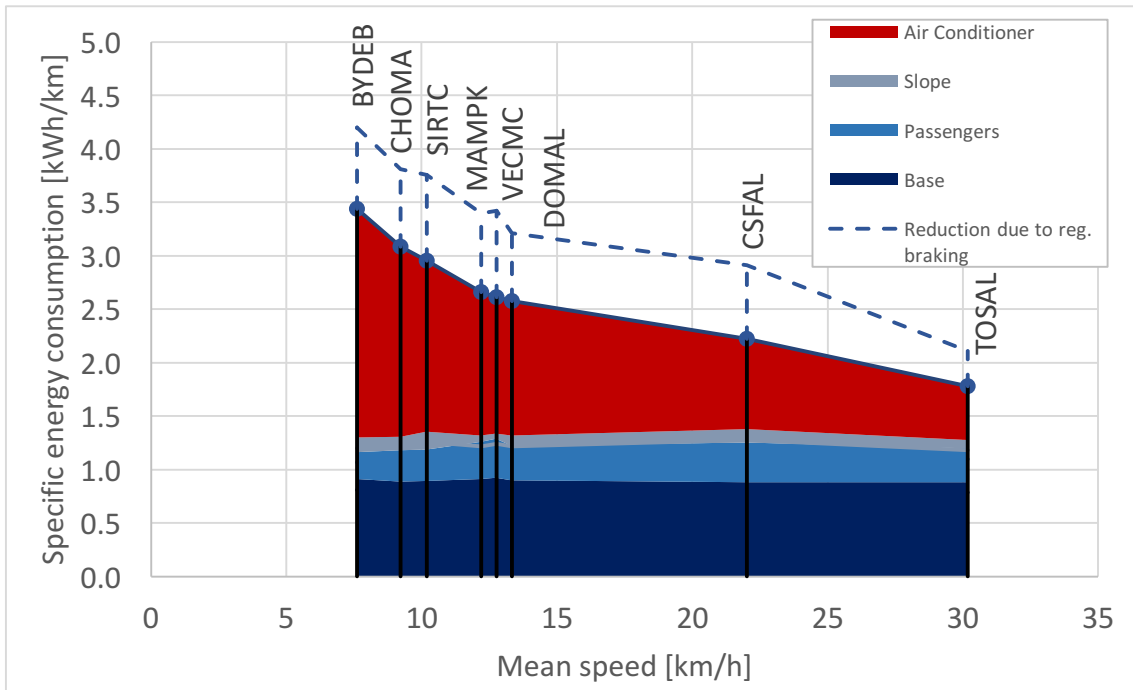


Figure 10. Slow charge electric bus specific energy consumption as a function of the different representative driving cycles mean speed.

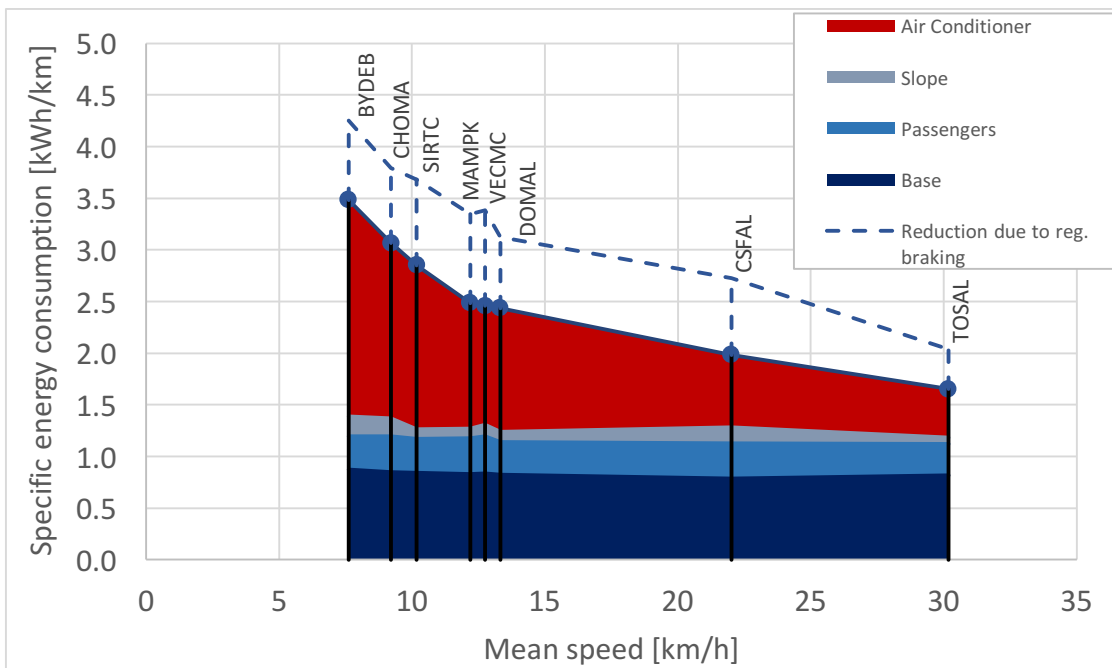


Figure 11. Fast charge electric bus specific energy consumption as a function of the different representative driving cycles mean speed.

As for the K7 bus results, the **Base** case consists of a simulation with no passengers, no slope and no AC. For the **Passengers** case, a full load of 80 passengers was added. On top of this, for the **Slope** case the slope profiles of each route presented on [Figure 9](#) were added to the model. Finally, the **A.C.** case takes in all the previous loads and adds the load of an AC

working at maximum capacity (15 kW). Also, the specific energy recuperated by the regenerative braking system of the buses is depicted.

Results show that, the base case SEC remains pretty much constant over the entire mean speed evaluated range. Overall, the latter remains flat at around 0.8 kWh/km for both the fast charging and slow charging buses.

The impact of passenger load and slope conditions increase the SEC by 0.35 kWh/km and 0.15 kWh/km, respectively, increasing the overall consumption to around 1.3 kWh/km. The VECEC route shows a higher increase in energy consumption relative to other routes, mainly due to the higher positive slope of the route in question.

Also, as expected, the use of the air conditioning system has considerable impact on the vehicles SEC. The latter more than doubles for mean speeds below 15 km/h and increasing it by 50% when operating at a mean speed of 30 km/h.

Regarding the regenerative capacity of the buses braking system, the latter remains almost constant at 0.75 kWh/km for driving profiles with mean speeds below 21 km/h. After this it is reduced to around 0.5 kWh/km. However, in relative terms, (i.e. as a percentage of the specific energy consumption of the bus) the regen capacity of the buses as a function of mean driving speed goes from 20% at 7.5 km/h, up to 35% at 21 km/h and back down to 21% at 30 km/h. This shows the impact of the bus operation on the regenerative capacity of the bus braking system.

Overall, the performance of both buses is similar over the entire analyzed spectrum. The reason for this is that whilst the fast charging bus has a higher battery capability for brake regeneration it has a smaller electric drive than the slow charging bus. Therefore, under the conditions of passenger load and slope the slow charging bus electric motor is under less stress than the fast charging bus motor. These two conditions offset each other resulting in very similar specific energy consumption for both vehicles.

Another interesting result is that, except for the VECMC route, a clear trend is exhibit for specific energy consumption as a function of driving cycle mean speed. Therefore, it can be assumed that the same trend can be used to evaluate the energy consumption of electric buses on other bus routes within Panama's public transport system, and therefore identify bus route that could potentially incorporate electric buses. This will be done in the following section.

3.4 Operation conditions in Panama City

As mentioned above, results presented in the previous section assume that buses are at maximum passenger capacity and that the air conditioning system is operating at full load.

Throughout this section, statistical data provided by MiBus will be used to tune the analysis to better represent the operational characteristics of the different bus routes over an entire day of operation. Commercial speed and passenger load will be assessed for both on-peak and off-peak times, ambient temperature will be evaluated to determine the air conditioning system load factor and bus route characteristic distances and daily mileage will be analyzed.

3.4.1 Bus commercial speeds

Figure 12 shows the mean speed of the different bus routes over the different periods of the day. It also shows the mean and minimum speed of each route during the day. The reason for establishing the mean and minimum speed of each route is that when evaluating

the incorporation of an electric bus into a given line the two evaluated technologies (fast charge and slow charge) require a different evaluation scenario.

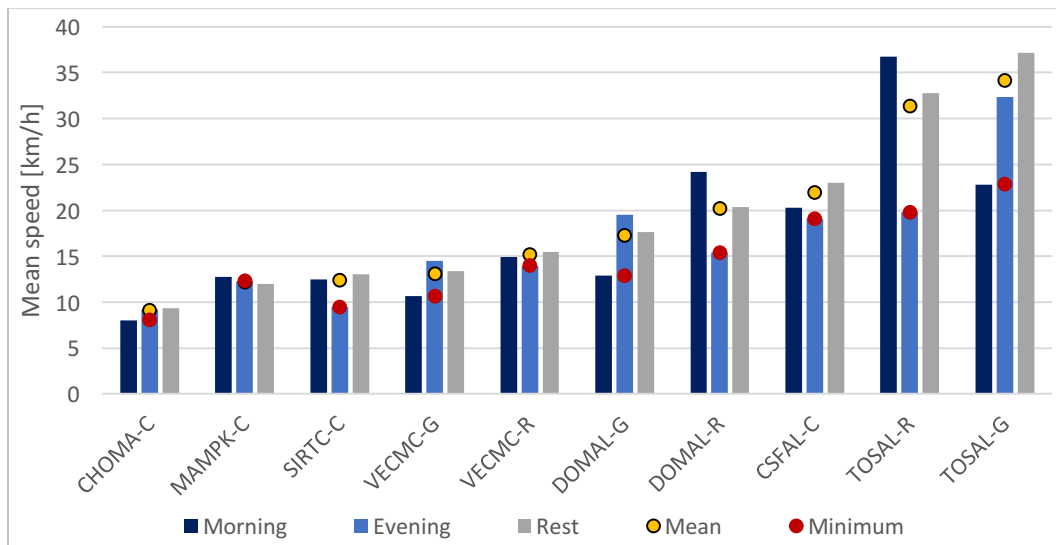


Figure 12. Mean speed of the different surveyed bus routes during the different periods of the day.

