# TECHNO-ECONOMIC AND ENVIRONMENTAL ASESSMENT OF ALTERNATIVE BUS TECHNOLOGIES IN AMFRI – BRAZIL

FINAL REPORT

July 2020

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## 1. Context

The Association of Municipalities of the Foz do Rio Itajaí Region (AMFRI) is formed by the municipalities of Balneário Camboriú, Balneário Piçarras, Bombinhas, Camboriú, Ilhota, Itajaí, Itapema, Luiz Alves, Navegantes, Penha and Porto Belo. It was created to promote the establishment of inter-municipal and inter-governmental cooperation and expand and strengthen the administrative, economic, and social capacity of the municipalities that comprise it. With the aim of integrating the region, in the year 2017 AMFRI developed an Intermunicipal Collective Transport plan, intended to provide a reliable, safe, comfortable, clean, and effective bus transport system. As a continuation of this effort, in March 2020 a second engineering study was conducted by Mcrit and JMSouto, which provided a revised plan of the required routes, together with a detailed fleet characterization as well as an economic estimate of required capital and operational expenditures (CAPEX and OPEX) of the system. In line with this, the work at hand evaluates the tecno-economic performance of different clean bus technologies (Diesel Euro VI, CNG Euro VI, and both fast charge and slow charge electric buses) into the system. In particular, the study evaluates the technical viability of incorporating electric buses into the different projected services. Finally, the environmental benefits of the different technologies are evaluated and compared to current reference bus systems.

## 2. Introduction

To understand the techno-economic and environmental performance of any vehicle fleet it is imperative to understand the operating conditions of the latter. This is considerably more pertinent for electric vehicle fleets, where vehicle range is limited and establishing the capability of a given bus of satisfying the required daily service, without the need of increasing the reserve fleet or incurring in large additional charging infrastructure expenditures is not trivial.

To estimate the expected range of the different commercially available electric bus technologies it is first required to have a clear understanding of the operating conditions imposed by the required service. This will be of course related to the vehicles energy capacity and the specific energy consumption per km resulting of the operation. Independent of the vehicle, specific energy consumption depends on factors that vary from one city to another and from one service to another.

Also, because the electricity generation and distribution matrix vary significantly from one country or region to another, the environmental impact of each technology will also differ. Coupled with the fact that price structures also change, there is a need to perform detailed studies to understand the real costs and benefits of alternative bus technologies deployed in a specific region.

Based on the above, at the beginning of the project the consulting team travelled to Brazil to meet with local stakeholders, obtain real operational data of the current bus system, and have a first-hand experience of the current transport system. A detailed description of the meetings held, and the information gathered during the mission can be found in deliverables 2.1 “Work done in Itajaí over data collection mission” and 2.2 “First package of processed data”. A third deliverable, deliverable 2.3, named “Local operating conditions” presented the methodology used to establish the main expected operating conditions and the projected driving cycles for each of the projected routes. As a continuation of this work, this report presents the results of the overall study, from required bus fleet projections to economic and environmental performance of each of the evaluated clean bus technologies.

The report begins with the redefinition of the operating conditions of the routes. This had to be done given that the driving cycles prepared for deliverable 2.3 were based upon the routes defined in the 2017 Transport Plan, which were updated by the recent 2020 engineering study. With the operating conditions re-established, the approach towards fleet projection is presented. After that, the report presents the methodology used to estimate the energy consumptions of each technology and compares the results as well as the technical electrification feasibility of each route. With these results, a forecast of the expected capital and operational expenditures is outlined, as well as the environmental impact of each technology.

## 3. Re-establishing AMFRI's Operating Conditions

In March 2020 Mcrit and JMSouto presented a pre-feasibility engineering study for an "Integrated Transport System at the Foz do Rio Itajaí Region". The scope of the project included determining the infrastructure requirements for developing a BRT in AMFRI based on existing demand estimates and the analysis of possible river crossing solutions. The study redefined the routes or systems upon which the BRT would be placed. Also, the project was divided into four systems, namely the North, West, South and Central systems, for which bus stops and expected fleet commercial speeds where outlined.

Based upon the existing demand, it was determined that the most critical systems are the North, Central and South systems, which are shown in Figure 1. For each of these, dedicated, reversable and/or shared lanes were defined to support the BRT system. As can be seen, the three systems connect the main urban settlements across the shore, form Piçarras to Bombinhas. The central system, which includes the most densely populated areas, has two ramifications, which connect Navigantes to either Camboriu or Balneario Camboriu and going through the largest city which is Itajaí.

Figure 1 Public transport systems defined in Mcrit and JMSouto engineering study. The most important systems are shown, namely south system, north system and both variations of the central system.

The West system connects Itajaí and Navegantes with other cities towards the continent, such as Brusque, Blumenau and Luis Alves. Because this system has a much lower demand than the rest, no route infrastructure modifications or dedicated lanes were produced. As will be seen in section "Fleet Projection" the approach towards building the bus system was different and defined a lower bus frequency.

As mentioned above, the updated transport system is different to the one defined in the 2017 Transport Plan, therefore, the operating conditions defined in deliverable 2.3 had to be also updated. Because the methodology used to establish the service operating conditions is explained in detail in deliverable 2.3, only a summary is presented next.

### a. Methodology

The energy consumption of buses, whichever their technology, depends on the operating conditions to which they are exposed, and these can vary greatly from one city to the next. The main parameters that define the energetic performance of a bus are:

1. **Driving cycles**: driving cycles synthesize the buses' expected speed and slope profiles along the different routes. They can be used to simulate and determine the energy consumption of different vehicles on specific routes.

2. **Passenger occupancy**: the number of passengers greatly affects the overall weight of the vehicle and therefore its energy consumption.
3. **Ambient conditions**: ambient conditions greatly affect the energy consumption of a bus. Not only because of its effect on the engine's performance, but also because they lead to the use of heating and/or AC, which draw large quantities of energy.

Because the routes were redefined, new driving cycles were created. Passenger occupancy factors were also adapted, as will be seen in section "Fleet Projection". Ambient conditions, however, are the obviously the same and therefore were not revised.

Because no real operational data is available to build driving cycles -given that the BRTs are yet to be built-driving cycles were built using operational data from BRTs in other cities collected by the 35South team, but adapted to fit the characteristic speeds and slopes of AMFRI's projected transport systems. The algorithm used to do this is presented in deliverable 2.3. Next, the specific speed and slope targets are described.

### b. Speed targets

The 2020 pre-feasibility engineering study defined the expected mean speeds for each segment that composes the North, West, Central and South systems. To do this, the amount of stops of each segment was considered, as well as the expected speeds for highway, urban and rural traffic. The resulting mean speeds calculated in the pre-feasibility study are shown in Table 1 and As can be seen, Central and North speeds range from 15 to 22 km/h which are reasonable speeds for BRTs in urban areas. The South system, on the other hand, has two urban segments (Bombinhas-Porto Belo and Porto Belo-Itapema) and one highway segment from Itapema to Balneario Comboriú. This segment comprises the BR-101 route and has much higher speeds of 35 km/h. Finally, the west system has high mean speeds, going from 42 to 47 km/h, given that it is composed of low traffic routes that cover long distances within low-density population areas.

Table 2.

Table 1. Projected total distance and mean speeds for each of the segments of the south and north systems.

| | South system | | | North system | |
|---|---|---|---|---|---|
| | Bombinhas - Porto Belo | Porto Belo - Itapema | Itapema – Bal. de Camboriú | Balneário Piçarras-Penha | Penha - Navegantes Aeroporto |
| Distance (go) [km] | 12 | 6.5 | 17 | 9 | 12.5 |
| Mean speed [km/h] | 21 | 19 | 35 | 17 | 22 |

As can be seen, Central and North speeds range from 15 to 22 km/h which are reasonable speeds for BRTs in urban areas. The South system, on the other hand, has two urban segments (Bombinhas-Porto Belo and Porto Belo-Itapema) and one highway segment from Itapema to Balneario Comboriú. This segment comprises the BR-101 route and has much higher speeds of 35 km/h. Finally, the west system has high mean speeds, going from 42 to 47 km/h, given that it is composed of low traffic routes that cover long distances within low-density population areas.

Table 2. Projected total distance and mean speeds for each of the segments of the central and west systems.

| | Central System | | | | West system | | |
|---|---|---|---|---|---|---|---|
| | Navegantes Aeroporto – Itajaí | Itajaí - Nações (BC) | Nações - 3a Av- Univali /Hospital (BC) | Nações– Tabuleiro (Camb.) – Camb Prefeitura | Itajaí-Brusque | Itajaí-Gaspar-Blumenau | Navegantes-Luiz Alves |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Distance (go) [km] | 8.5 | 8.5 | 3.5 | 5.4 | 36.9 | 48.5 | 36.6 |
| Mean speed [km/h] | 17 | 20 | 15 | 16 | 42 | 45 | 47 |

Given the greater importance of the Central, North and South systems, driving cycles were devised for each of them. In the case of the South system, because it is made up of two very different forms of traffic, two driving cycles were made, one for urban traffic from Bombinhas to Itapema, and another one for highway traffic from Itapema to Balneario Camboriú.

For the case of the Central system, even though it has two extensions, most of the route is the same for both, and their mean speeds end up being very similar. The resulting mean speeds of each system used to build the driving cycles is shown in Table 3.

Table 3. Projected means speeds for each of the segments of the central and west systems.

| | Central | North | South Bominhas - Itapema | South Itapema- Bal Camboriu |
|---|---|---|---|---|
| Target speeds [km/h] | 17.6 | 19.5 | 20.4 | 35.2 |

For the case of the West system, because of the much lower demand, and given the fact that it covers lower density areas, requiring a smaller fleet, the approach towards the estimation of energy consumption was less detailed. This means that no driving cycle was built for this system, and energy consumptions were estimated based on the results for the other systems. This will be further explained in section "Energy consumption".

### c. Slope targets

The characteristic slopes of each system were not defined in the 2020 engineering study, and was therefore estimated by the 35South team. To do this the coordinates of each route were defined using the information in the detailed engineering study and the altitude for each point in the route was extracted using Google Earth.

With this information it is possible to calculate the slope along each route, and therefore build driving cycles that take this parameter into account. The equations used to calculate the slopes are detailed in deliverable 2.3. The resulting topographical relief of the North, Central and South system can be seen in Figure 2, with the altitude of each point augmented for visualization purposes.

