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Optimization model for the location of charging infrastructure and battery sizing for a public network of electrified buses

Academic Supervisor

Prof. Paolo Guglielmi

Candidate

Paulina Belén Flores Hernández

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Abstract

The growing number of electric buses and high power charging systems within the public transport sector seeks to reduce carbon dioxide emissions and the use of fossil fuels in cities. But the transition process from the conventional bus fleet to an electrified one is expensive due to the high costs of battery systems. Then it's necessary to develop an optimal planning of charging infrastructure and determine the required capacity of the battery system to minimize the total cost of ownership and at the same time to comply with the operational schedule. This thesis presents a mixed-integer linear optimization model to determine the location of charging infrastructure and battery sizing for a public network of electrified buses. The energy consumption for each bus line is determined according to the bus configuration, the geographical characteristics of the route and the specific driving cycle. The analysis is developed on the real-world data of the bus network in Santiago, Chile.

Keywords: Electric Bus, Charging Infrastructure, Battery Systems, Cost Optimization Model, Bus public transport network

Contents

List of Figures

List of Tables

Introduction

The introduction of battery electric buses into the public bus network requires a high investment from both the bus operator and the electric distribution company. First, there is the total cost for the bus operator to purchase the electric buses. Then, the electric distribution company has to invest in charging infrastructure. Furthermore, the planning of charging points has to consider the impact of high power charging processes on the electrical demand on the power system.

Several research projects have developed optimization models to address these challenges. However, each case has to be studied in detail because local operational conditions and their particular technical requirements are fundamental to the selection of the battery system design and the charging system. The goal of these studies is to help advance the electrification process of the bus system by looking for the most economical solutions in terms of the investment costs in infrastructure, the number of electrified buses, as well as the life cycle. In this context, this project looks to reduce the initial investment of the operator and ensure a simple transition process from the conventional bus fleet to an electrified one. The research here will focus on the project being currently developed by the company Reborn Electric for the public bus system of the city of Santiago, Chile. This project involves the conversion of some of the Santiago bus lines' current buses into electric buses. The cost of electrifying the bus lines is lower than the total cost of purchasing a completely new fleet of electric buses. For this reason, this thesis will advocate for the electrification of the bus lines.

The contributions of this thesis can be summarized as follows: we present an optimization model which takes into consideration battery sizing and the location of charging infrastructure for a public network of electrified buses. This model keeps the existing bus routes, and runs them on the same operational schedule. The cost of this optimized model is lower than the total cost of replacing the entire fleet of diesel buses, which would entail buying a completely new fleet of electric buses.

The first chapter presents the state of the art of research on development of electric vehicles and their respective challenges for the adoption of electric vehicles in the cities. Secondly, the electrification project of the public transport system of the city of Santiago, Chile is explained. Third, the principle features that need to be considered for in the implementation of an electrified bus system are presented. Furthermore, it also gives a framework of the currently available technology on the market for electric buses.

The second chapter reviews the optimization model developed, detailing the simulation model that was created to determine the energy consumption of the bus. Second, the chapter turns to the cost parameters and assumptions considered in the model.

The third chapter details the 2 options considered for the optimization model. Then the results of the required charging infrastructure and batteries obtained for each case are presented. Third, the results of the sensitivity analysis for the different scenarios considered are discussed.

The last chapter presents the optimal solution of the project, summarizes the main results as well as suggestions to carry out the electrification project are given.

1 State of Art

The following chapter presents the state of the art of research on development of electric vehicles and their respective challenges for the adoption of electric vehicles in the cities. Second section presents the project being currently developed by the company Reborn Electric for the electrification of the bus network of Santiago, Chile. In addition, this part takes a look at the current state of technology for bus electrification, in order to provide important background to possibilities for this project.