In the case of slow charging buses, these require long periods to charge and therefore should be able to cover the entire work day with one charge. Consequently, the overall mean speed of the route is a more representative condition to evaluate this technology. On the other hand, fast charging buses must be able to cover at least one full trip in order to return to the charger and recharge their battery pack before returning to service. Thus, the bus must be evaluated in the most aggressive condition, which as shown in Figure 11 is that with the lowest mean speed.

3.4.2 Passengers transported

The same principle applied when establishing the adequate operation mean speed to evaluate the viability of the different bus technologies, applies to setting the passenger load representative of the service. In the case of slow charging buses, the mean daily condition is the most representative because the bus operates all day, so the daily averaged passenger load is used. On the other hand, fast charging buses must be able to full fill the bus route in the most demanding condition, meaning, in this case, the highest passenger load.

As an example, Figure 13 shows the number of passengers and bus occupancy factor as a function of the time of day for the VECMC return route. As expected, there is a clear difference in passenger load between peak and valley time periods of the day. Also, this route shows a considerably higher occupancy factor in the early morning compared to the rest of the day.

Using the data provided by MiBus for all routes, as that presented for VECMC return route on Figure 13, the mean number of passengers and bus occupancy factor for the different evaluated routes can be calculated. These are shown on Figure 14.

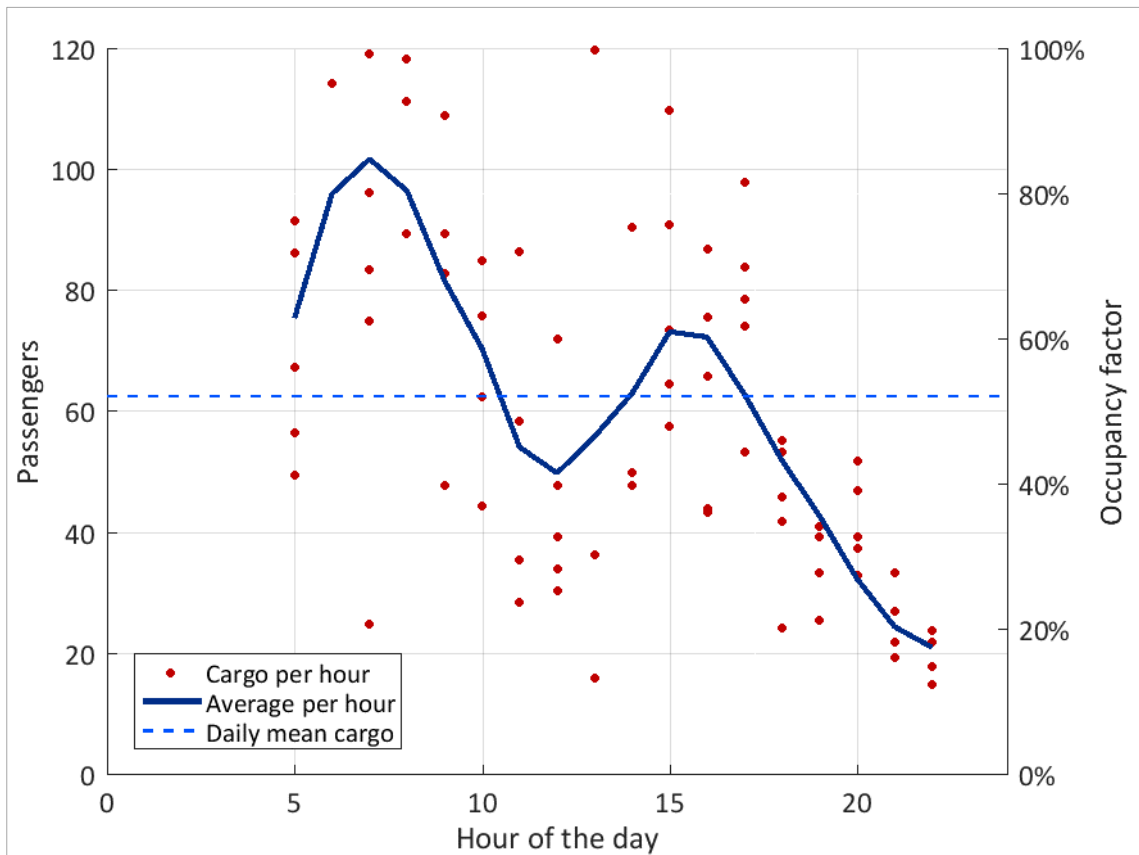


Figure 13. Number of passengers and bus occupancy factor as a function of the time of day for the VECMC return route.

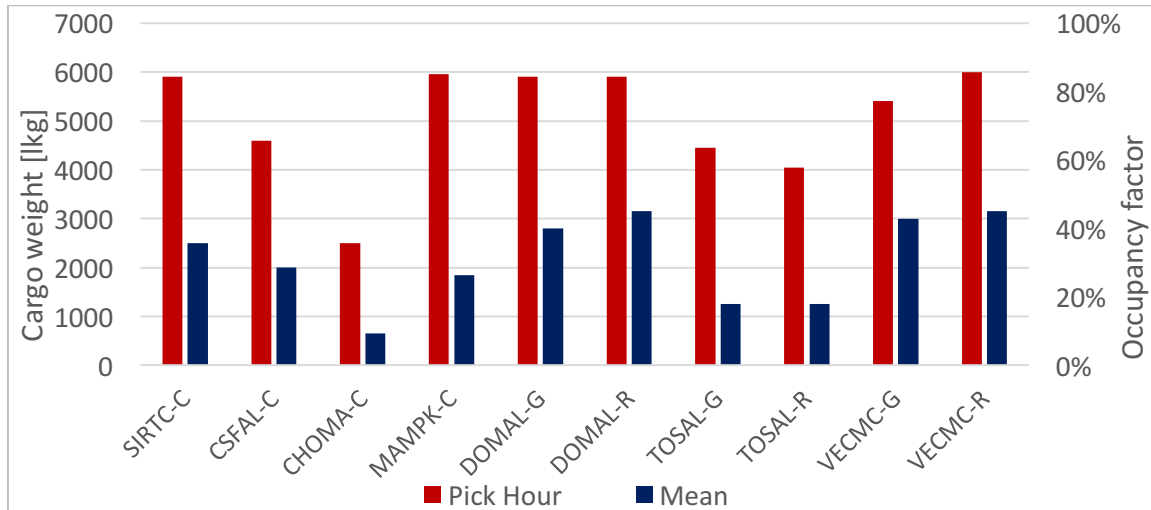


Figure 14. Peak and Mean number of passengers and bus occupancy factor for the different evaluated bus routes.

3.4.3 Ambient temperature & Air conditioning intensity

Results presented in the previous sections show the impact of the air conditioning system on a given electric bus specific energy consumption. These show that it is crucial to establish an appropriate air conditioning load when assessing the viability of introducing a given electric bus technology into a given bus route operation.

There are three main factors that affect the use of the air conditioning system in a bus: relative humidity, ambient temperature and number of passengers.

Relative humidity in Panama is always high, with an annual average of 76%¹, and normally constant throughout the day. Therefore, its effect is considered constant throughout the day.

On the other hand, **Figure 15** shows the average ambient temperature in Panama City and the number of passengers in the bus as a function of time. As expected, the ambient temperature in the city is normally high. The lowest temperatures are of around 24°C in the early morning, with a maximum of around 34°C at 1 pm. On the other hand, passenger occupancy is maximum between 7-9am in the morning and again between 5-7pm at night. Therefore, it could be argued that in order to maintain the cabin at a reasonable temperature, the air conditioning system should be at maximum capacity between 8am and 7pm, ramping up from nominal capacity between 4-8am and ramping down to nominal capacity between 7pm to midnight.

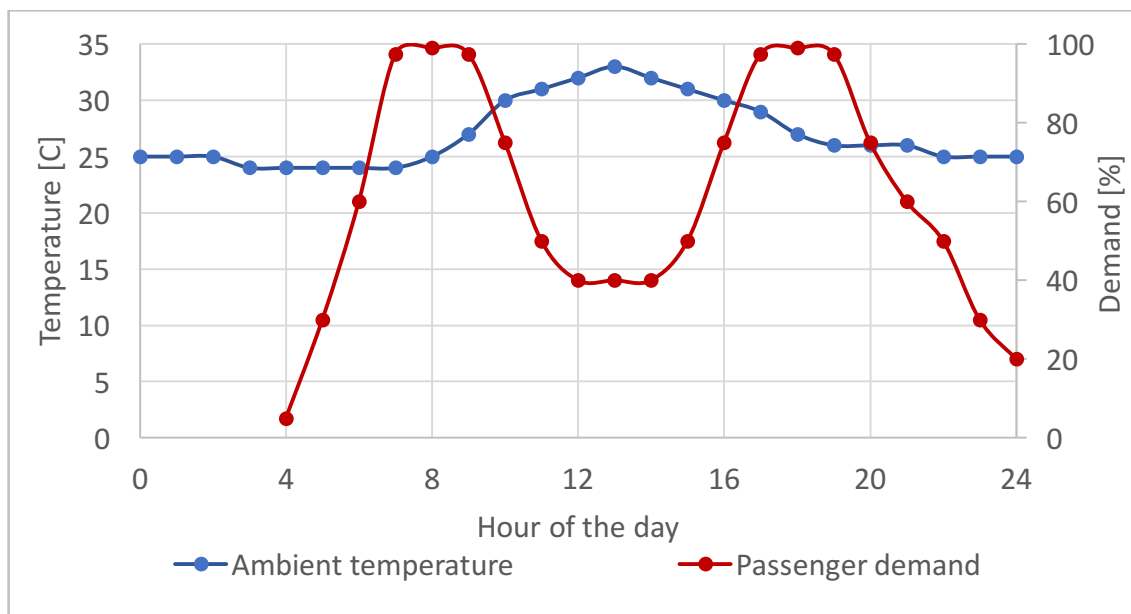


Figure 15. Panama City average temperature and number of passengers in a given bus route as a function of the time of day¹.