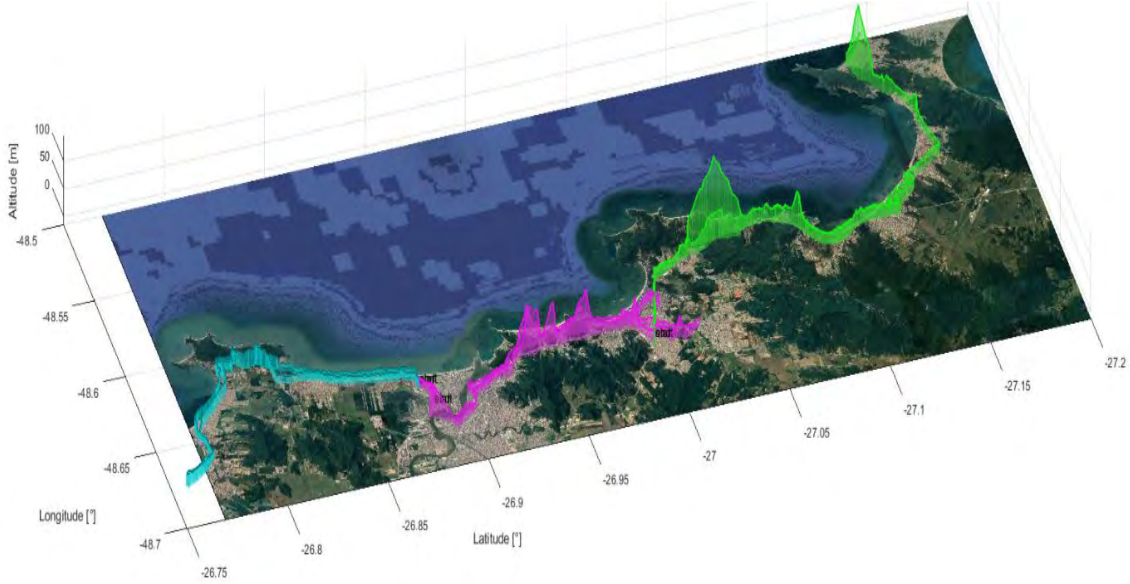

Figure 2 Augmented topographical relief of the north (cyan) central (magenta) and south (green) systems used to determine the slope characteristics of these three main systems.

As can be seen, the Central and South systems have the greatest variations of altitude. The Morro do Boi and Morro do Macaco stand out in the South system. As for the Central system, even if it does not have reach great altitudes, many variations can be seen, causing rather high slopes in the system. The projected altitude of the bridge from Itajaí to Navegantes was included in this study as well.

Table 4 summarizes the main characteristics of each system, including mean positive and negative slopes and means speeds. These are the targets used to build the four driving cycles that represent the different operating conditions of the region. The high slopes observed in the previous figure are made evident when comparing the mean slopes of the Central and South systems, to that of the rather flat North system.

Table 4. Slope and speed targets for the three most important systems. Colors are as in previous figure.

| | Central | North | South Bominhas - Itapema | South<br>Itapema- Bal Camboriú |
|---|---|---|---|---|
| Mean positive slope [%] | 2.58 | 1.02 | 2.59 | 2.28 |
| Mean negative slope [%] | -2.72 | -0.97 | -2.53 | -2.24 |
| Mean speed [km/h] | 17.6 | 19.5 | 20.4 | 35.2 |

Before moving on to calculating the energy consumption of the different bus technologies under these operating conditions, the type of bus to be used must be defined. Namely, if conventional 12-meter buses will be suitable, or articulated 18-meter buses will be necessary. This is done in the following section in which the required fleet is calculated.

## 4. Fleet projection

A projection of the fleet necessary for the four systems outlined was prepared. The fleet was calculated based on preliminary demands projections shared by the World Bank Group, and looking to produce a high-quality, reliable service that would increase the amount of people using public transportation.

### i. Methodology

The methodology used to calculate the fleet projection was based on the same starting points and basic hypothesis as that of Mcrit and JMSouto engineering study. For the case of the Central, North and South systems, the fleet projected was based on the daily trips demanded between their main locations, which are shown in. Given that the West system has a much lower demand, a fixed frequency was set, and the amount of buses was calculated accordingly.

Also, the same demand distribution during the day was used, with 3 peak hours and 14 of peak hours, and having each peak hour take up 13% of the daily demand.

Table 5. Preliminary demand used to estimate the required fleet. Demand is expressed in daily trips between locations.

| year | Bombinhas - Porto Belo | Porto Belo - Itapema | Piçarras-Penha | Penha-Navegantes | Itapema – Bal. Camboriu | Navegantes-Itajai | Itajaí - Nações (BC) | Trecho central – Bal.Camb | Trecho central - Camb |
|---|---|---|---|---|---|---|---|---|---|
| 2016 | 1,322 | 3,291 | 2,197 | 6,086 | 3,437 | 20,333 | 7,524 | 13,219 | 12,495 |
| 2020 | 2,059 | 3,877 | 9,554 | 6,170 | 7,031 | 24,954 | 13,562 | 13,363 | 15,756 |
| 2030 | 3,927 | 7,778 | 14,390 | 11,891 | 12,305 | 40,806 | 22,896 | 21,162 | 25,721 |
| 2045 | 7,603 | 13,778 | 19,283 | 19,213 | 20,904 | 63,493 | 37,244 | 31,231 | 40,129 |

Because the peak hours take up the greatest demands, these are used to determine the minimum amount of buses needed for each segment of the system. As in Mcrit and JMSouto's study, the demand distribution during the day was assumed to be composed of 3 peak hours and 14 off-peak hours, with each peak hour taking up 13% of the daily demand.

The amount of buses and their frequency obviously depends on the capacity of buses considered. The engineering study by Mcrit and JMSouto initially considered three types of buses: standard 12-meter, articulated 18 meter and biarticulated 24-meter buses. However, the capacity assumed for each of these -buses was too high to be considered a high-quality service. Table 6 shows the capacity of each of these buses, as considered by 35South and Mcrit and JMSouto. Their seated capacity is also shown for reference.

Table 6. Bus capacity of 12, 18 and 24-meter buses.

| | Bus length | | |
|---|---|---|---|
| Capacity | 12 | 18 | 24 |
| Seated | 34 | 55 | 70 |
| Full-35South | 60 | 100 | 160 |
| Full-Mcrit & JMsouto | 100 | 130 | 160 |

Once the capacity of the buses has been determined, the frequency with which each of these buses would have to circulate to provide all the demanded trips in peak hour can be determined. These results are shown in Table 7 for the case of the year 2020. As can be seen, the higher the demand, the lower the frequency needed. Also, as the bus capacities increase, so do the frequencies. This means, in the case of Itapema-Balneario Camboriu for example, that a 12-meter bus carrying 60 people every 8 minutes will transport the same amount of people as an 18-meter bus carrying 100 people every 13 minutes.

Table 7. Frequency (minutes) of buses needed to satisfy demand in peak hour for each segment

| bus length | Bombinhas - Porto Belo | Porto Belo - Itapema | Itapema – Bal. Camboriu | Piçarras-Penha | Penha - Navegantes | Navegantes-Itajai | Itajaí - Nações (BC) | Trecho central – Bal.Camb | Trecho central - Camb |
|---|---|---|---|---|---|---|---|---|---|
| 12 | 27 | 14 | 8 | 6 | 9 | 2 | 4 | 4 | 3 |
| 18 | 44 | 24 | 13 | 10 | 15 | 4 | 7 | 7 | 6 |
| 24 | 71 | 38 | 21 | 15 | 24 | 6 | 11 | 11 | 9 |

Table 7 also shows that for some of the segments, frequencies can be very high. For instance, for the case of Bombinhas-Porto Belo, even using 12-meter buses, the frequency obtained is of 27 minutes, which is clearly too high when aiming to have a high-quality transport service. Frequencies of more than 15 minutes are generally considered too high.

Once the required frequencies have been established, knowing the expected speeds and distances traveled by the buses (see Table 1), it is possible to calculate the amount of buses that would be needed to meet each frequency. These results are shown in Table 8. Also, the amount of buses needed to have a maximum frequency of 15 minutes is shown in the table.

Table 8. Amount of buses needed to transport passengers in peak hour and amount needed to keep frequency below 15 minutes.

| bus | Bombinhas - Porto Belo | Porto Belo - Itapema | Itapema – Bal. Camboriu | Piçarras-Penha | Penha - Navegantes | Navegantes-Itajai | Itajaí - Nações (BC) | Trecho central – Bal.Camb | Trecho central - Camb |
|---|---|---|---|---|---|---|---|---|---|
| 12 | 3 | 4 | 9 | 13 | 9 | 30 | 14 | 8 | 13 |
| 18 | 2 | 2 | 5 | 8 | 5 | 18 | 9 | 5 | 8 |
| 24 | 2 | 2 | 4 | 5 | 4 | 12 | 6 | 3 | 5 |
| *15min* | *5* | *3* | *5* | *5* | *5* | *5* | *4* | *3* | *3* |

When choosing the type of bus for each segment, in general, the lower the amount of buses, the better, mainly given that drivers' salaries are generally the largest component of bus transport systems' operative expenses. Therefore, the larger capacity buses are usually the best way to go in terms of cost efficiency. However, as stated before, the higher the bus capacity, the higher the service frequency.

Therefore, the criteria used to determine the type of buses was to choose the 18-meter buses when these implied a reduction in amount of buses compared to the 12-meter buses, but without producing frequencies of more than 15 minutes. Otherwise, 12-meter buses were chosen. Bi-articulated buses are implemented when frequencies are very low to avoid big overlaps in services. However, in this case, the lowest frequency obtained with 18-meter buses is of 4 minutes, which is acceptable. Thus, no 24-meter buses were selected. Table 9 shows the resulting necessary type and amount of buses needed for each segment, and the resulting service frequency.

Table 9. Resulting necessary fleet and service characteristics for each segment.

|  | Bombinhas - Porto Belo | Porto Belo - Itapema | Itapema – Bal. Camboriu | Piçarras-Penha | Penha - Navegantes | Navegantes-Itajai | Itajaí - Nações (BC) | Trecho central – Bal.Camb | Trecho central - Camb |
|---|---|---|---|---|---|---|---|---|---|
| Bus length | 12 | 12 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Buses needed | 5 | 4 | 5 | 8 | 5 | 18 | 9 | 5 | 8 |
| Freq [min] | 14.7 | 11.0 | 12.6 | 8.7 | 14.7 | 3.6 | 6.3 | 6.1 | 5.4 |

It is not yet clear whether the different systems will share buses amongst them, or where the buses will be parked. Consequently, for this initial calculation, it was assumed that each system is composed of an independent fleet, and therefore, the fleet needed for the different segments was added separately to each individual system. Table 9 indicates the resulting fleet needed for the 2020 demand. For the case of the West system, the target frequency for 2020 was 60 minutes and the fleet is composed fully of 12-meter buses. A reserve fleet of 10% was added, same as in Mcrit and JMSouto's study.

Table 10. Resulting necessary fleet compared to results for previous engineering study

| | Central | South | North | West | Reserve | Total |
|---|---|---|---|---|---|---|
| New fleet | 40 | 13 | 13 | 7 | 8 | 81 |
| *Previous fleet* | *36* | *13* | *11* | *7* | *7* | *74* |

Having the total fleet calculated, it is possible to project the total annual kilometers that will be traveled in each system. This is a critical number, since it is used to calculate the total fuel/energy that will be consumed by these buses, as well as their required maintenance.

When calculating this number, it was assumed that during off-peak hours, only 60% of the fleet will remain operative, given the decline in demand. This implies a considerable increase compared to the 33% projected by Mcrit and JMSouto but was found necessary for the system's frequency to remain acceptable. The final annual kilometers traveled for each system are shown in Table 10.

Table 11. Annual kilometers traveled by each of the transport system

| Central | South | North | West |
|---|---|---|---|
| 2,400,000 | 1,260,000 | 860,000 | 760,000 |

It is clear, from Table 9 and Table 10, that the Central system is by far the one with the biggest demand, taking up around half of the total necessary fleet annual kilometers traveled.

### ii. Fleet growth

All of the results presented above, from Table 7 to Table 11, are for the case of the demand of 2020. However, given that the financial viability of the project will depend on its performance during the next 20 years, and since the demand is projected to grow (see Table 5), the required fleet for the 2020-2040 period was calculated, using the above methodology.