1.1 Literature Review

The growing development of electric vehicles can help reduce emissions and the use of fossil fuels, whether with Plug-in electric vehicles (PEVs), battery electric vehicles (BEVs), or plug-in hybrid electric vehicles (PHEVs). These vehicles can contribute to radically improving air quality, particularly in urban areas. Specifically, PEVs are crucial in bringing CO_2 emissions down 50% per mile compared to internal combustion engine vehicles (ICEVs) [11]. At the same time, the operating cost of PEVs is lower than with conventional vehicles, with ICE vehicles costing 5 times as much at 13 cents per mile compared to prices as low as 2-3 cents per mile with PEVs [11]. However, one of the major barriers to massive market adoptions of PEVs include the cost of the battery system [17]. The purchase of a PEV still ends up being more expensive than with conventional vehicles due to the additional battery costs. The batteries alone represent up to a third of the total cost of the vehicle including battery replacement [1] – [8]. Furthermore, another barrier is the strong impact the vehicles have on the electricity distribution network, due to the high charging power used by PEV. Then, the PEV will put considerable additional demand on the electric power system [1]. The third and final obstacle is the low availability and limited deployment of charging infrastructure, because the installment of charging points entails a huge economic investment, high power requirements for the charging process and is subject to constraints of the electrical distribution system and street grids [23] – [1]. Consequently, the general power profile will have a geographical dependence, due to the location of the charging sites. Therefore, these factors must be taken into account when planning the charging infrastructure in order to preserve the stability of the electric network and to not concentrate high demands in certain areas. To summarize, due to cost restraints, its important to keep expenses low, and thus absolutely crucial to optimize the battery capacity within the parameters of the operational requirements in order to minimize the required investment. With the goal of promoting further adoption of electric vehicles, the PEV charging infrastructure will need to be carefully planned, in order to minimize the negative effects of increased charging demand on the electric distribution system [8] – [1].

A number of researchers have sought to help ensure cities' adaptation of PEVs by drawing up models by periods for the installment of charging facilities. Ahn and Yeo [27] developed an analytical planning model to determine the optimal density of charging stations for certain urban areas, while still yielding minimal cost. The result is subsequently integrated into a wider analysis and scaled up to city level planning. Li, Huang and Mason [9] established a multi-period location model which minimizes the total cost of the installations of new charging stations and the relocations of existing ones. This model was developed with the aim of expanding the public electric vehicle (EV) charging network to dynamically satisfy the demand for more origin–destination (O–D) trips with the growth of the EV market.

Others studies have looked at developing mathematical models for the optimal planning of charging infrastructure. Yang, Dong and Hu [26] proposed a model that sought to minimize the investment in the charging infrastructure and take into account that the dwelling pattern of the EV taxi fleet when selecting of the location for charging stations. Shahraki et al. [20] introduced a optimization model to identify strategic locations of public charging stations for EV taxis based on their travel patterns, in order to maximize the public charging demand covered.

However, these studies were carried out with reference to electric Light-Duty Vehicles (LDVs), and not Heavy-Duty Vehicles (HDVs), such as buses [25]. The driving patterns of electric passenger vehicles in general differ from the operational characteristics of public transport buses within a urban transport network [8]. The buses have a fixed route and operational schedule. Hence, it is not appropriate to use the above approaches to model the location of the charging infrastructure and the battery sizing of public transport electric buses. Several researchers have worked on the process of introducing electric buses to run jointly with the current fleet of buses, without modifying their current daily operations. Paul and Yamada [13] developed a k-Greedy algorithm to map out the joint operation diagram of electric buses and diesel buses, without changing the departure and arrival times of the bus lines. They drew up a schedule for charging the electric buses, and also considered potential charging locations and how much each bus would need to be charged in the overall bus charging plan. Xylia et al. [25] dedicated their research to developing an optimization model to determine the location of charging infrastructure for battery electric buses in the city of Stockholm, taking into account the current fleets of buses available that use biofuels. This model seeks to achieve synergies between electrification and the available biofuel bus fleets. Hence, only bus stops and terminal stations are considered as charging points, but not bus depots. Referring to technical requirements of the electrification of the bus network, Rogge, Wollny and Sauer [18] analyze the feasibility of implementing electric bus systems with a fast charging infrastructure at terminal stops, without changing existing routes and the operational (or daily) schedule. However, for an all-electric bus system, these approaches are not suitable for picking out the location of charging stations or the size of the battery system.