Based on the technical specifications of the air conditioning system detailed on **Table 5** and the above information, the air conditioning power requirement can be established. **Figure 16** shows the proposed air conditioning system hourly power demand as a function of time of day, along with the resulting mean power capacity over the entire work day.

Following the line of thought applied in the previous sections, the slow charge electric bus will be evaluated based on the mean air conditioning power requirement (12 kW), whilst the fast charge electric bus will be assessed under maximum air conditioning power load (15 kW) conditions.

¹ ETESA Hydrometeorology Department

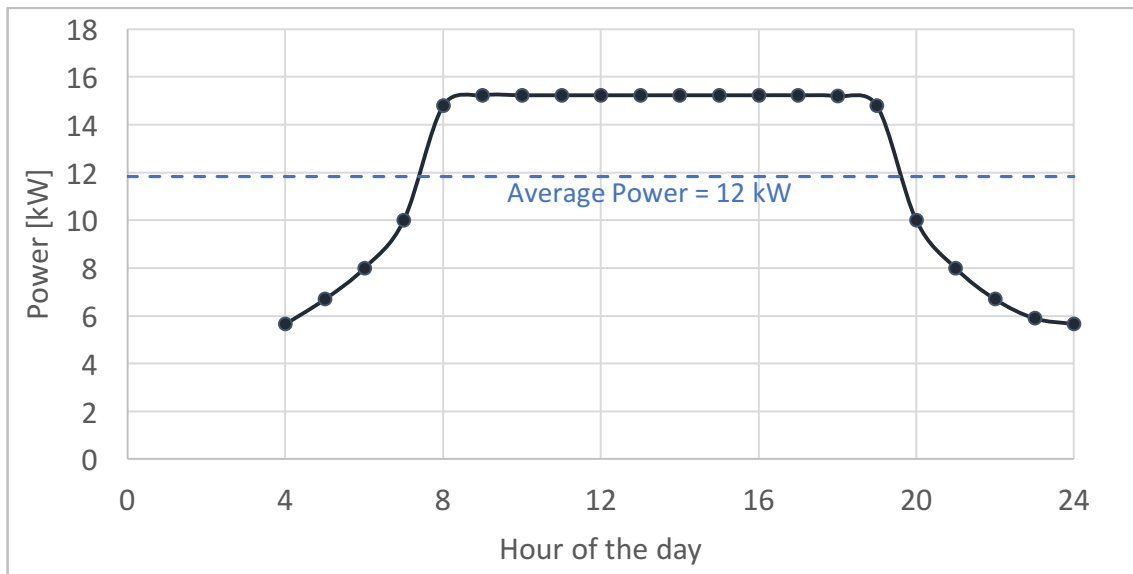


Figure 16. Proposed air conditioning system hourly power requirement as a function of the time of day, along with the mean power capacity throughout the entire day.

3.4.4 Route characteristic distances

Another crucial parameter when establishing the viability of introducing a given electric bus into a given operation are the latter’s “characteristic distances”.

These are established as, the round-trip distance of the route and the overall daily distance covered by the vehicle. The second is relevant to the slow charging buses, given that as mentioned before, these should be able to cover the entire daily operation on one charge. In the case of the fast charging buses, the round-trip distance of the route is more relevant, given that, even under the worst operating conditions, these must be able to fulfil the trip and recharge.

Information provided by MiBus regarding both the daily and round-trip distances of the different services operating in the city are plotted as a function of the service daily mean speed on **Figure 17** and **Figure 18**, respectively.

Figure 17 shows that almost all primary bus routes cover more than 200km per day. This are services that operate a full work day of 18-20 hours. On the other hand, secondary routes operate in a limited time frame and cover less then 200 km per day and in some case as little as 50 km per day. Regarding round trip distances covered by each route, **Figure 18** shows that these vary considerably. Whilst some routes are only a few kilometers long, others cover 90 km.

The surveyed routes cover a broad range of daily distances going from just under 200 km to more than 600 km per day, with trips ranging between 5 to 40 km.

Using the information presented in the current section, it is now possible to make a preliminary assessment of the electrification potential of the different services operating in Panama City and identify which technology is a more suitable match for each of them. This will be addressed in the following section.

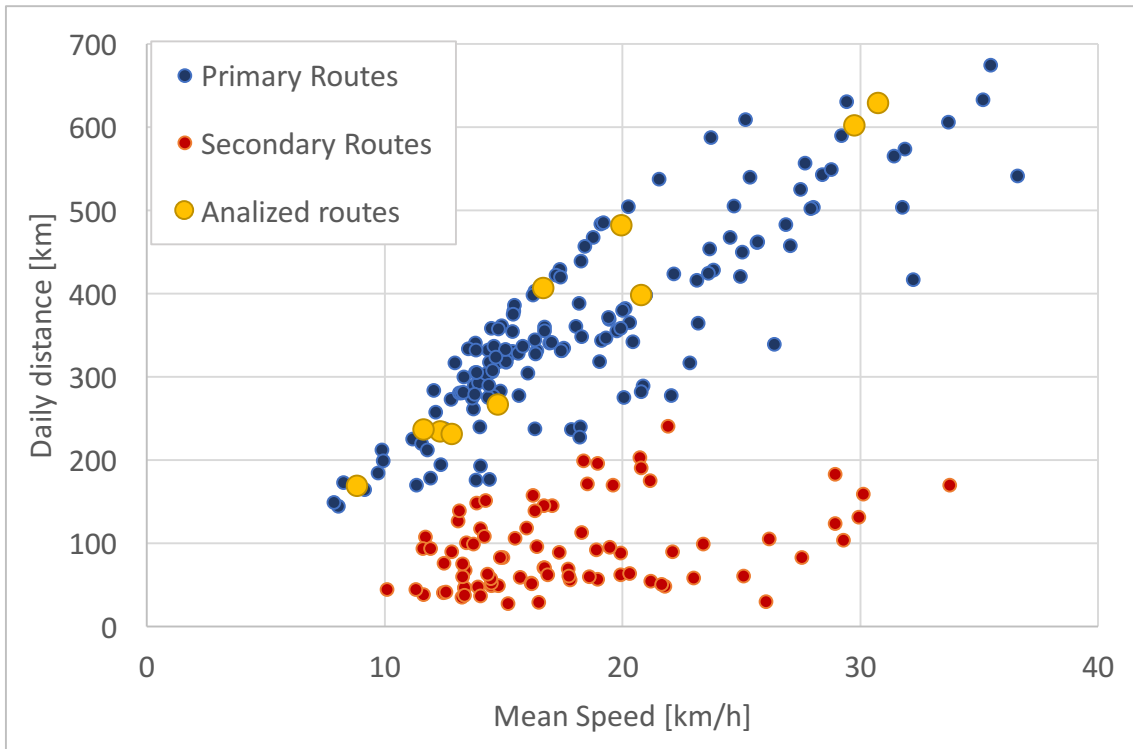


Figure 17. daily distance covered over the different bus routes as a function of their daily mean speed. Primary routes, secondary routes and the specific routes surveyed by LOGIOS are identified.

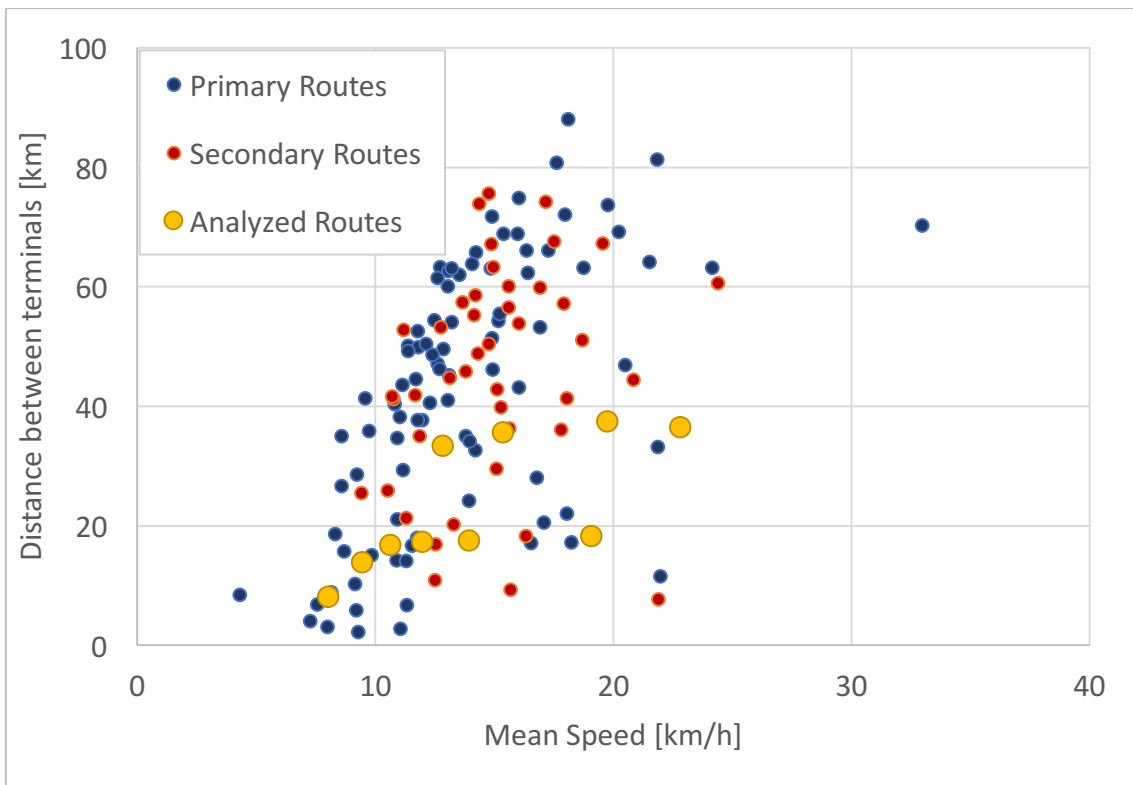


Figure 18. Round trip distance covered over the different bus routes as a function of their minimum mean speed. Primary routes, secondary routes and the specific routes surveyed by LOGIOS are identified.