Assuming buses have an operative life of around 10 years, the projected necessary fleet purchases to satisfy the 2020-2040 demand was calculated. The results were split in 18 and 12-meter buses and are shown in Table 12. As can be seen, every 10 years a big fleet renewal must be done, given that the initial buses are retired. Also, after 2020, 12-meter buses are only bought for the West system, given that the rise in demand makes 18-meter buses more suitable for all the other systems. Also, for the case of the West system, in accordance to what was projected by Mcrit and JMSouto, the required frequency of the system was set at 45 minutes for 2030 and 30 minutes for 2040.

These results will be used to address the expected capital and operational expenditures of the system over the next 20 years. But first, the expected energy consumption of this fleet will be calculated for a variety of technologies to understand the implications of implementing Diesel, CNG or electric bus solutions.

Table 12. Projected fleet purchases to satisfy 2020-2040 demand

| | 18m buses | | | | 12m buses | | | |
|---|---|---|---|---|---|---|---|---|
| year | Central | South | North | West | Central | South | North | West |
| 2020 | 44 | 9 | 14 | 0 | 0 | 6 | 0 | 8 |
| 2022 | 4 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 2024 | 7 | 1 | 2 | 0 | 0 | 0 | 0 | 0 |
| 2026 | 4 | 1 | 2 | 0 | 0 | 0 | 0 | 0 |
| 2028 | 6 | 1 | 2 | 0 | 0 | 0 | 0 | 0 |
| 2030 | 52 | 15 | 15 | 0 | 0 | 0 | 0 | 11 |
| 2032 | 9 | 3 | 3 | 0 | 0 | 0 | 0 | 0 |
| 2034 | 11 | 2 | 3 | 0 | 0 | 0 | 0 | 0 |
| 2036 | 9 | 1 | 3 | 0 | 0 | 0 | 0 | 0 |
| 2038 | 10 | 3 | 3 | 0 | 0 | 0 | 0 | 0 |
| 2040 | 57 | 18 | 18 | 0 | 0 | 0 | 0 | 14 |

## 5. Technologies evaluation

As was stated before, one of the main purposes of 35South's work in AMFRI is to evaluate the feasibility of implementing electric buses in the proposed BRTs, and to compare their performance with other available technologies, such as CNG and Diesel. This comparison begins with the characteristic energy consumption of each technology.

### a. Energy consumption

Once the routes have been characterized in driving cycles and the types of buses to be used have been defined, the next step towards calculating the energy consumption of each technology is to produce a computational model of the different buses. Once the models have been built, they can be simulated under the established local conditions to estimate their overall energy consumption and understand how this energy is spent in the bus.

#### i. Electric bus modeling

The computational models were built using the simulation platform AUTONOMIE[1]. This platform allows the user to choose a specific powertrain and adjust the parameters of each component within that powertrain to model a specific vehicle. Figure 3 shows the powertrain that corresponds to an electric bus, with each of the blocks representing a specific component within the powertrain.

Both fast charge and slow charge electric buses have the same basic powertrain, with the power being delivered from the battery to the motors and through a series of mechanical gears to the wheels which ultimately move the chassis. In electric buses, the energy can move from the wheels to the battery when the vehicle is breaking, and the electric motor is used as a generator. This is called regenerative breaking. The difference between slow and fast charge buses, however, lies in how the characteristics of each of the components in the powertrain is set, specially the battery.

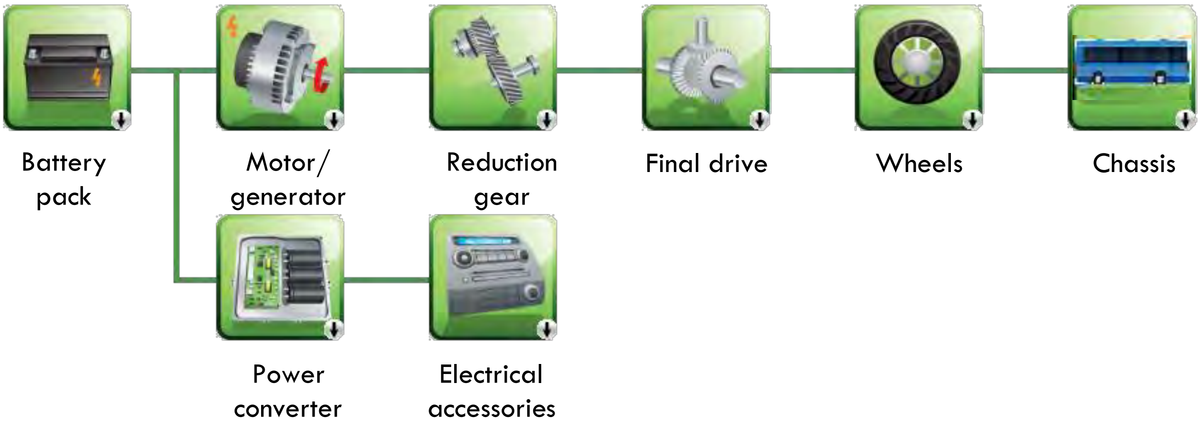

Figure 3 Electric bus powertrain architecture. Each block represents a modeled component of the bus.

Table 13 shows the main differences between the components of fast and slow charge buses for conventional and articulated buses. The buses were modeled based on available data from commercial buses. The models

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[1] www.autonomie.net

have been validated by 35South based on known operational conditions and consumptions in other cities. As can be seen, the battery nominal energy changes substantially between slow and rapid charge buses. This impacts directly on the curb weight of the buses given the batteries' heaviness.

Table 13. Electric buses' powertrain main characteristics

| Electric buses | | | | |
|---|---|---|---|---|
| | Conventional 12m | | Articulated 18m | |
| | Slow Charge | Rapid Charge | Slow Charge | Rapid Charge |
| | Chassis | | | |
| Drag coefficient | 0.65 | 0.8 | 0.65 | 0.8 |
| Frontal Area [m2] | 6.6 | 6.5 | 6.6 | 6.5 |
| Curb weight [kg] | 14500 | 12900 | 19.000 | 17.000 |
| | Battery pack | | | |
| Nominal Energy [kWh] | 324 | 100 | 450 | 160 |
| | Motor | | | |
| Maximum power [kW] | 300 | 200 | 300 | 250 |
| | Air conditioning | | | |
| Nominal power [kW] | 6 | | 8 | |
| Maximum power [kW] | 12 | | 15 | |

As can be seen, articulated buses have larger batteries because they have a greater consumption but need to achieve a similar range as conventional 12-meter ones. Also, because they have a larger chassis, they also have a bigger curb weight. Not to mention, because they carry many more passengers, the difference between the weight of 12 and 18-meter buses will be even greater when they operate.

Finally, carrying more passengers also entails needing a more powerful air conditioner (AC). The difference in weight and the need for a more powerful AC, both bring about a greater energy consumption.

### ii. Diesel buses

For the case of diesel buses, the powertrain is quite different. In this case, the power comes from a fuel which is burned in the internal combustion engine (ICE) and flows in only one direction towards the wheels. Diesel buses do not have the possibility to regenerate energy when breaking as electric buses do. Also, the efficiency of the conversion of the chemical energy in the fuel to kinetic energy in the engine is much lower than the conversion done in electric buses when batteries' chemical energy is transformed to electricity, and consequently to kinetic energy in the motors. Both factors make electric buses much more energy efficient than internal combustion buses, whether the fuel is Diesel, CNG or gasoline.

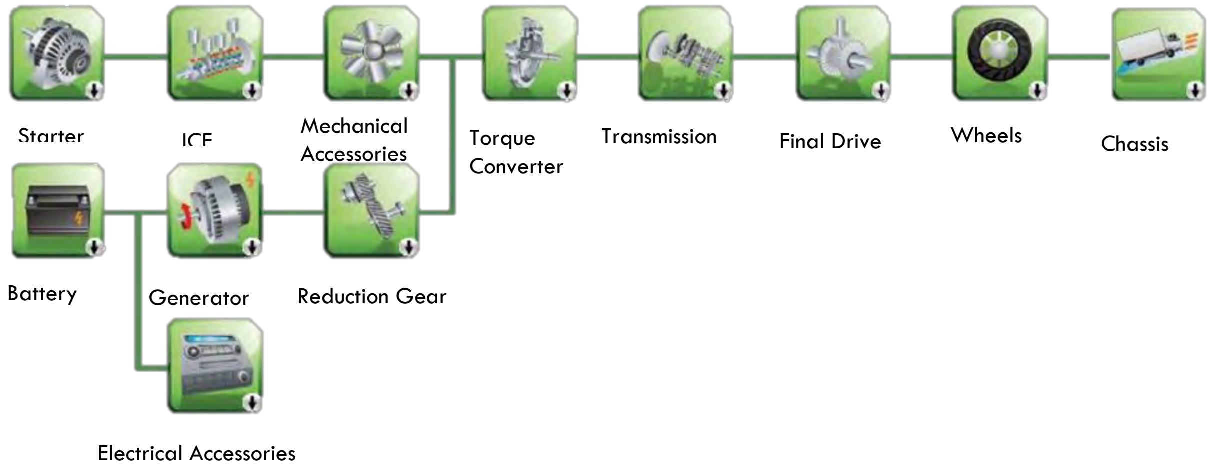

Figure 4 Conventional diesel bus powertrain architecture. Each block represents a modeled component of the bus.

Two different Diesel Euro V buses were modeled, one 12-meter bus and one articulated bus. Their main characteristics and differences are shown in Table 14. Again, the main differences to consider when modeling are the difference in weight and air conditioning needs.

Table 14. Conventional diesel buses' powertrain main characteristics

| Diesel Euro V buses | | |
|---|---|---|
| | Conventional 12m | Articulated 18m |
| | Chassis | |
| Drag coefficient | 0.65 | 0.65 |
| Frontal Area [m2] | 8.7 | 8.7 |
| Curb weight [kg] | 10.300 | 14.500 |
| | Engine | |
| Maximum power [kW] | 213 | 230 |
| Maximum torque [Nm] | 1200 | 1350 |
| | Air conditioning | |
| Nominal power [kW] | 6 | 8 |
| Maximum power [kW] | 12 | 15 |

As for Diesel Euro III, Diesel Euro VI and CNG Euro VI, their results were extrapolated from the results for Diesel Euro V results, given that they are all ICE technologies. Even if this may not provide results as accurate as having a model for each one, given that the operational conditions and driving cycles and bus passenger occupancy are being broadly estimated, going into too much detail into modeling does not make sense. If more detail on how the real operation will be was available, then it might be worth investing more time into modeling.

For the case of Diesel Euro III and Diesel Euro VI, the Handbook Emission Factor for Road Transport (HBEFA)[2] was used to estimate fuel consumptions in relation to Diesel Euro V. The HBEFA provides emission factors and

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[2] www.hbefa.net

fuel consumptions for most current vehicle categories (including conventional and articulated buses) over a wide variety of traffic situations. It was found that for operating conditions like those expected in Brazil, Diesel Euro III buses have around 10% higher fuel consumption than Diesel Euro V for low mean operative speeds. For the case of high mean speeds, as is the case of the West System, the fuel consumption is similar to that of Euro V buses. On the other hand, it was found that Diesel Euro VI buses have similar fuel consumptions as Diesel Euro V buses for all analyzed speeds.

On the other hand, however, the HBEFA does not provide data on CNG Euro VI buses. Therefore, empirical data published by the VTT regarding the energy consumption of buses operating under the Brunswick driving cycle was used to establish a direct proportion between Diesel Euro V and CNG Euro VI energy consumptions. The following section presents the resulting energy consumptions for each technology operating in the different projected transport systems.