Some studies, which have been done regarding the scheduling problem of a electric bus network. Wang and Shen [24] utilized an algorithm of multiple ant colonies (ACA) to solve electric bus scheduling problem with charging points at bus depots. The algorithm has been designed to minimize the number of trips (or vehicles) and the total deadhead time. However, this model does not consider the optimal location of the charging infrastructure. Kunith, Mendelevitch and Goehlich [8] presented a model for the location and optimal number of fast charging stations for a bus network, as well as the battery sizing needed for each bus line. This model proposes installing the chargers at terminal stops as well as at bus stops en route. This approach makes use of a mixed-integer linear (MILP) optimization problem in order to minimize the initial investment cost. But, this research does not take into account the lifetime and maintenance costs of the battery system and charging facilities.

Optimal planning of the charging infrastructure and battery system of an electric bus system is crucial for maintaining a stable bus operation that runs smoothly even under demanding conditions, while also minimizing total investment costs. This thesis presents and puts forth an optimization model which can minimize the total investment cost involved in electrifying the bus lines of the urban public transport system of Santiago (Transantiago). The model determines the minimum required battery capacity and the location of the charging infrastructure for each bus line, while maintaining the existing bus routes and schedules and considering the technical and operational constraints.

This model is based on the project being currently developed by the company Reborn Electric for the electrification of the bus network of Santiago, which aims to transform some of the existing public bus lines to electric power, without changing the existing bus routes and trips. In this way, the operator will not have to adjust the already optimized operational planning, thus ensuring a fast transition from conventional diesel buses to electric buses. In addition, this model takes into account specific network features in order to identify cost synergies when planning the charging infrastructure.

1.2 Reborn Electric Project

The public transport system of the city of Santiago, Chile is characterized by its extensive bus service in conjunction with its metro service. The bus service is provided by 7 private operators. One of the bus operators, Metbus S.A, was selected to carry out the current Transantiago project to electrify all the bus fleets. In order to help advance the electrification process, the company Reborn Electric is working on the project to convert of some of the buses run by Metbus that are currently combustion-powered to 100% electric. For this conversion, all of the components of the diesel engine are completely removed and replaced with an electric motor, control drivers, battery packs and other complementary components. The goal of Reborn Electric's project is to reduce the initial investment cost by using the buses that currently are operating. Because the main cost-pusher for electric buses is the costs of the battery systems and their lifetime [19]. Thus, the cost of electrifying bus lines is lower than the total cost of purchasing a new full fleet of electric buses.

Some limitations should be considered in this project, such as the technical constraints of weight and reduced space for the battery system. Therefore, it is convenient to minimize the size of said battery system to not only save on expenses, but also to accommodate the spatial limitations. Furthermore, the buses will stick to the current routes and schedule, so that the operator won't need to change that operational plan.

1.3 Charging Infrastructure

The charging systems available on the electric buses market differ on their charging mode. The two options are manual charging interfaces (depot charging) and automatic charging interfaces (opportunity charging) [15] (see Figure 1.1). Depot charging is done with a slow charge, mainly in the bus depot overnight and during longer breaks. If the buses have to run all day, a larger battery system is necessary, which implies a higher overall system weight [21]. Thus, from the operator's perspective, the need for a higher capacity battery increases the total ownership cost. The available options for charging interfaces are AC plugs, on-board chargers and stationary fast chargers of 50 –300 kW with a standardised interface (CCS). Opportunity charging is performed with high power charging, mainly in the bus terminal, during short breaks and along the course of its route [8]. This charging system requires a much lower battery capacity, allowing for a significant reduction in battery weight [18]. However, opportunity charging requires many expensive chargers since the power requirement is high, raising the initial cost. Thus, this system requires careful planning of infrastructure to identify the correct number of charging points and comply with the operational schedule. There are four types of opportunity charging options. First, are the two types of pantograph, one of which can be mounted on top of the vehicle (rooftop pantograph) and the other which is installed on the infrastructure side and attaches to the top of the vehicle from above (inverted pantograph). Next, there are two plug-in options, which can be connected from the side of the vehicle or from underneath. Finally, there is inductive charging done from the street [15].