3.5 Preliminary identification of electrifiable routes

The information presented in the previous sections is used to tune the models of each electric bus technology and adjusted these to local conditions. As mentioned above, the representative parameters of slow charging and fast charging bus technologies differ for each other. **Table 6** and

Table 7 sum up the operational parameters that will be used for the different vehicles to establish the range of each of these as a function of the driving profile mean speed.

Table 6. Operation parameters of each circular route for both vehicle types, rapid charge (RC) and slow charge (SC).

Route	SIRTC		CSFAL		CHOMA		MAMPK	
	RC	SC	RC	SC	RC	SC	RC	SC
Type								
Mean speed [km/h]	10	12	19	22	8	9	12	12
Passengers	79	33	61	27	33	9	79	25
A.C. Power [kW]	15	12	15	12	15	12	15	12
Daily distance [km]	236		397		168		234	
Distance between terminals [km]	14		18		8		17	

Table 7. Operation parameters of each two way route for both vehicle types. rapid charge (RC) and slow charge (SC). The letter "G" beside the names stands for go, and letter "R" for return.

Route	DOMAL-G		DOMAL-R		TOSAL-G		TOSAL-R		VECMC-G		VECMC-R	
	RC	SC	RC	SC	RC	SC	RC	SC	RC	SC	RC	SC
Type												
Mean speed [km/h]	13	17	15	20	23	34	20	31	11	13	14	15
Passengers	79	37	79	42	59	17	54	17	72	40	80	42
A.C. Power [kW]	15	12	15	12	15	12	15	12	15	12	15	12
Daily dist.[km]	406		481		628		601		231		266	
Distance bet. terminals [km]	33		36		36		37		17		17	

As for the evaluation of the K7 BYD bus, used in the pilot test, the operational range of the 12-meter electric buses analyzed is calculated assuming that the battery's minimum SOC cannot be lower than 20%. Therefore, the usable energy of a given battery pack is assumed to be 80% of the system's nominal capacity and the operational range of the vehicle can be calculated as:

$$Rg = \frac{BC [kWh]}{SEC [kWh/km]} * 0.8,$$

where Rg represents the operation range of the electric bus [km per charge], BC is the nominal energy capacity of the battery pack and SEC is the vehicle's specific energy consumption [kWh/km].

Figure 19 shows the operational range per charge for both the slow charge and the fast charge buses. The difference in the representative mean speed of the different routes

between the two technologies relies on the fact that, as mentioned before, the SEC of the fast charge vehicles is calculated using the minimum mean speed of the operation whilst the slow charge buses are evaluated using the daily mean average speed.

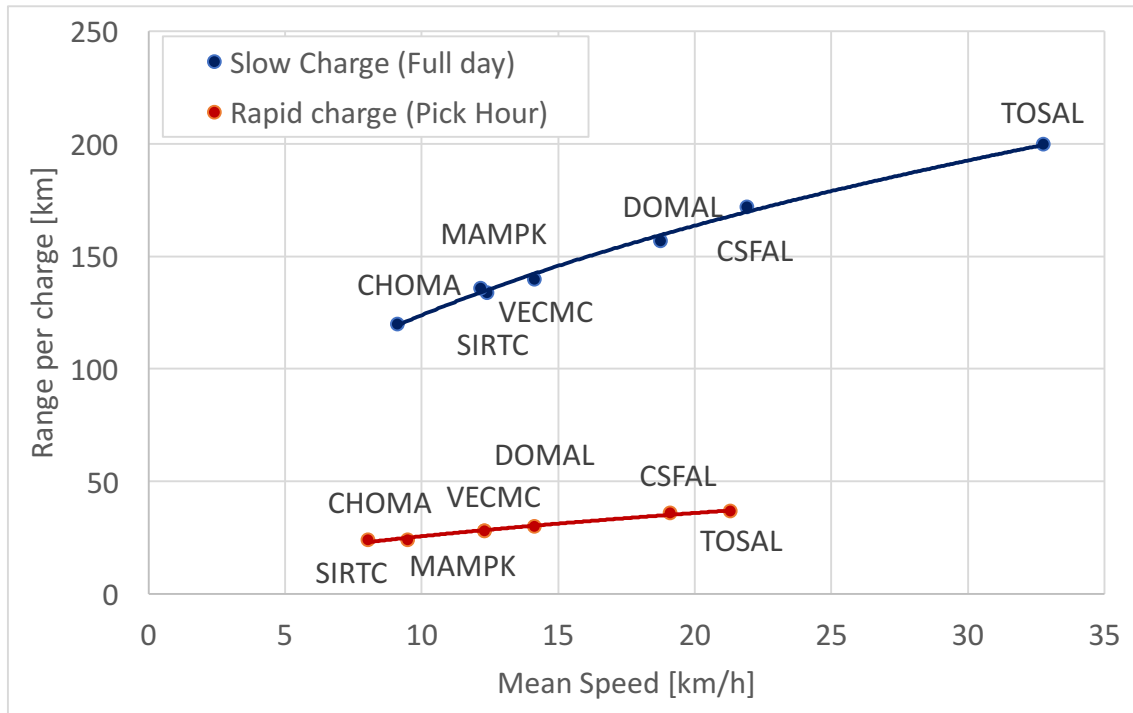


Figure 19. Operational range for both slow charging and fast charging e buses as a function of the representative driving profile mean speed.

Results show that in the case of the slow charge vehicles the operational range per charge is of between 120 to 200 km, for the slowest and fastest routes, respectively. On the other hand, as expected, fast charge vehicles have a considerably lower range per charge. This is due to the lower energy capacity of the battery, but also to the fact that these buses are evaluated under worst case conditions, whilst slow charge vehicles are evaluated based on the mean daily average.

Once the operational range per charge as a function of the mean driving profile has been established for each technology, the compatibility of these with the different bus routes can be assessed by comparing their operational range to the adequate representative route distance.

In the case of slow charging buses, the representative distance to which the operation range of the vehicle must be compared to is the daily mileage of the service. **Figure 20** shows the operational range of slow charge electric buses compared to the daily distance covered over the different bus routes as a function of their daily mean speed.

Results show that the modelled bus cannot satisfy any of the primary service routes on a single charge, included the surveyed operations throughout this project. It could be argued that the bus could stop during the middle of the day for a couple of hours to recharge, as the K7 is doing. However, this would mean that additional fleet is required to cover the service during these times, which will have a negative impact on the economic balance of the transport system. On the other hand, these buses could be used to operate on secondary service routes, given that these run for a limited period of the day. The viability of this will come down to economics. I.e. is it worth paying the extra cost for an electric vehicle if it will only be operating a few hours per day. This will be analyzed in Deliverable 2.3.

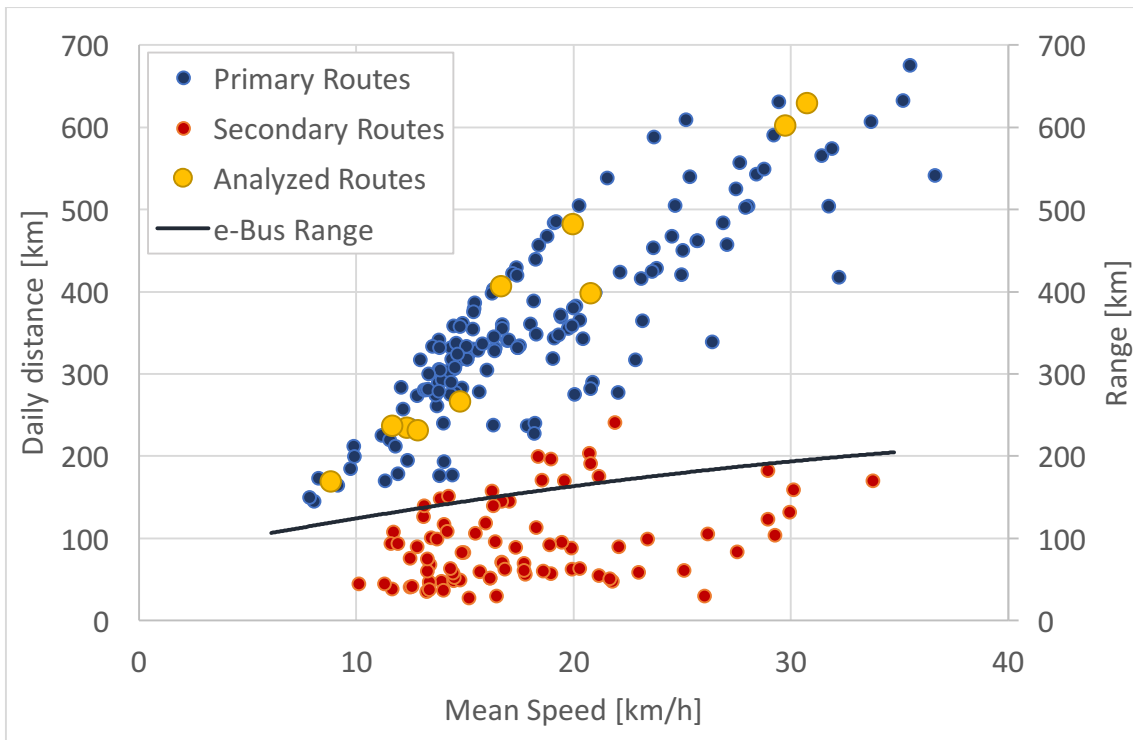


Figure 20. Slow charge electric bus operational range compared to the daily distance covered over the different bus routes as a function of their daily mean speed. Primary routes, secondary routes and the specific routes surveyed by LOGIOS are identified.