## b. Simulation results

### i. Energy consumption overview

Before going into the resulting energy consumptions for each technology and system, it is worth understanding how the different operating conditions actually impact the energy consumption of the buses. As has been mentioned before, the parameters that tend to have the most impact on energy consumption of buses are driving cycle's speed and slope, the passenger load, and the air conditioning system.

However, the influence of each of these is not the same. Figure 5 shows the energy consumption distribution of the 12-meter slow charging electric bus model operating over three different driving cycles, and four scenarios. The "Base" scenario indicates the consumption the bus would have with no passengers, no slope and no AC. "Passengers" scenario adds a full load of passengers (60) to the bus. "Slope" includes both the passengers and the slope of the driving cycle. In this case, slopes similar to those expected for the Central system were used.

Finally, the "AC" scenario includes the energy consumption of an air conditioner functioning at full capacity. For all scenarios, a dotted box was added to illustrate the amount of energy that is saved due to regenerative breaking. The first thing that comes to attention is the huge impact that AC can have on energy consumption, specially for low speeds. As bus speeds go higher, its impact per kilometer is lower. Of course, these results are for an AC at full capacity, which is probably only the case for buses operating at peak hour in summer, and do not illustrate the mean energy consumption that can be expected during the whole year. But because buses the same fleet is expected to work over the whole year, buses must be able to cope with these most demanding operating conditions.

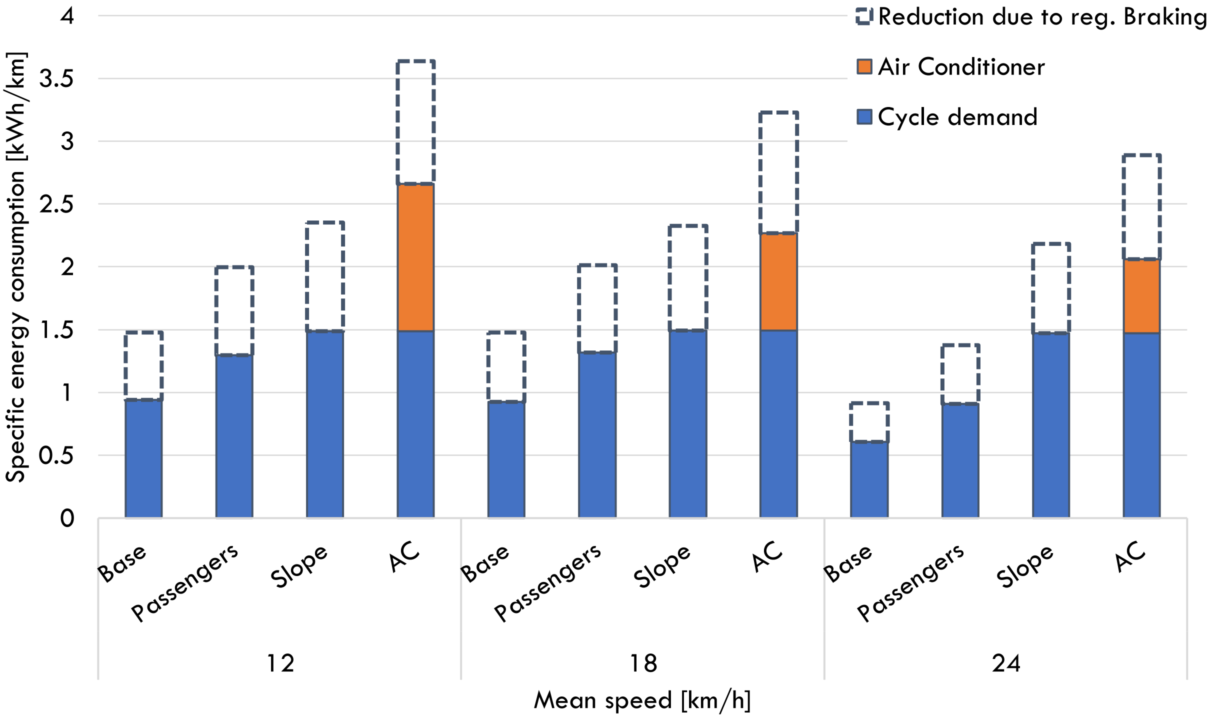

Figure 5 Energy consumption distribution for three different driving cycles with different speeds. Base consumption implies an empty bus in a plain terrain. Passengers implies a bus at full capacity, but flat terrain. Slope indicates the same condition but with the cycle´s slope. Finally, AC adds air conditioning to all the previous.

On the other hand, passengers and slope have an important, yet lower contribution to energy consumption. In general, as the mean speed of a driving cycle goes up, the distance between stops is increased, and the bus tends to be less time accelerating and braking, which leads to a lower energy consumption. The aggressiveness with which a driver accelerates, and brakes has been seen to have an important influence on the energy consumption of the buses, and can lead to high energy consumptions, even if mean speeds are also high. Because these parameters are estimated and taken from BRTs in other cities, the results presented next should be taken as an approximation. For more precise estimations, measurements of the actual driving conditions must be made.

### ii. Resulting energy consumptions

Once the operating conditions of each system, as well as the fleet requirements have been established, the energy consumption of each system can be calculated. Figure 6 shows the energy consumption of all analyzed technologies across the different systems. For those fleets that included both 12 and 18-meter buses, both were calculated, and the final result is a pondered average. For the case of the South system, which was modeled with two different driving cycles (highway and city), again the results were averaged considering the kilometers traveled in each driving cycle.

As expected, the Central and North systems have similar energy consumptions given that their operating speeds are very similar. The South system has lower consumptions given that it is comprised largely by highway driving conditions, and finally, the West system has the lowest because of its light traffic and high speeds.

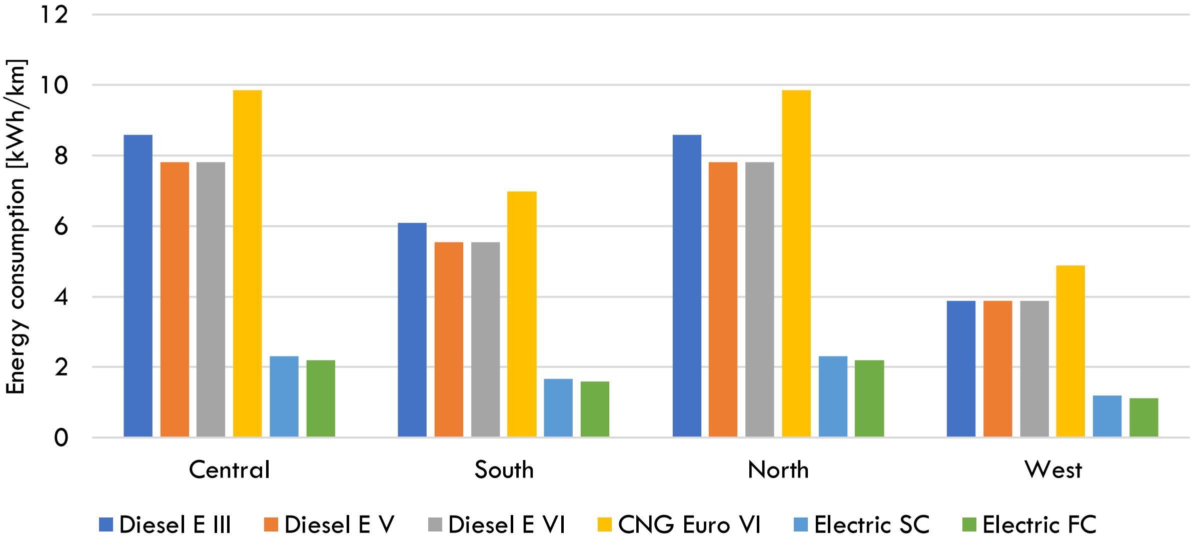

Figure 6 Energy consumption of all analyzed technologies in each system. The lower heating value of the fuels was used to relate fuel consumption to energy consumption.

Within each system, the energy consumption of the different technologies follows the same tendency. The lowest consuming technologies are the electric ones, as expected, with the fast charge having a slight advantage over the slow charge given its lower weight and typically higher regenerative breaking capacities. Given the much higher energy efficient powertrain and regenerative breaking capabilities of electric technologies, they consume between 70 and 80% less than their Diesel and CNG counterparts.

As for the fossil fuel technologies, CNG Euro VI buses have the greatest energy consumption, even higher than Diesel Euro III buses. This is because the Otto cycle under which CNG engines operate is inherently less efficient than the Diesel cycle. This, of course, does not directly translate to a poor environmental performance, as will be seen in section 7 when the environmental assessment is performed.

As was mentioned before, Diesel Euro V and Euro VI technologies are expected to have similar fuel consumptions across the different operating conditions. Diesel Euro III tends to operate more poorly at lower speeds, producing higher energy consumptions in the Central, South and North systems, but similar ones in the West system.

Knowing the energy consumption, the electric and fuel expenses can be calculated, as well as the environmental impact of each technology. However, first, the energy consumption of the electric buses will be used to understand the electrification viability of the different systems.

### c. Electrification viability

The electrification viability analysis consists of determining if the electric buses will be able to cope with the operation expected of the system. Unlike preexisting systems in which a bus service and a timetable already exists and electric buses need to comply with a typically Diesel-oriented operation, this is a new system with an operation yet to be defined. This means that the main concern for this stage of the project is that buses have the necessary range.

#### i. Fast charge buses

Because fast charge buses have a much more limited range than slow charge and, of course, Diesel buses, the main concern is whether they will be able to complete a whole trip without running out of energy. To calculate this, the length of the different routes has to be compared with the range of the vehicle. Because energy consumption depends on the operating conditions of the bus, which change during the year and during the day, the range to be used for the comparison is that obtained in the most critical conditions.

For this purpose, new simulation were run for 12 and 18-meter fast charge buses operating at full passenger capacity (see Table 6) and with the AC at its maximum power (see Table 13). The range was calculated assuming buses begin their operation at a State of Charge (SOC) of 100% and can exhaust their batteries up to an SOC of 20%. Depleting batteries below 20% SOC leads to accelerated degradation and shortened life of the batteries. This means that only 80% of the energy shown in Table 13 is available.

The results for 12-meter buses are shown in Figure 7. Because of the rather long distance of each system, two charging scenarios were considered: first, assuming only one charger is available and the bus must do the whole trip (go and return) on one charge; and the second supposing two chargers are available and the bus can be charged at both ends. Each of the route's total length is shown as dotted lines.

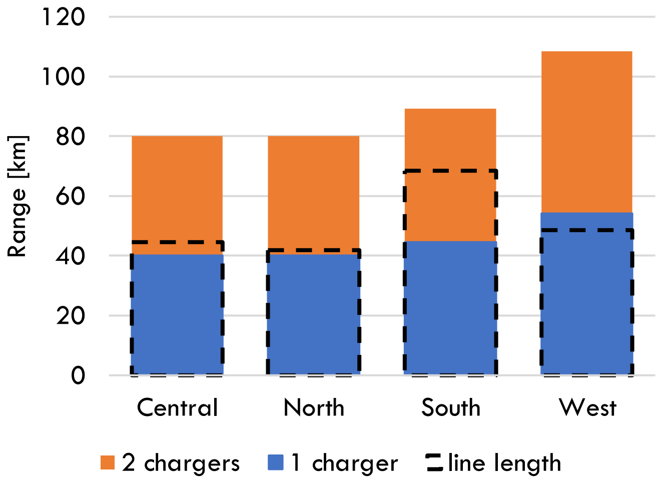

Figure 7 Range of fast charge 12m buses considering one or two charges, compared to the corresponding line's length.