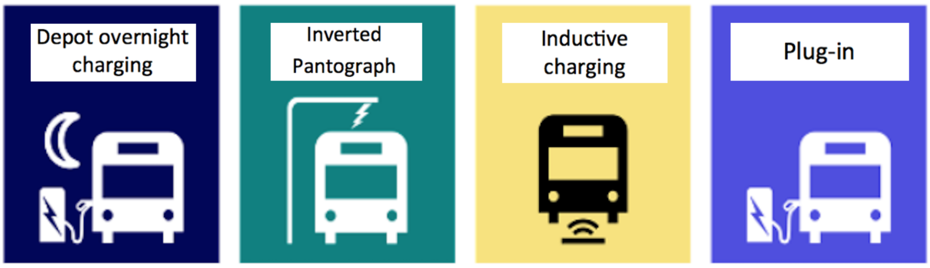


Figure 1.1 – Charging Methods: Depot overnight charging, Opportunity charging: Inverted Pantograph, Inductive Charging and Plug-in.
Source: Kunith 2017. Elektrifizierung des urbanen öffentlichen Busverkehrs.

There are several constraints to consider when planning for the charging infrastructure. First, there is the operational schedule, with its daily hours of operation and dwell times. Then, the energy consumed by each bus on its line's route must be factored in. Also crucial is information regarding the topology of the bus network, the available charging infrastructure, and the availability of suitable sites for charging stations. Finally, the most suitable type of battery for the electrification of bus system needs to be identified [8].

In general, the terminal stops are considered as suitable initial locations for the charging stations, since the terminals are located outside of the city center, where multiple installations of charging points in the same bus station can be done more easily. In addition, the longest dwell time typically is at the terminal stops, where the charging process can be carried out with greater flexibility to comply with the operational schedule [18].

1.4 Battery System

The high cost of battery systems currently represent a major challenge to the introduction of electrified public buses into the public bus transport system [21]. The cost of the battery system depends mainly on the chemical composition of the battery. There are different battery technologies that can be used for electric buses depending on the desired operating range, the location of the charging stations and the amount of charging power available [18]. The different types of battery available on the electric bus market for public transport include lead-acid batteries, lithium ion batteries and Li-polymer batteries [1]. Battery systems for electric public transport buses today typically utilize lithium-ion technology, because lithium-ion batteries meet specific requirements for high specific power and energy densities [18] – [2].

There are different types of lithium-ion batteries (li-ion cell types), the variety depends on the selection of their anode (negative electrode materials) and cathode (positive electrode materials) materials. The options for anode materials are graphite and lithium titanium oxide (LTO), while cathode materials include lithium iron phosphate (LFP), lithium manganese oxide (LMO), lithium mixed Nickel-Manganese-Cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA) [16]. The main advantages of using lithium-ion batteries are they have a high volume capacity, high specific energy, low weight, good high-temperature performance and require low amounts of maintenance [2].

The aging process of lithium-ion batteries is a major problem to be considered when looking at possible applications in electric vehicles [4]. The end of life (EOL) of a lithium-ion battery is defined as when 80% of the original capacity is remaining at the test discharge condition [18]. The rate at which the battery ages depends on several factors; principally the current used when charging, the depth of discharge (DOD) and the ambient operating temperature [4]. In addition to facing loss in capacity across their lifespan, lithium-ion batteries also have to confront increasing internal resistance as they age. Both of these issues are crucial and have to be taken into account for battery sizing. The key to a battery's longevity is to always try to keep a relatively low depth of discharge and to carefully set the charging parameters such as current, voltage and temperature. Depending on the charging frequency, as overnight charging or opportunity charging at each bus stop or at the terminal station, the charging current applied has to be precise so as to not exceed the upper voltage limit of the battery, which could lead to an over-charging. In the long run, this causes the cell to fail and may cause safety problems [10] – [4]. Another important factor to consider is that the performance of the battery depends on the ambient temperature, making it crucial to control the temperature of the battery system and not to operate in extreme conditions [4].

2 Models

The purpose of the chapter is to present the methodology developed in this thesis, with the aim of gathering actual results to advance the process of electrifying the Santiago bus network. In the first section, a general mixed-integer linear optimization model is outlined. Second, an energy consumption model of each service trip is laid out for every bus line. In the third section, the data and general assumptions undergirding the optimization model are detailed and the operational conditions of the bus lines are presented. The next section goes over cost parameters considered in the optimization model. Finally, the last section provides an explanation of the simulation process developed in this thesis.