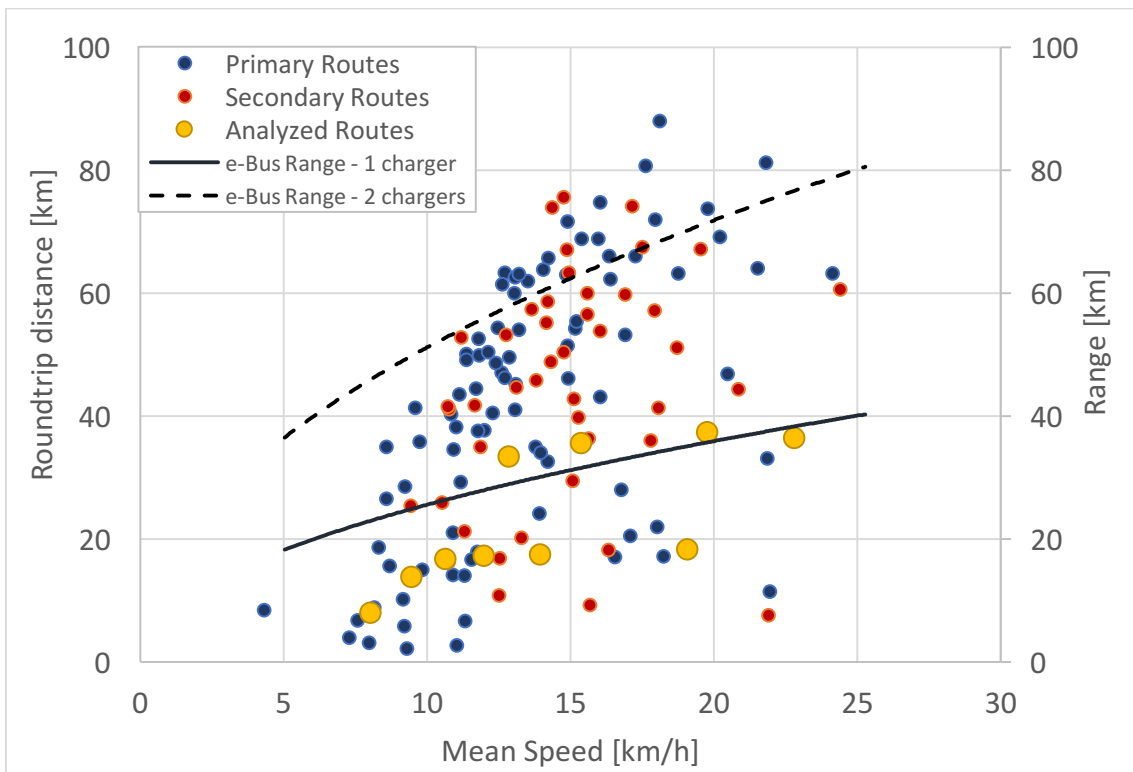


Figure 21. Fast charge electric bus operational range compared to the round-trip distance covered over the different bus routes as a function of their minimum driving profile mean speed. Primary routes, secondary routes and the specific routes surveyed by LOGIOS are identified.

Figure 21 shows the operational range of a fast charge electric bus compared to the trip distance of the bus routes as a function of their minimum mean speed.

In this case, results show that several primary routes could be potentially electrified using this technology, including most of the surveyed throughout this project. The reason for this is that, although the fast charging buses have a considerably lower range per charge than slow charging systems, local routes are predominately short, with buses doing multiple rounds a day. Therefore, the capability of these vehicle to recharge after every trip makes them very versatile. Furthermore, **Figure 21** also shows that if additional chargers were to be deployed throughout the city, the number of potentially electrifiable bus routes almost doubles.

Of course, the fleet management planning involved in operating this sort of technology is considerably greater than in the case of slow charging vehicles and deploying further infrastructure is expensive and not always possible. Therefore, the deployment of this technology requires an in-detail study to guaranty that the vehicles will be able to satisfy the service requirements.

4. Projection of fuel/energy consumption of available low emission bus technologies

To understand where electric buses stand in terms of energy consumption and environmental impact compared to other available low emission bus technologies, throughout this section the emission profile of Diesel Euro VI and CNG Euro VI buses will be assessed and compared to that of an electric bus. Furthermore, given that Panama's bus fleet is currently mostly composed of Diesel Euro III buses, the latter will be used as the baseline against which all other technologies, including the electric, will be compared to.

4.1 Fuel consumption of diesel Euro III buses in Panamá City

As mentioned above, Euro III buses are used to establish the baseline scenario against which other technologies will be compared to. Given the lack of information regarding fuel consumption of the different buses operating in the surveyed routes, a model of a Volvo B290R Euro III bus was developed and validated against empirical data from a commercial database on fleet emissions and consumption (Handbook Emission Factor for Road Transport (HBEFA)²). HBEFA is a commercial database of fuel consumption and emission factors for all current vehicle categories driven in a wide range of traffic situations developed on behalf of the environmental protection agencies of France, Germany, Switzerland, and Austria.

4.1.1 Diesel bus computational modeling

The Volvo B290R Euro III bus is one of the most common bus models operating in the city's formal public transport system. The technical specifications of the latter are shown on Table 8.

Table 8. Volvo B290R Euro III bus's specifications used to create the bus's computational model

Volvo B290R		
Chassis		
Length [m]		11.546
Max. Cargo [kg]		19,500
Engine		
Max. Power[kW]		213
Max. Torque [Nm]		1200
Reduction Gear / Final Drive		
Number of transmission ratios		4
Transmission ratios		5.05:1 to 0.73:1
Differential ratio		5.29:1
Battery Pack		
Battery capacity [Ah]		2x170
Battery Voltage [V]		24
Alternator current [A]		2x100

² <http://www.hbefa.net/e/index.html>

These parameters are used to model each component of the conventional bus shown in **Figure 22**. This is a typical powertrain found in most conventional buses. The engine is located upstream and powers all energy consumptions downstream: mechanical and electrical accessories as well as the whole transmission all the way to the wheels. This powertrain is very different to the one used to model an electric bus (**Figure 3**).

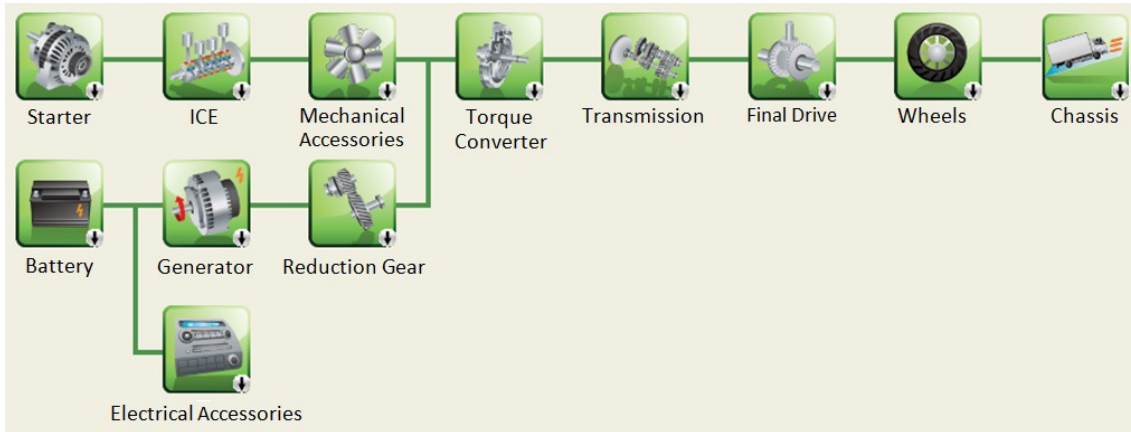


Figure 22. Powertrain architecture of a conventional bus. Each block is adapted to fit the specifications of the Volvo B290R bus.

4.1.2 Simulation results

To portray the spectrum of driving conditions facing the Panama City public transport system, the model of the Euro III bus was run for each of the driving cycles shown in **Figure 9**. Fuel consumption results for these are shown as black triangles in **Figure 23**. As for electric buses, the fuel consumption of the Euro III bus increases as the mean speed of the driving cycle is reduced. Given the low mean speed of the evaluated driving cycles, aerodynamic and rolling resistance losses are low, even for the fastest operating condition. Therefore, as the mean speed of the operation is reduced, the impact of the air conditioning and vehicle's idling losses per kilometer result in an overall increase of the vehicles fuel consumption.

The obtained results are compared to those produced by the Handbook Emission Factor for Road Transport (HBEFA) for a Euro III diesel buses considering the following parameters:

1. Total weight of bus between 15 and 18 tons.
2. Urban driving conditions, including stop and go, saturated and heavy traffic.
3. Mean route slope of 0% and 2%.

These are also shown in **Figure 23**. As can be seen, the shape of the three curves is very similar, with the model results fitting between the two curves generated with the HBEFA results, but closer to that with a mean slope of 0%. This is expected given that Panama's driving profiles have a mean slope close to zero but have rather high mean positive (and negative) slopes which makes the operation more energy consuming.