As can be seen, for most of the systems, one charge por trip is not enough. In fact, the only system for which only one charger is enough is the West system, and even for this one, the range is quite close, and two chargers would have to be deployed to provide a reliable operation. This means that operating with 12-meter fast charge buses is feasible, but the location of the chargers will not be redundant. When determining the operation, it should be taken into account that these buses will not be able to operate if the four systems have each a single independent charging location.

On the other hand, Figure 8 shows the results for 18- meter buses in Central, North and South systems. West systems will not be operating with this type of buses, so they were not included. According to section 4, this type of buses is the optimal for both the Central and North system, and both of these appear to have enough range to perform a full trip with only one charge. However, the difference between the range and the routes' length is very slim, and a second charging spot should be considered to avoid repeated excessive depletion of the batteries.

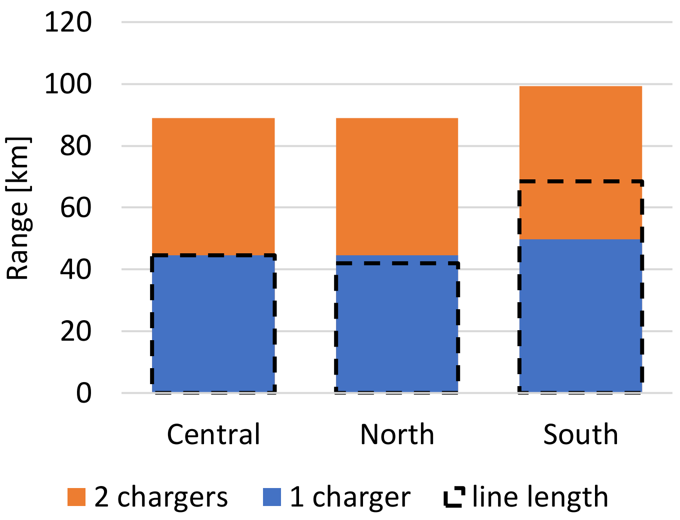

Figure 8 Range of fast charge 18m buses considering one or two charges, compared to the corresponding line's length.

The South system, which is the longest of the four, will be needing two charging locations, for both its 12 and 18-meter buses.

The general conclusion that can be drawn from this section is that if fast charge buses are chosen for the transportation systems, the locations of the chargers must be considered carefully. An optimal system probably entails sharing charging locations between the different systems, given that they are all connected.

### ii. Slow charge buses

For the case of slow charge buses, the range is typically between 100 and 300 km, and therefore their limitation does not have to do with the length of the route. Rather, it has to do with how many hours can it remain operative before it must recharge. Given the long time it takes to recharge these vehicles, they typically operate during the day and recharge during the night. If the battery is depleted before schedule, recharging fast is not an option, as with Diesel or fast charging electric. Rather, another bus will have to fill in for it.

For the case of AMFRI's devised transport system, using the average energy consumptions in Figure 6 and again assuming only 80% of the energy available of the batteries (Table 13), the range of the fleet of each system was calculated. The results are shown in Table 15 for 12-meter buses and Table 16 for 18-meter buses. For both types of buses, the obtained ranges are similar, ranging from 156 to 180 km for the Central, North and South systems. As expected, 12-meter buses in the West system have the highest range given their low energy consumption.

Knowing the range of the buses, it is possible to calculate how long they will be in service by dividing it by the line's mean speed. The operating hours of all the buses are also shown in Table 15 and Table 16. These results are not quite as intuitive as the range, because a higher speed generally means a longer range but also less operating hours. Therefore, for example, even though buses operating in the West system will travel 212 km before recharging, they will actually only be in service during almost 5 and a half hours. Before needing recharging.

Table 15. Range, line speed and resulting operating hours 12m buses can operate before the need to recharge.

| | Range [km] | Line speed [km/h] | Operating hours [hrs] |
|---|---|---|---|
| Central | 162 | 17.6 | 9.2 |
| North | 162 | 19.5 | 8.3 |
| South | 180 | 25.6 | 7.1 |
| West | 212 | 41.0 | 5.4 |

Table 16. Range, line speed and resulting operating hours 18m buses can operate before the need to recharge.

| | Range [km] | Line speed [km/h] | Operating hours [hrs] |
|---|---|---|---|
| Central | 156 | 18 | 8.9 |
| North | 156 | 19 | 8.0 |
| South | 174 | 26 | 6.8 |

If buses are expected to circulate during the whole operative day, which is 17 hours, this can be a problem, given that the results show the buses will only operate between 7 and 9 hours for the most part, and less for the West system. Nevertheless, the entire fleet does not have to operate during the entire day. Rather, during 14 of the 17 hours only 66% of the fleet will remain operative while the rest remains in the station (see section 4). Also, a reserve fleet of 10% is available during the entire day.

This means that the a fleet of slow charge electric buses should be able to cope with daily operation without the need of a fleet larger than the one calculated in section 4. However, a detailed schedule of the expected operation of each system must be devised before finalizing the reserve fleet needed. Devising the schedule from scratch considering charging times is essential to have an optimal fleet size, and this is an opportunity AMFRI has, given that the system doesn´t yet exist.

In conclusion, both slow and fast charge electric buses are feasible options for AMFRI from a technical standpoint. To define a final number of buses and charging points needed, however, more information on the expected schedule and possible interaction between systems must be outlined. Nevertheless, it is expected that a fleet like that required for Diesel buses would suffice. Having established electric buses as a feasible technical option, an economic comparison between the different available technologies is presented next.

## 6. Economic assessment

The economic assessment presented next consists of detailed comparison of expected OPEX and CAPEX of each of the four projected systems and considering all of the above-mentioned technologies. The only exception is Diesel Euro III, which is already an obsolete technology, and is only part of the study to provide technical and environmental comparisons with the currently operating buses but should not be considered for purchase.

The 2020 engineering study by Mcrit and JMSouto already performed an approximation of expected OPEX and CAPEX for a Diesel fleet. The scope of this study was generally considered comprehensive enough, so it was used as a starting point for this study. However, several assumptions and hypothesis have been revised, so the results of this study will be presented alongside those of Mcrit and JMSouto for ease of comparison.

Because there is another consulting team performing financial modeling for the World Bank, this study will not delve into these, and the full economic comparison will come from the complementation of both studies. The study has been adapted to provide the inputs necessary for the financial model of the other team, which mainly implied projecting the OPEX and CAPEX for the next 20 years. This report will present all assumptions and hypothesis used and illustrates results mainly for 2020. The full results can be found in excel “OPEX and CAPEX 2020-2040.xlsx” delivered with this report.

## a. OPEX

### i. Scope

As was mentioned before, the same scope as Mcrit and JMSouta’s study was considered when modeling the OPEX of the bus service. Briefly, this OPEX is composed of:

- Personal salaries and backoffice: including a variety of necessary employees, from drivers and maintenance workers, to management and security. For most of the categories, the number of workers needed is proportional to the size of the fleet.
- Fuel expenses: obtained from the annual kilometers traveled, a certain fuel consumption and fuel price.
- Maintenance: proportional to annual kilometers traveled.
- Insurance: proportional to the fleet’s value.
- Vandalism: proportional to the fleet’s value

The values of the different categories were corroborated using data obtained from Itajaí’s current bus transport system. Itajaí has the largest bus service of the region, with a total fleet of 42 buses, and while on mission to Brazil, 35South’s team met with the municipalities’ public transport management staff to understand its current operation and cost structure. Even if this is not the only bus service of the region and it is not intermunicipal, it was the one with the most information available and, given its size, its costs can be considered a good reference for all the region.

However, comparing two different cost structures can often be challenging if they are produced by different actors, as is this case, because costs may be allocated differently. For the most part, Itajaí’s cost structure was used to corroborate the salaries’ expenses -which is typically one of the main components of the cost structure- and maintenance. Next, the modifications introduced to Mcrit and JMSouta’s study are outlined.

### ii. Salaries

The staff expenses were divided between operating salaries and management. The operating salaries include the drivers, security, terminal agents and mechanics. Other managenment salaries and backoffice were grouped as management expenses. This was done mostly to be able to compare the operating salaries with the cost structure from Itajaí. Regardless of where the line is drawn between which expenses are considered operating salaries, and which management, by far the largest component is the driver’s salaries. Therefore, as long as these are considered operating salaries by cost structures, a reasonable comparison can be made.

Because drivers’ salaries are such a big part of the OPEX (can make up almost 50% in some cases), the amount of drivers projected for the system is a critical number. Mcrit and JMSouta initially established a reasonable 3 shift operation, having three drivers for each bus in the system. When comparing the final operating salaries with Itajaí’s in USD/km, it was found that the difference was around 2%, which is much better than expected.

It must be pointed out, however, that when revising the spreadsheets of OPEX provided by Mcrit and JMSouto, it was found that the number of drivers was reduced when making the final calculations, and it is unclear why. Given the close correlation with Itajaí's data using 3 drivers per bus, this is the number that was finally used by this study.

The rest of the salaries, apart from some management positions, are mostly proportional to the amount of buses in each fleet and were left as they were.

### iii. Fuel expenditures

Fuel expenditures were completely recalculated using the energy consumptions calculated in section 0. Table 17 shows the energy consumptions determined for each line and technology but using the most typical unit of each technology. The previous study by Mcrit and JMSouto used a higher 0.85 lt/km consumption for all lines using diesel buses.

Table 17 Mean fuel or energy consumption of each technology across the different routes.

| | Diesel E VI [lt/km] | CNG [m3/km] | Electric SC [kWh/km] | Electric FC [kWh/km] |
|---|---|---|---|---|
| Central | 0.78 | 0.91 | 2.30 | 2.19 |
| South | 0.55 | 0.65 | 1.67 | 1.59 |
| North | 0.78 | 0.91 | 2.30 | 2.19 |
| West | 0.39 | 0.45 | 1.18 | 1.12 |

As for the fuel and electricity prices, these were all re-calculated as well. Establishing fuel prices can be challenging given that there are subject to big fluctuations over time and great dependence to global context. As an example, in January 2020, the price of diesel was around 0.91 USD/lt in Brazil[3,4] whereas they are now around 0.64 USD/lt. For this study, the price was fixed at 0.8 USD/lt, which is 4.26 RS/lt at a 5.33 RS/USD rate. CNG price was found to be around 0.7 USD/m3[4], which is currently 3.73 RS/m3.

As for electricity rates, these were obtained directly form Santa Catarina's electricity provider, CELESC. A meeting was held between 35South consultants and CELESC staff while on mission in Brazil to understand current the current electricity price structure. It was made clear by CELESC staff that in order to have a clear estimation on the price of electricity, they would need to perform an analysis on the necessary additional infrastructure that would be needed for such a power-intensive consumption as is charging electric buses. Nevertheless, it was suggested to use, for an initial estimation, the A2 category within their current tariff structure[5].

The tariff structure is divided by peak and off-peak prices. Also, the price is based both on energy consumed (kWh) and power needed (kW). For this initial estimation, an average was made between the peak and off-peak prices, and an initial power installation was made considering the use of fast high-power chargers for the fleet established. The resulting fuel and electricity prices are shown in Table 18.

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[3] https://es.globalpetrolprices.com/Brazil/diesel_prices/

[4] https://www.chetoba.com.ar/precio-combustible-en-brasil-nafta-diesel.php

[5] https://celesc.com.br/tarifas-de-energia#tarifas-vigentes

Table 18 Fuel and electricity prices of each evaluated technology.

| Diesel E VI [RS/lt] | CNG [RS/m3] | Electric SC [RS/kWh] | Electric FC [RS/kWh] |
|---|---|---|---|
| 4.26 | 3.73 | 0.62 | 0.62 |

### iv. Other expenditures

A few other minor corrections to other expenditures were made. In the first place, maintenance costs were updated to 0.62 RS/km (from 0.3 RS/km), using Itajaí's cost structure as reference. Secondly, the insurance used was found to be somewhat excessive and was decreased from 3% to 2% of the fleet cost. This was based on experience with costs structures in other countries.

### v. Results

The resulting OPEX for each of the four systems are shown in Figure 9. As was expected, the Central system has the highest OEX for all technologies given that it has the largest fleet and does the most kilometers per year. As can be seen, electric buses present a big reduction in OPEX when compared to their diesel and CNG counterparts, with fast charge buses producing the lowest operative costs. Mcrit and JMSouta's results are shown as a refence.

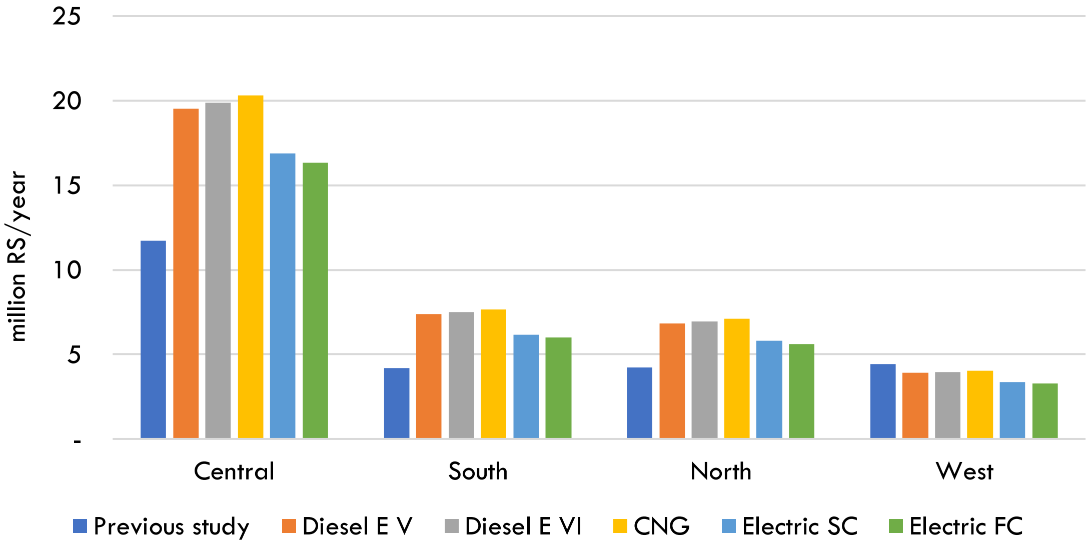

Figure 9 Resulting annual OPEX for each transport system and technology in 2020. Results by Mcrit and JMSouta are included for reference.

To understand where the differences between diesel, CNG and electric technologies lie, Figure 10 shows the disaggregated OPEX of the Central system. As expected, operating salaries and fuel costs are the highest expenditures of the system. The reduction in fuel costs when comparing diesel and CNG technologies to electric ones is one of the first things that stand out in the figure. This reduction, together with the lower maintenance costs, is typically one of the main appeals for transitioning to electric buses. In some countries, such as Argentina or some European regions, CNG buses can be a tempting option because of its lower fuel cost, but this is not the case of Brazil, which has a high CNG cost.

Operating salaries and management are the same across all technologies since the same fleet was assumed for all, and therefore, the same staff composition. Electric buses do have higher costs in the insurance and vandalism categories, given that the buses are much more expensive than conventional diesel buses, as will be seen in the following section.

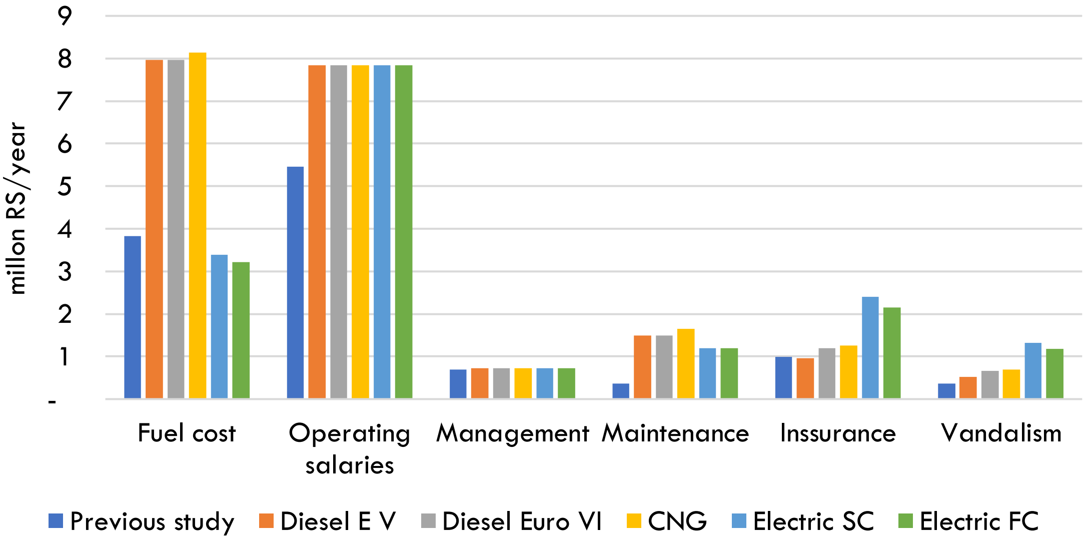

Figure 10 Disaggregated OPEX for the Central system in 2020. Results include the five analysed technologies and those devised by Mcrit and JMSouta.

When comparing results to the previous study, the main differences lie within the fuel cost and the operating salaries. The fuel cost difference comes mainly from the difference in annual kilometers traveled by the systems. This difference arises both from a larger fleet, and a more intensive operation to guarantee a good service both in peak and off-peak hours. As for the difference in operating salaries, this is because of the difference in fleet and because, as mentioned, a bigger driver per bus ratio was used.

## b. CAPEX

### i. Scope

The scope of the CAPEX in this study is made up from the cost of the buses and refueling or charging infrastructure.

As for infrastructure CAPEX for refueling and charging, a similar approach was taken.

Table 20 outlines the values used in this study. In this case, it is not enough to simply define the unitary cost of the infrastructure because refueling/charging stations are shared by different buses, and their usage changes one technology to the next. Therefore, for each case the cost of a unitary charger or facility is defined together with the amount of buses it can service.

Table 19 details the prices used for the buses. These are mostly reference values that are observed in Latin America, and that can be used to perform initial estimations and to perform general comparisons between technologies. This information comes from 35South's participation in pilot tests of different technologies in Argentina, Colombia and Panama, and some values that can be found in the literature[6,7,8].

As for infrastructure CAPEX for refueling and charging, a similar approach was taken.

Table 20 outlines the values used in this study. In this case, it is not enough to simply define the unitary cost of the infrastructure because refueling/charging stations are shared by different buses, and their usage changes one technology to the next. Therefore, for each case the cost of a unitary charger or facility is defined together with the amount of buses it can service.

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[6] NDC Support Facility, Steer, World Bank Organization. (2019). *Green your bus ride, clean buses in Latin America.*

[7] Hooftman, Messagie & Coosemans. (2018). *Analysis of the potential for electric buses.*

[8] Civitas. Smart choices for cities. Clean buses for your city.

Table 19 Reference price of buses in USD and RS, for all five technologies and both 12 and 18-meter buses

| | Diesel Euro V | Diesel Euro VI | CNG Euro VI | Electric SC | Electric FC |
|---|---|---|---|---|---|
| | Price of buses (USD) | | | | |
| **12m** | 160,000 | 200,000 | 210,000 | 350,000 | 315,000 |
| **18m** | 200,000 | 250,000 | 262,500 | 500,000 | 450,000 |
| | Price of buses (RS) | | | | |
| **12m** | 852,800 | 1,066,000 | 1,119,300 | 1,865,500 | 1,492,400 |
| **18m** | 1,066,000 | 1,332,500 | 1,399,125 | 2,665,000 | 2,132,000 |

Table 20 Reference costs of fuelling or charging infrastructure for the five technologies analysed, both in USD and RS. The last row, "Buses per infra or charger" indicates for how many buses that infrastructure would suffice.

| | Diesel Euro V | Diesel E VI | CNG Euro VI | Electric SC | Electric FC |
|---|---|---|---|---|---|
| USD | 350,000 | 350,000 | 364,000 | 25,000 | 50,000 |
| RS | 1,865,500 | 1,865,500 | 1,940,120 | 133,250 | 266,500 |
| Buses per infra or charger | 50 | 50 | 50 | 2 | 8 |

It must be understood that these are merely reference numbers. The estimation of refueling infrastructure costs for diesel and CNG is particularly challenging as it greatly depends on local legislations, size of fleet, construction prices, utility values, etc. and it entitles a deeper and more detailed engineering study. Nevertheless, a ballpark figure may be enough for this stage of the study since the infrastructure represents less than 1% of the total CAPEX.

### ii. Results

The resulting necessary initial CAPEX for the four transport systems is shown in Figure 11. These results entail both the fleet expenses required to get to the 2020 fleet, and the infrastructure costs that should only be purchased at the start of the project. Further bus purchases to keep up with the projected demand and for bus renewal were calculated for the following 20 years of the project. These are detailed in the excel "OPEX and CAPEX.xlsx".

As with OPEX, the highest CAPEX is found in the Central system, given its larger fleet size. As expected, electric buses require a much greater initial investment than Euro V and Euro VI fossil fueled buses. A significant difference can be found when comparing the results of the previous study with current results. This is not only because of the smaller fleet projected in the previous study, but also because the bus prices were significantly lower, being 313 and 920 thousand RS for the 12 and 18-meter buses respectively.

The big gap between electric and conventional technologies presents an interesting financial challenge. Given that OPEX are favorable to electric technologies, there is potential to find a financial solution that makes electric buses competitive or even cheaper than conventional buses when looking at the entirety of the project's timeline. This analysis is to be performed by another consulting group working with the World Bank in the financial modeling of the system.