The close agreement between results attained by the developed model and those of the HBEFA suggest that the computational platform is an accurate tool. However, the impact of the air conditioning system on fuel consumption is of particular concern to LOGIOS. The Euro III bus model assumes a nominal air conditioning consumption of 6 kW, in accordance to the equipment specifications detailed above and relates well to the results of the handbook. However, the electric bus showed a higher air conditioning load, operating close to maximum capacity for most of the operation resulting in a higher overall energy

consumption. Results could have been further related to the real operating conditions of Panama city if data regarding fuel consumption had been provided by local authorities.

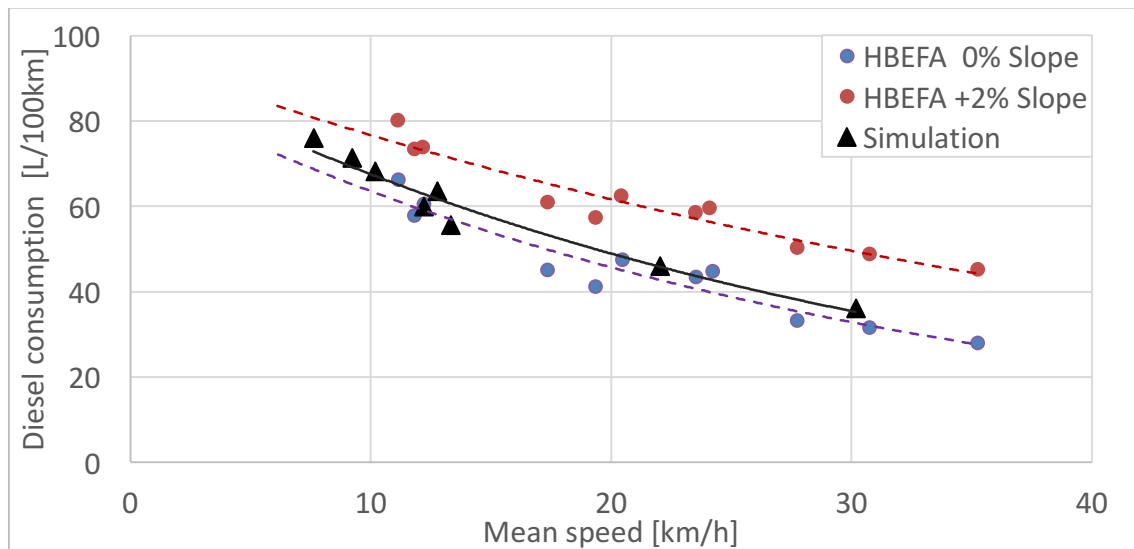


Figure 23. Fuel consumption as a function of mean speed for a Euro III diesel bus under Panama city operating conditions compared to results generated by the HBEFA with and without positive slope conditions.

4.2 Fuel consumption for Euro VI buses: Diesel & natural gas

Given the close resemblance between results obtained by the Euro III bus model, under Panama driving conditions to those produced by the HBEFA for the same vehicle, it is assumed that results from the latter for a Euro VI diesel buses are valid representation of the performance of these buses under local operating conditions. Since the Euro III diesel bus model shows a slightly higher fuel consumption than the HBEFA results, it was assumed that the same would be true for Euro VI buses, so the HBEFA fuel consumption rates for Euro VI are corrected accordingly.

On the other hand, given the fact that no data is available for Euro VI CNG buses in the HBEFA data base, further estimations are required. Experimental results published by the VTT regarding the energy consumption and emissions of different bus platforms operating under the Brunswick driving cycle, show that Euro VI CNG buses have a specific energy consumption of around 25% higher than a diesel Euro VI bus³. Therefore, it will be assumed that the energy consumption of a Euro VI CNG buses under a given operating condition, are be 25% higher than that of a Euro VI diesel buses. The resulting fuel consumptions of the different vehicles is shown in **Figure 24** as liters equivalent of diesel per hundred kilometers.

One major conclusion that can be drawn from **Figure 24** is that for low mean speed operating conditions, Euro VI diesel buses have a significantly lower fuel consumption than Euro III diesel buses. On the other hand, as the mean speed of the cycles increases, the fuel consumption of Euro III buses goes down faster than the other technologies and results in lower energy consumptions than Euro VI CNG vehicles and practically pairs that of Euro VI diesel buses.

³ Clean and Efficient Technologies for Buses, International Conference Electric Mobility and Public Transport, Santiago de Chile, 10-11 May 2017, Nils-Olof Nylund, Research Professor

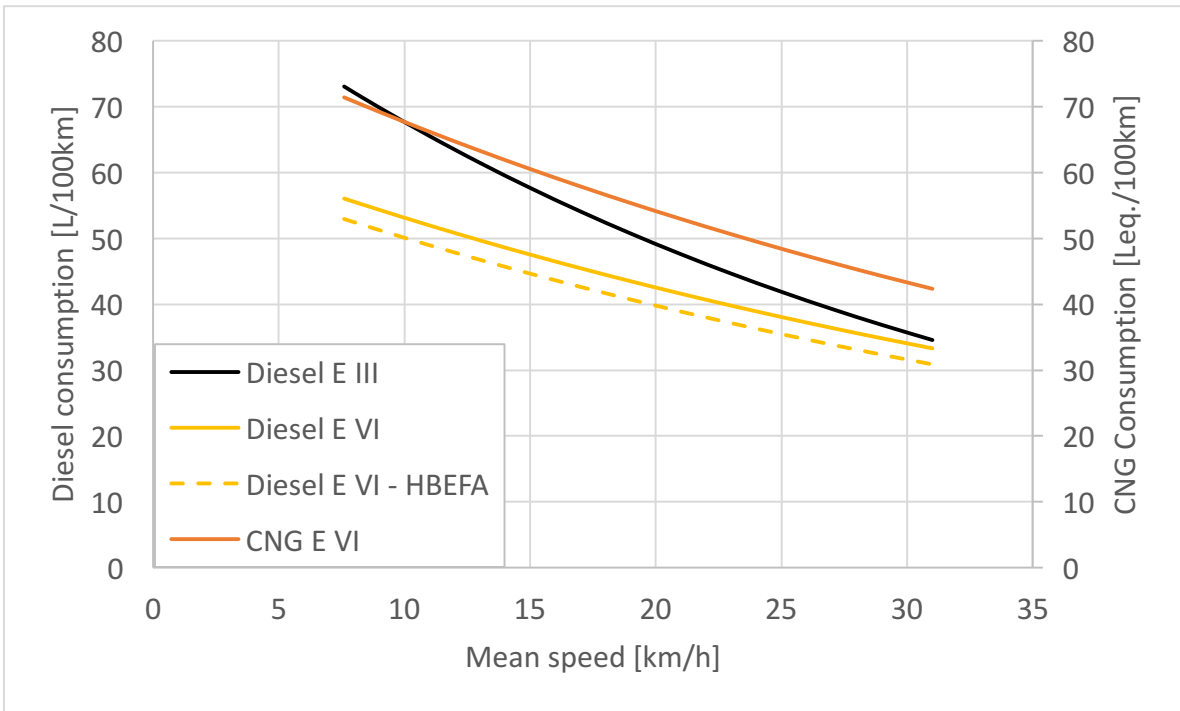


Figure 24. Fuel consumption, in liters equivalent of diesel, as a function of mean speed for Euro III, Euro VI Diesel and Euro VI CNG buses under Panama operating conditions. The original results of HBEFA for a Diesel E VI bus are shown in dashed lines to illustrate the increase projected in consumption due to Panama Operating conditions.

Using the energy consumption results of each bus, including that of the electric platforms discussed in the previous section, it is now possible to calculate and compare the environmental impact/benefit of each technology operating under local conditions. This will be addressed in the following section.

5. Environmental impact of the different bus technologies

Environmental impact studies of transportation technologies are normally divided into two parts: carbon footprint or greenhouse gas (GHG) emissions, and air quality related emissions. GHG emissions are a global polluter and therefore their reduction requires an international collaboration. In this regard, the Paris agreement details the contributions of GHG emissions reductions pledge by most industrialized countries. On the other hand, air quality is a local concern and has a direct impact on people's health.

5.1 Carbon footprint of each evaluated technology

As illustrated on **Figure 25**, the full carbon footprint of any vehicle involves the full life cycle emissions of the vehicle and those of the fuel/energy vector.

The vehicle lifecycle or embedded emissions are those produced during the entire production and disposal process of the vehicle, all the way from raw material extraction and refining to end of life scrapping and recycling. On the other hand, the life cycle emissions of the fuel/energy vector consider the GHG emissions related to the refining and production of the (indirect emissions) and those produced by the vehicle whilst operating (direct emissions).

In the case of a bus, due to the large amount of energy used over the lifetime of the vehicle, its embedded emissions are relatively small when compared to fuel/energy life-cycle emissions and will be therefore neglected throughout this study.

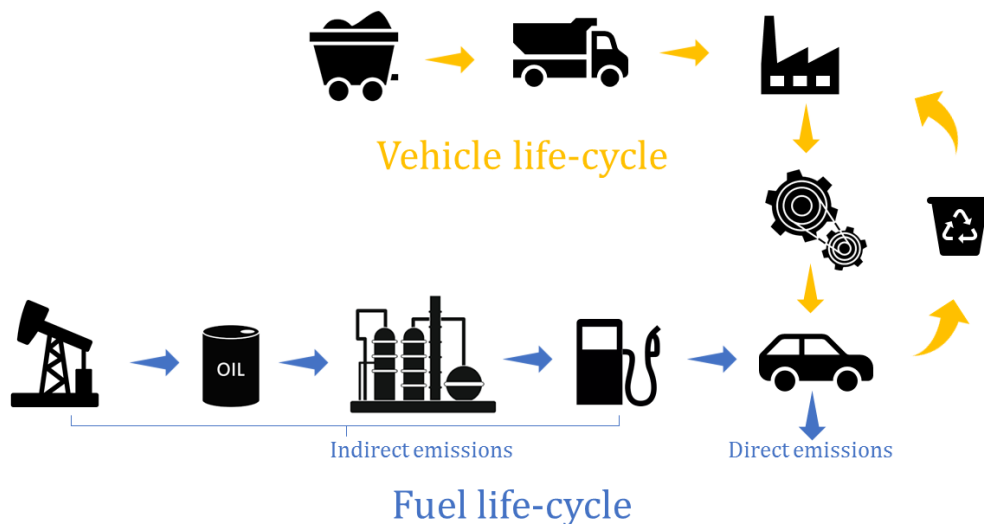


Figure 25. Vehicle and fuel life-cycle illustration. When assessing the carbon footprint of a technology, both the vehicle and the fuel's life cycles must be appraised.