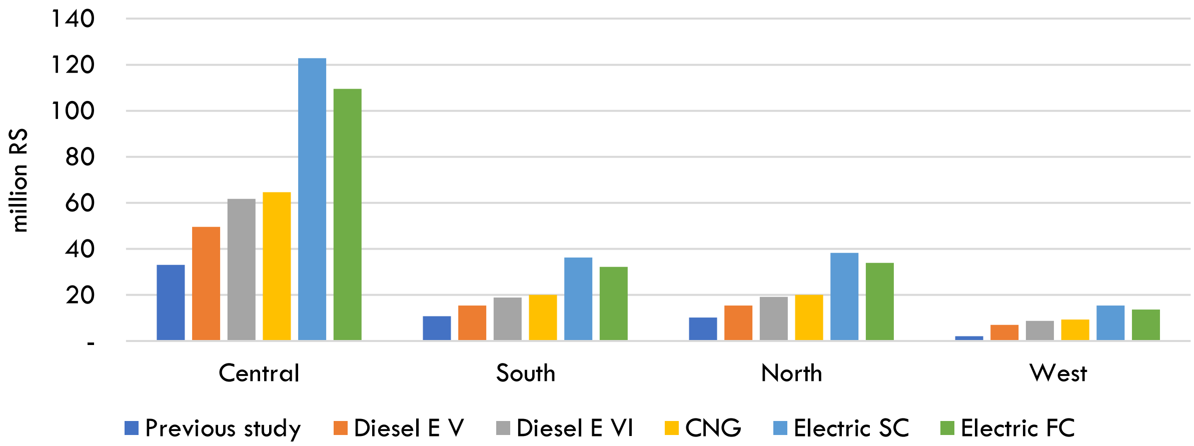

Figure 11 Comparison of CAPEX for all analysed technologies across the four transport systems. Results by Mcrit and JMSouto are displayed for reference.

Once the technical and economic implications of adopting electric vehicles in AMFRI's new system have been established, it is time to quantify their actual benefits to produce a suitable cost-benefit analysis. For this purpose, an environmental assessment is presented next.

## 7. Environmental assessment

Environmental impact studies of vehicles 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. On the other hand, air quality is a local concern and has a direct impact on people's health. Throughout this section the GHG emissions and the toxic pollutant emissions of the different technologies pertinent to this study will be analyzed in other to understand which of the latter provides the best environmental outlook.

### i. Carbon footprint

As illustrated on Figure 12Error! Reference source not found., carbon foot print analysis of any vehicle must involve its full life cycle and that of the fuel/energy vector it uses. The vehicle embedded emissions are those produced during its production and disposal process, all the way form raw material extraction and refining to end of life scrappage and recycling. The life cycle emissions of the fuel/energy vector, on the other hand, consider the GHG emissions related to the refining, production and transport process of the latter (indirect emissions) and those produced by vehicle consumption whilst operating (direct emissions).

It is worth noting that in the case of a buses, embedded emissions are relatively small when compared to fuel/energy life-cycle emissions, due to the large amount of energy used over the lifetime of the vehicle. Therefore, vehicle embedded emissions will not be considered in this study. Throughout this section the GHG emissions of the different fuel/energy vectors considered will be estimated.

#### *1.1.1.1 Electric carbon footprint*

Electric buses have no direct emissions; however, they could have indirect emissions related to the production and distribution of electricity. To calculate the carbon footprint of this technology, the electric matrix of the city/state must be assessed.

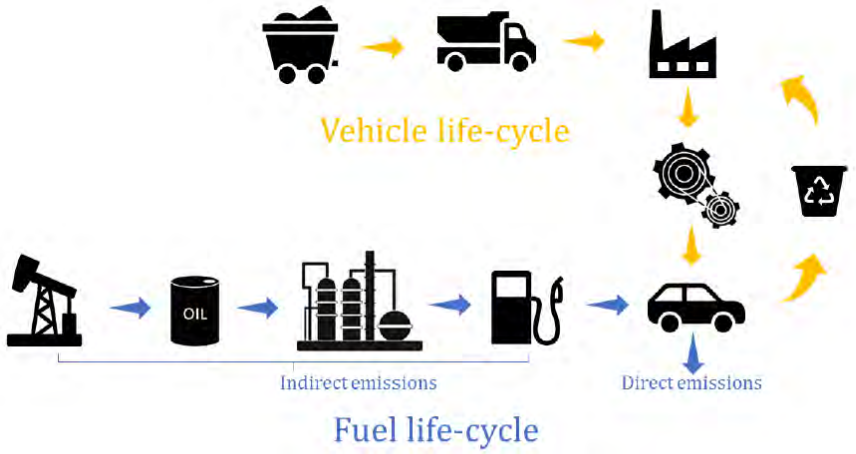

Figure 12. Vehicle and fuel life-cycle illustration. When assessing the carbon footprint of a technology, both the vehicle and the fuel's life cycles must be appraised.

Given that all of Santa Catarina's electricity is distributed by the same energy company (CELESC), the installed capacity of the entire state was used to characterize the future source of energy of the buses. Figure 13 shows the three main sources of electricity of the state[9]. As can be seen, the state, as the country, relies mostly on hydropower, which is a very clean source of electricity. GHG emissions of hydropower have mostly got to do with the construction of the plant, and not with its operation.

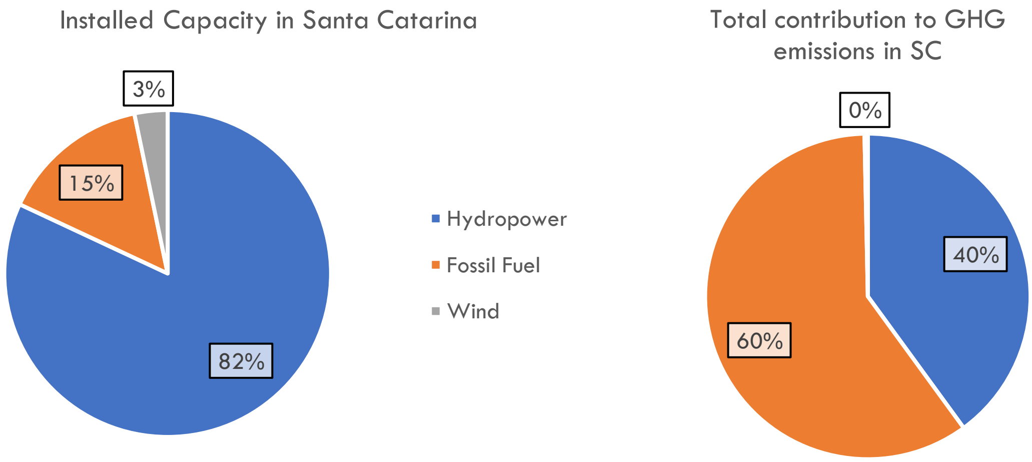

Figure 13 Characterization of Santa Catarina's electric matrix. In the left, the installed capacity of the state is shown, whilst in the right the total contribution of each component is displayed.

To calculate the GHG emissions of each of these components, the emission factors of a report by Barros, Piekarski and de Fransisco, outlining the carbon footprint of electricity generation in Brazil, were used[10]. Also, it was assumed that the fossil fuel mix was similar to that of the country's, which is mostly reliant on natural gas (64%) and diesel (23%)[11]. Wind generation was assumed to have no environmental impact. The

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[9] InovAMFRI. (2016). Final Report, Regional Development Plan.

[10] Barros, Piekarski & de Fransisco. (2018). Carbon Footprint of Electricity Generation in Brazil: An Analysis of the 2016-2026 Period.

[11] Operador Nacional do Sistema Elétrico. (2018). http://www.ons.org.br/paginas/sobre-o-sin/o-sistema-em-numeros

resulting contribution of each component of the electric matrix is also shown in Figure 13. Here the contrast between fossil fuels' and hydropower's emission factors are made clear: despite making up only 15% of the installed capacity, compared to the 82% of hydropower, fossil fuels end up taking up 60% of the emissions.

#### *1.1.1.2 Diesel and CNG carbon footprint*

For the case of diesel and CNG, indirect emissions were calculated using Greenhouse gases, Regulated Emissions, and Energy use in Transportation database (GREET[12]). 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. For this study 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 Santa Catarina is used.

In the case of direct emissions, these can be easily calculated with the fuel's lower heating value 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 21. Whilst electricity has the highest indirect emissions of all energy vectors assessed, given the lack of direct emissions, it results in almost less than 50% the overall emissions per kWh compared to the fossil fuel alternatives. Indirect emissions for the latter are similar, but CNG, having a higher LHV and lower carbon ratio than diesel, results in a lower overall energy specific emission intensity.

Table 21. Direct and indirect GHG emissions related to each technology per kWh of fuel or electricity consumed.

| Fuel | Indirect emissions | Direct emissions | Total [gCO2/kWh] |
|---|---|---|---|
| Electricity | 151.2 | 0 | 151 |
| Diesel | 54.2 | 270 | 324 |
| CNG | 51.1 | 203 | 254 |

Using the energy specific GHG emission intensity factors of the different energy vectors in combination with the fuel/energy consumption of the different buses under the different operating conditions calculated above, it is possible to calculate the GHG emissions per kilometer of each bus technology. Figure 14 shows the resulting carbon footprint of the entire system. A weighted average of the four systems was made considering the annual kilometres travelled by each one.

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[12] https://greet.es.anl.gov/

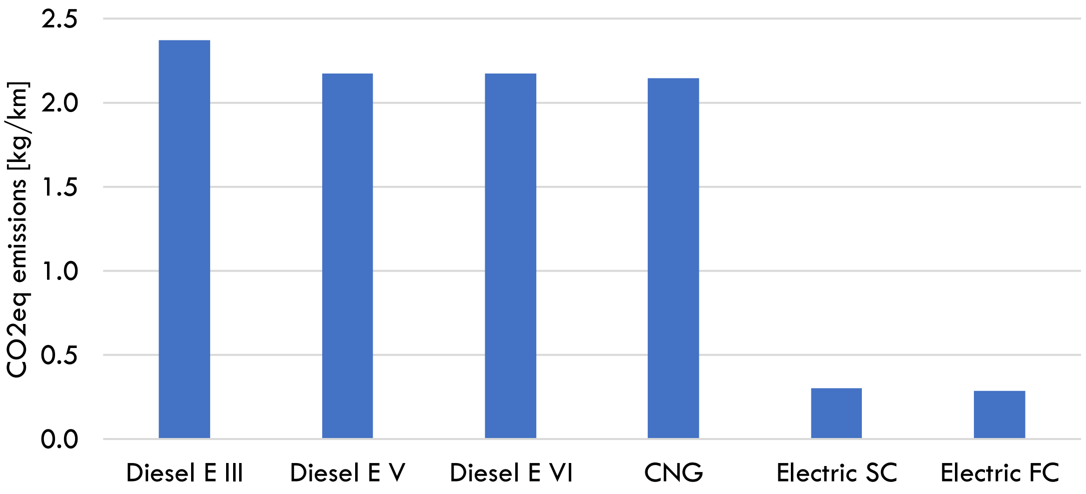

Figure 14, GHG emissions per kilometer for each evaluated bus technology operating under mean operating conditions of the four systems.

The GHG emissions of CNG and Diesel Euro V and VI buses is almost identical. 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, with savings close to 85% when compared to either Euro VI bus. This is due to the lower carbon footprint of electricity and the higher efficiency of electric buses.

### ii. Air quality emissions

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 people and the environment. They include carbon monoxide (CO), unburned hydrocarbons (UHC), volatile organic compounds (VOC), Sulphur oxides and nitrogen oxides (NOx) and particulate matter (PM), amongst others, however, given the nature of heavy-duty diesel vehicles this study will focus on the two latter. Although, some studies have shown that zero emission buses such as electric or hydrogen, are a source of PM[13] given the wear and tear of disc brakes and tires this study will focus on powertrain generated emissions, which as mentioned before, electric buses have none.

In the case of diesel vehicles, the HBEFA database provides empirical measurements of NOx and PM emissions for diesel Euro III, Euro V and Euro VI buses, operating under varying conditions. The emission factors were therefore exported from the database. 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 NOx and PM emissions to diesel Euro VI buses. Therefore, the emission factors of the different buses can be estimated using the above-mentioned data base and applying the following hypothesis

- Articulated buses
- Average ambient temperature of 20°C
- Air Conditioning correction
- Slopes of +/-2%.