As mentioned above, the fuel life-cycle emissions can be classified as indirect and direct emissions. For instance, in the case of diesel fuel, indirect emissions are those produced during oil extraction, refining, transportation, etc. until the fuel is ready to be pumped into the vehicle. These are measured in terms of mass of GHGs emitted (g) per unit of energy of fuel produced (kWh). In the case of electric buses, because the "fuel" is electricity, indirect emissions are those related to electricity generation and distribution process.

Alternatively, direct emissions are those that are produced during vehicle operation. These are measured in mass of GHGs (g) generated per energy of fuel consumed (kWh). Because electric cars do not have combustion engines, they produce no direct emissions.

Adding direct and indirect emissions, we get the total GHG emissions of the fuel cycle per energy of fuel consumed. When this is multiplied by the fuel consumption of the vehicle (calculated in the previous sections), we get the emissions of the vehicle per kilometer, as shown in the following equation:

$$E_i = F_{c,i}(F_{IE,i} + F_{DE,i}),$$

where E_i is the overall GHG emissions of technology i per kilometer, measured in g/km; $F_{c,i}$ is the fuel consumption of technology i in kWh/km; and $F_{IE,i}$ and $F_{DE,i}$ are the fuel's indirect and direct emissions of technology i . This way, the carbon footprint of all the evaluated technologies can be calculated and compared.

Next, the direct and indirect emissions of electric, diesel and CNG technologies are estimated.

5.1.1 Electricity carbon footprint

As mentioned before, electric buses have no direct emissions, and their indirect emissions are those related to the production and distribution of electricity. Therefore, to calculate the carbon footprint of this technology, the electric matrix of the city must be assessed.

The electric mix of the country was constructed using information provided by Panama's National Energy Secretary. The emission factors for all non-renewable technologies were calculated using the Greenhouse gases, Regulated Emissions, and Energy use in Transportation database (GREET⁴). It is a full vehicle and fuel life-cycle model sponsored by the Argonne National Laboratory of the U.S. Department of Energy. The model progressively builds up the carbon footprint of an electric mix, starting with the emission factors and efficiencies related to fuel extraction and production, on to transportation and power generation. The database is based on empirical data taken mostly from the U.S. but allows the user to adjust critical parameters. This way, the model can be adapted to calculate the carbon footprint of any desired electric mix.

Figure 26 shows the carbon footprint of the electric matrix of Panama divided by type of generation and including the processes required to produce the fuels necessary to feed each power plant (Bunker C, Diesel and Coal). In the same figure, the emission factors of fuels' life cycles, as well as the assumed efficiencies and emission factors for each type of energy generation are detailed. Also, the contributions of each type of generation to the matrix are shown. These were established based on information provided by the National Energy Secretary of Panama⁵.

Emissions related to the building of the different power plants are not accounted for, since none of these were built to power buses. Therefore, only plant operational emissions

⁴ <https://greet.es.anl.gov/>

⁵ Energy Secretary of Panama. (2017). *Sustainable Energy Policies: Promotion of the Paris objectives. (Pathway to Paris)*.

are considered meaning that electricity generated by renewable power stations, specifically hydroelectric, wind and solar, is carbon free.

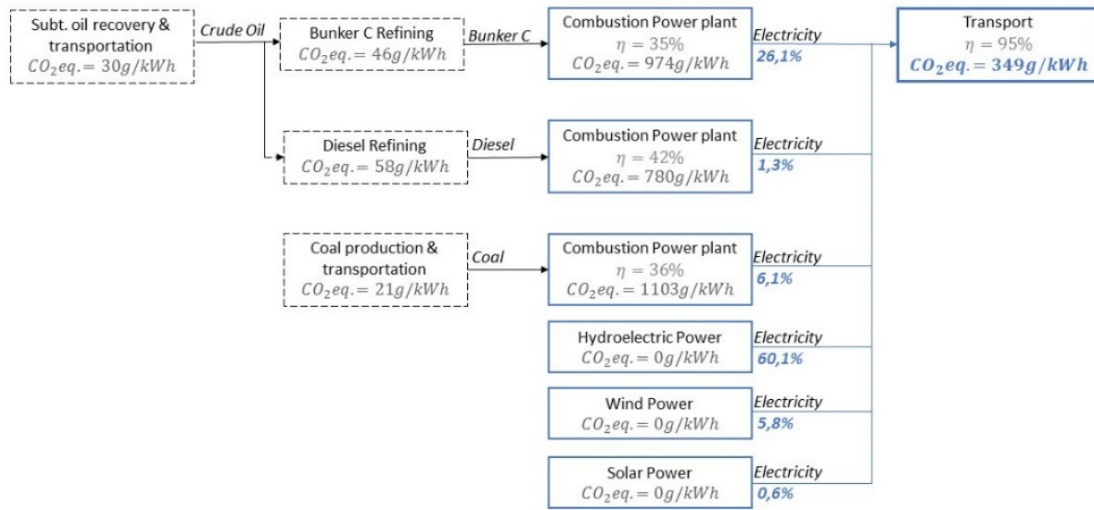


Figure 26. GHG emissions due to electricity generation. Each box represents a process and in it are displayed its efficiency and the accumulative GHG (or CO₂eq.) emissions until that point. The blue percentages represent the relative weight of each type of generation in the electric matrix. Information was provided by Panama’s Energy Ministry and modeled using GREET.

Results show that, when accounting for transmission losses, the average GHG emission of the Panamanian power generation system is of 349 gCO₂/kWh. Most emissions come from the production of electricity in thermal power plants fueled with Bunker C oil. This is a high carbon intensity power generation technology and accounts for most of the non-renewable generation.

5.1.2 Diesel and CNG carbon footprint

For the case of diesel and CNG fuels, both direct and indirect emissions must be calculated. Again, the GREET database is used to estimate the indirect emissions of each fuel. It is assumed that the process for the production and transport of the fuels is similar to that of the U.S., except for those that involved use of electrical power, for which the electricity carbon footprint of Panama calculated above is used.

In the case of direct emissions, these can be easily calculated with the fuel’s lower heating value (that is, the energy released during combustion), and the amount of carbon contained in the fuel. Assuming all the carbon will turn into CO₂, the direct emissions can be calculated as:

$$F_{DE} = \frac{C_{r,fuel}}{LHV} \cdot \frac{1}{C_{r,CO_2}},$$

where $C_{r,fuel}$ is the fuel’s carbon ratio, LHV is the fuel’s lower heating value (in kWh/g), and C_{r,CO_2} is the carbon ratio of carbon dioxide.

The resulting energy specific direct and indirect emissions for electricity, diesel and CNG are shown in **Table 9**.

Table 9. Direct and indirect GHG emissions related to each technology per kWh of fuel or electricity consumed.

GHG [g/kWh]	Electricity	Diesel	CNG
Indirect emissions	349	58	57
Direct emissions	0	270	203
TOTAL [g/kWh]	349	328	259

Whilst electricity has the highest indirect emissions of all energy vectors assessed by far, given the lack of direct emissions, it results in a comparable energy specific GHG emission intensity. Indirect emissions for both fossil fuels are similar, but CNG, having a higher LHV and lower carbon ratio than diesel, results in a lower overall emission intensity.

5.1.3 GHG emission of the different evaluated bus technologies.

Using the energy specific GHG emission intensity of the different energy vectors in combination with the fuel/energy consumption of the different buses under the different operating conditions, it is possible to calculate the GHG emissions per kilometer of each bus technology.

Figure 27 shows the resulting GHG emissions of the different bus technologies as a function of the driving profile mean speed.

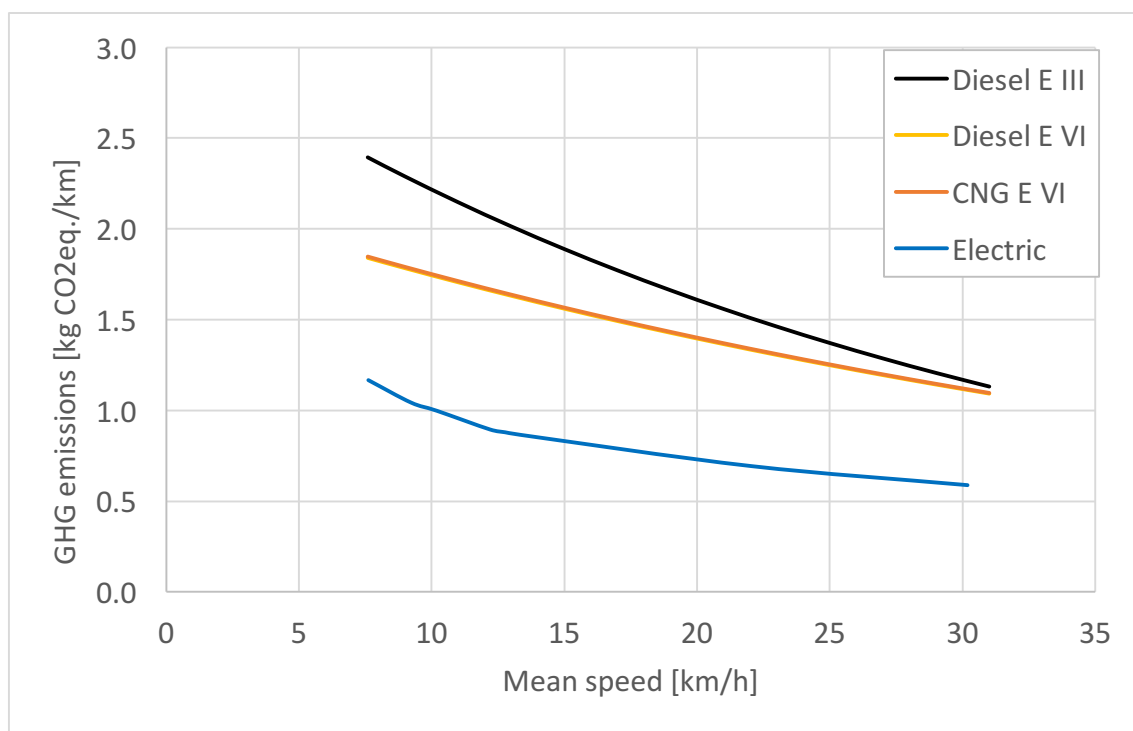


Figure 27. Carbon footprint of each evaluated technology per kilometer, as a function of mean speed. Diesel Euro VI and CNG Euro VI results are almost identical, so the lines overlap.