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[13] Timmers and Achten. (2016). Non-exhaust PM emissions from electric vehicles.

Results are shown in Figure 15 and Figure 16 for NOx and PM, respectively.

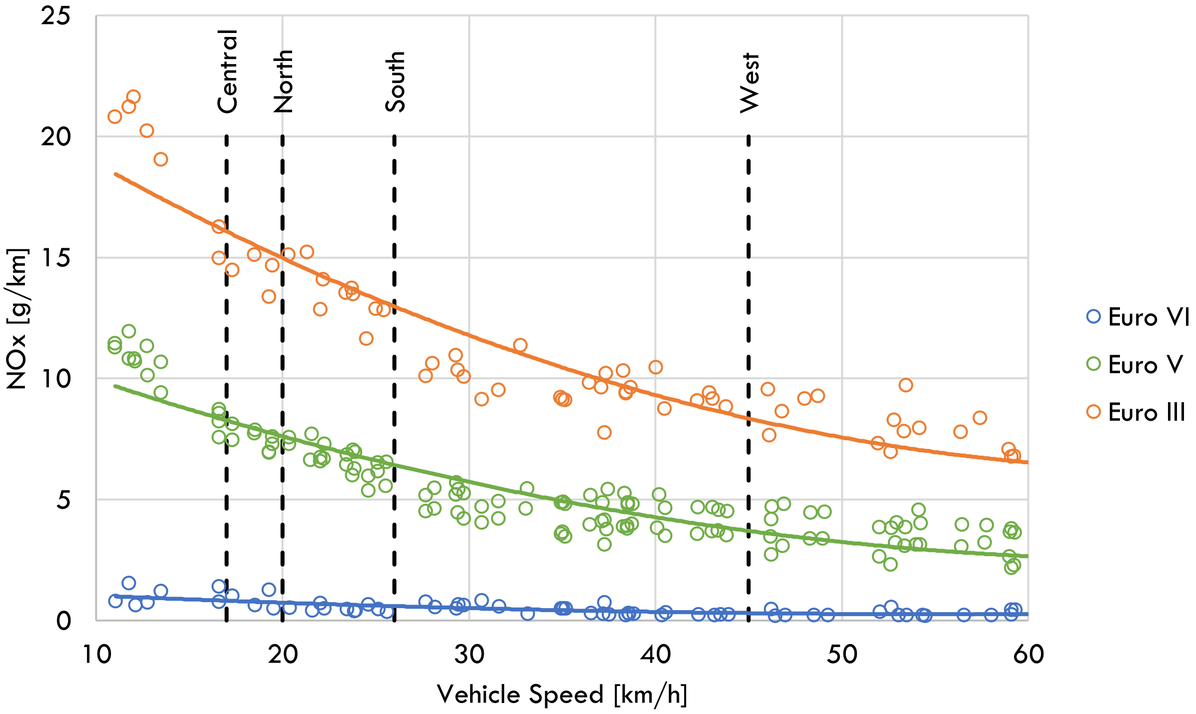

Figure 15. NOx emissions as a function of vehicle driving cycle mean speed for diesel Euro III, Euro V and Euro VI buses. Note that emission for CNG Euro 6 buses are considered equal to those of the diesel Euro VI vehicle.

Therefore, using the above emissions intensity coupled with the mean velocity of the systems that will operate in Itajaí it Is possible to establish the emission intensity per km of the different buses under average public transport projected operating conditions. Results are shown in Figure 17.

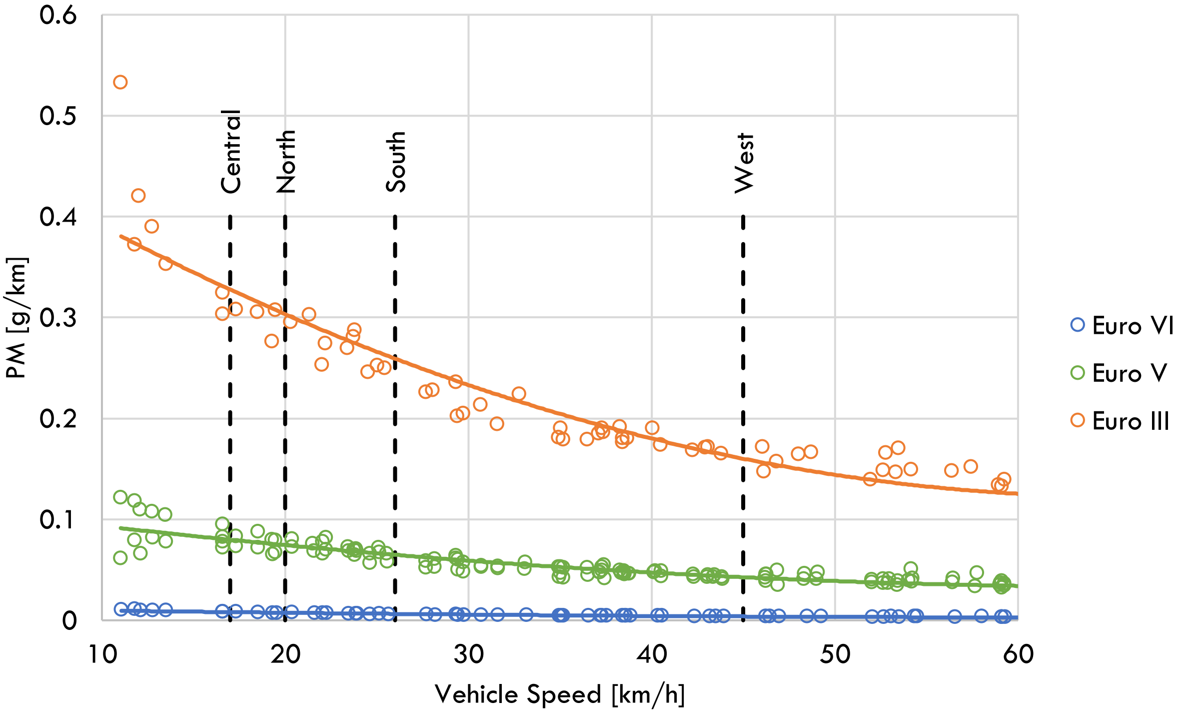

Figure 16. PM emissions as a function of vehicle driving cycle mean speed for diesel Euro III, Euro V and Euro VI buses. Note that emission for CNG Euro 6 buses are considered equal to those of the diesel Euro VI vehicle.

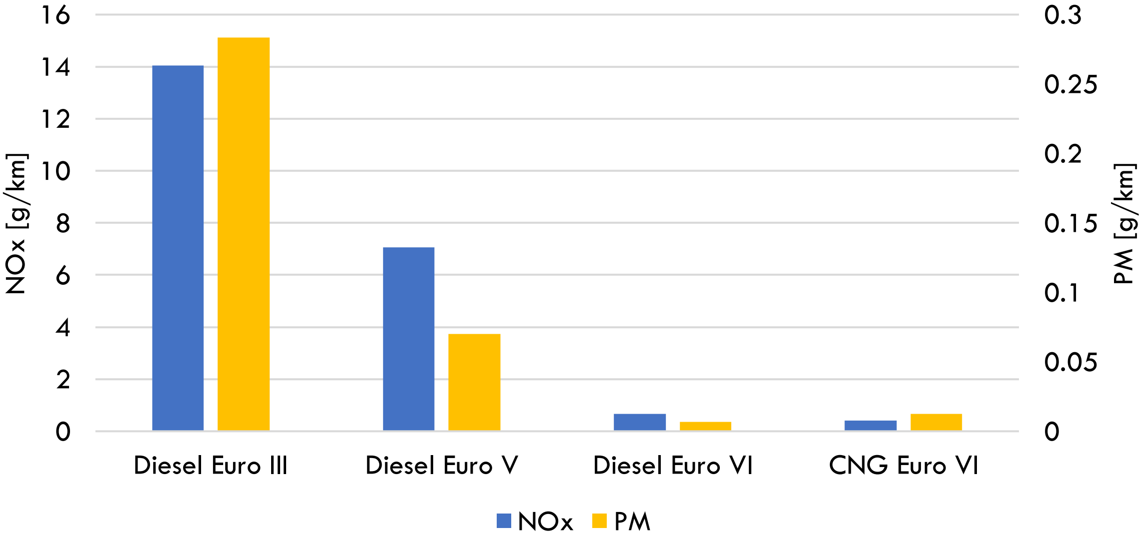

Figure 17. NOx and PM emission for the different bus technologies under the projected local public transport conditions.

Results show that whilst transitioning to Euro VI buses has little impact in reducing GHG emissions they show to be a significant improvement compared to Euro III and even Euro VI vehicles in terms of local pollution mitigation.

## 8. Conclusions

Throughout this report first the current operating conditions of municipal public transport in Itajaí was analysed, through empirical data collected on the field and interviews with the local stakeholders. Using this information and that projected for the future intermunicipal public transport services, along with topographic information of the metropolis, the local operating conditions of the different services was established. This information was then used to evaluate the energy consumption of Diesel CNG and electric buses operating under the establish local conditions. Furthermore, based on the projected demand of the different bus lines the required fleet was established, defining not only the number of buses per line but also their size (12m, articulated 18m or biarticulated 24m). Using all the above information, the energy/fuel consumption of the different bus technologies operating under the projected conditions was estimated via computational simulation. In terms of electric buses, both fast charge and slow charge technologies where evaluated to assess the electrification feasibility of the different corridors. Also, this information was used to establish the CAPEX and OPEX of the different technologies and their environmental impact/benefit. This will provide the financial team of the bank the required information to do a cost benefit analysis of the required investments.

In terms of energy consumption both the fast and slow charge electric buses outperformed the conventional diesel and CNG buses. The use of the former under local operating conditions would result in Tank to Wheel energy savings of between 60% to 80% depending on the bus route. However, both electric technologies showed ambiguous results in terms of electrification of the different services. Fast charge buses, on one hand, would require in most cases two chargers per route, one on each end, to have a sufficient range to cover the service without exposing the latter to a high failure provability. Slow charge buses, on the other hand, do not have the range to cover the mean distance required for a full day operation and therefore partial charging events would be required to fulfil the operation. Either scenario is achievable, but both need considerable planning to reduce risk, uncertainty, and infrastructure and additional fleet costs, to provide the required service within the economic restrains of the system.

As expected, CAPEX and OPEX calculations for the different analysed technologies showed that the electric options are considerably more CAPEX intensive than the diesel counterparts, with CNG buses slightly more expensive than the diesel Euro VI option. However, in terms of OPEX, the relatively low price of electricity in Santa Catarina compared to CNG and the considerable higher efficiency of the electric vehicles results in these having a considerably lower fuel/energy cost than other technologies, with other operating costs similar to all technologies. Overall, the economic performance of the different technologies will depend on the financial structure of the required investments. If long term flexible low rate loans are available, then the electric options could be economically competitive.

In terms of environmental benefits brought about the incorporation of the evaluated technologies compared to a Euro V bus (current standard for new buses in Brazil) the electric options result in a considerable reduction of GHG emission with savings mounting up to 80% in some routes and of course in a 100% reduction of pollutant emission. The EURO VI buses, both CNG and diesel, show negligible reductions in terms GHG emission, but are a good alternative in terms of reducing the fleet pollutant emission. The cost of GHG emission abatement of the different technologies will of course depend on the financial terms of the required expenditures.