The GHG emissions of CNG and Diesel Euro VI buses is almost identical with curves overlapping in the figure. The reason for this is that, whilst Diesel Euro VI buses have a lower specific energy consumption than CNG buses, diesel fuel has a higher GHG specific emission factor than CNG. It is evident that the use of electric buses results in the highest GHG emission reduction over the entire operating range of the public transport system. Even though electricity has higher total emissions per unit energy than CNG, as seen in **Table 9**,

given considerably lower specific energy consumption of electric buses, their overall carbon footprint is the lowest of all.

On the other hand, whilst at low operating speeds the CNG and Diesel Euro VI vehicles also result in a noticeably lower GHG emission than the Euro III diesel bus, at high mean speeds of around 30 km/h the emissions of the Euro III bus seem to match those of the EURO VI buses.

5.2 Air quality emissions of Euro III and Euro VI technologies

The second part of the environmental impact study consists on studying the impact of each technology in air quality emissions. These emissions are toxic or harmful to citizen's health and the environment. Although these emissions include carbon monoxide (CO), unburned hydrocarbons (UHC), volatile organic compounds (VOC), nitrogen oxides (NO_x) and particulate matter (PM), due to the nature of diesel vehicles this study will focus on the two latter. As stated before, electric buses produce no emissions during operation, so changing to that technology would result in a complete elimination of air quality emissions.

In the case of diesel vehicles, the HBEFA database, used in section 4.1.2 to estimate fuel consumptions, also provides empirical measurements of NO_x and PM emissions for diesel Euro III and Euro VI buses, operating under similar conditions to those of Panama (see section 4.1.2). The emission factors were therefore exported from the database and corrected to better fit Panama's operating conditions, in the same manner as for fuel consumption. On the other hand, no data is available in the handbook for CNG Euro VI buses, however, experimental results published by the VTT regarding the energy consumption and emissions of different bus platforms, under the Brunswick driving cycle, show that Euro VI CNG have almost equal NO_x and PM emissions to diesel Euro VI buses. **Figure 28** shows the resulting air quality emissions of diesel Euro III buses and Euro VI buses.

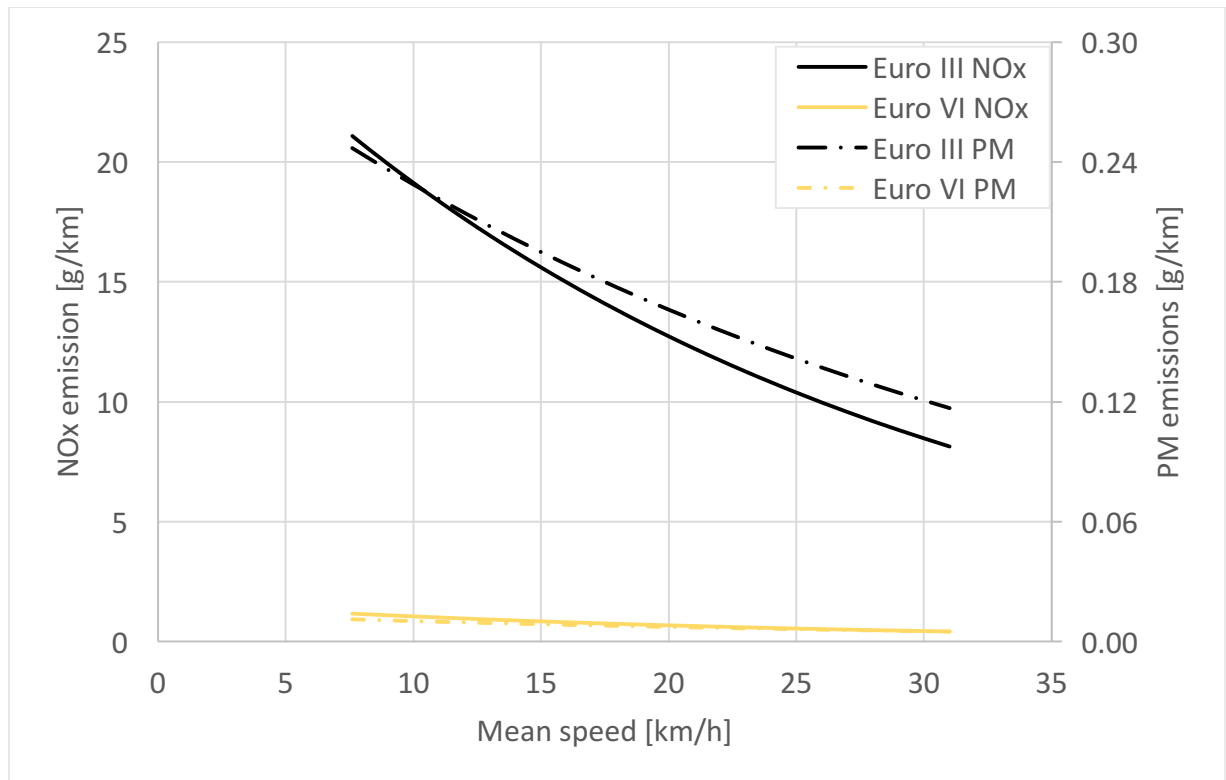


Figure 28. Air quality emissions of diesel Euro III buses compared to Euro VI buses. The solid lines correspond to NO_x emissions (left axis), and the dash-dot ones to PM emissions (right axis).

As can be seen, Euro VI standards are much more demanding than Euro III when it comes to air quality emissions, with the implementation of this technology resulting in a reduction of more than 90% compared to current vehicles. Even though improvements were also seen in fuel consumption and GHG emissions, this is where Euro VI technology makes a significant leap compared to former conventional technologies.

5.3 Potential of emissions reduction of each evaluated technology

As was shown in the previous sections, there is great potential for improving the environmental performance of Panama’s bus fleet using any of the technologies evaluated. A summary of the findings can be found in **Table 10**, where the emission reduction that would come from replacing the current Euro III buses by electric, diesel Euro VI and CNG Euro VI buses is outlined.

Electric buses are clearly the most environmental-friendly option: given Panama’s relatively clean electric matrix they greatly reduce GHG emissions, whilst eliminating toxic emissions.

Table 10. Direct and indirect GHG emissions related to each technology per kWh of fuel or electricity consumed.

Emission type	Electric	Diesel Euro VI	CNG Euro VI
GHG	48 – 57 %	4 – 23 %	3 – 23 %
NOx	100 %	94 %	94 %
PM	100 %	95 %	95 %

On the other hand, changing from Euro III buses to Euro VI buses would mean a great improvement in terms of the air quality of Panama. There would also be a decrease in the total GHG emissions of the fleet, but this improvement is not as big as the one obtained by switching to electric. As mentioned before, both Euro VI technologies share the same reductions because the higher energy consumption of the CNG buses is compensated by their lower emissions factor. It must be mentioned that electric and CNG buses have the additional advantage of being a silent technology, when compared to diesel.

6. Summary

The average energy consumption of the BYD K7 bus operated under the conditions established by the pilot test turned out to be considerably higher than the expected average consumption.

The great majority of the higher energy consumption is attributable to the use of air conditioning, which at low speeds has a considerable impact on the consumption per km of the vehicle. The slope of the route also shows to have an impact on the specific energy consumption of the vehicle, but this is lower compared to the effect of the HVAC.

The performance results, for both fast charging and slow charging 12-meter electric bus operating under local conditions, show very similar trends of specific energy consumption as a function of mean speed as those obtained by the K7 bus subject to the pilot test. Again the energy consumption requirements of the air conditioning system are projected to have a considerable impact on the specific energy consumption of the bus, and thus on its range.

When evaluating the feasibility of incorporating electric vehicles into the different bus routes operating today in Panama, it was observed that slow charge electric buses could only be used to electrify secondary lines that do not operate during the whole day. On the other hand, a significant number of primary lines could be electrified using fast-charging vehicles, and most lines could be electrified if two charging events per cycle are used.

Regarding the environmental impact / benefit of incorporating electric, Diesel Euro VI or CNG Euro VI buses into the city's public transport system, because of the high fraction of carbon-free sources in the electricity mix of Panama, electric buses will be the most effective GHG reduction technology. The latter results in an offset of around 50% compared to the Euro III vehicles currently used. Whilst the introduction of Euro VI diesel or CNG buses also results in a GHG emission reductions compared to Euro III buses, these are considerably lower than those attained by electric buses.

The introduction of electric buses results in a 100% reduction of toxic emissions. Nonetheless, the use of Euro VI buses, fueled with either diesel or CNG, are also an effective solution, capable of reducing by 95% particulate matter NOx emissions, relative to those of Euro III buses.