2.1 Optimization Model

In the following section, a general mixed-integer linear optimization model is used to represent the main technical and operational constraints of the bus network. In addition, it sorts out the correct balance between charging stations and battery size for each bus line in order to minimize costs. The optimization model was implemented using python 3.7, with the optimization package Pyomo 5.5, and the GUROBI solver was used to solve the model.

2.1.1 Objective Function

The total investment cost of the optimal selection of the battery size for each bus line and the location of the charging station for these bus lines is defined by Eqs. (1) - (3). The objective function, as shown in Eq. (1), minimizes the capital costs ($C_{CAPITAL}$) (total investment costs)(see Eqs. (1) and (2)).

$$\text{Minimize} \qquad C_{CAPITAL} \tag{2.1}$$

$$\begin{aligned} \text{Minimize} \quad & \sum_{b=1}^{N_{BUSESxLINE}} Q_{battery_b} \cdot P_{battery} \cdot CAP + \sum_{j=1}^{N_{STOPS}} Q_{chargers_j} \cdot P_{charger} \\ & + N_{buses} \cdot P_{electrification} \end{aligned} \tag{2.2}$$

The capital costs are calculated as a sum of first, the cost of the number of modular battery packages required for the bus lines; second, the installment and purchase costs of the charging infrastructure and last, the electrification cost for the entire bus fleet. The first, the cost of the entire bus fleet's battery system, is the sum of the cost for the number of modular battery packages needed in each bus line b. The cost of each bus line's battery system is calculated by taking the product of the required battery units ($Q_{battery_b}$), the price of each modular pack ($P_{battery}$) and the capacity of each battery system (CAP). Secondly, the costs of the charging infrastructure are calculated multiplying by the number of chargers installed at each bus stop and the installment and purchase costs of each charger. Finally, electrification costs are calculated as the product of number of electrified buses (N_{buses}) and unit cost of electrification ($P_{electrification}$). The optimization model is then performed by minimizing total investment costs of the system.

2.1.2 Constraints

The main constraints which represent the technical parameters of the charging process and operational schedule of the bus network are considered. First, a nodal energy balance constraint is applied for each station, in order to ensure that the current state of charge (SOC) of the battery at each stop j, for each trip n and for each line bus b, is equal to the state of charge at the previous station j-1 excluding the energy consumed for traveling from the previous stop C plus energy recharged at the current station j. The necessary differences between intermediate stops along the route or and start or end stops are factored in, with different equations applied. It's assumed that there will be an available charging station at the terminal to enable charging after each outbound or inbound trip, and that there will also be opportunity charging at bus stops.

For the stops at the beginning of the routes j=0, Eq. (2.3) applies, presupposing that there will be a full charge (i.e. initial charge equals maximum battery capacity).

$$\text{START POINT} \qquad e_{n,j,b} = CAP \cdot Q_{battery} \qquad j = 0, \quad \forall \quad n,\ b \tag{2.3}$$

Eq. (2.4) shows the general energy balance assumed for each stop along a route. When departing midway stops along the bus line route b, the energy in the battery of the bus when leaving bus stop j ($e_{n,j,b}$) is equal to the energy remaining when the bus had departed from the previous stop j-1 ($e_{n,j-1,b}$), excluding the energy consumed travelling from stop j-1 to stop j ($C_{n,j,b}$) plus the energy added from the charging process at the stop j ($\gamma_{n,j,b}$)

$$\text{EN ROUTE} \qquad e_{n,j,b} = e_{n,j-1,b} - C_{n,j,b} + \gamma_{n,j,b} \qquad \forall \quad n,\ j,\ b \tag{2.4}$$

The parameter of energy consumed to travel to stop j ($C_{n,j,b}$) is obtained from the energy consumption matrix, which includes the sequential energy consumption between all stops of each bus line. This matrix are extracted from the energy consumption simulation that will be explained in more detail in the next section.

Where γ represents the amount of energy added from the opportunity charging process. This variable is limited to a minimum between the amount of energy added from the fast charging process, during the waiting time (t_1) at the stop j with charging power (CP), and the upper limit of the battery. In order not to exceed the waiting time at the bus stop j and not run the fast charging process at the upper region of the SOC to avoid an over-charging of the battery system. An upper limit of three minutes is set for the charging during the route.

$$0 \leq \gamma_{n,j,b} \leq min\,\{CP * t_1 * Q_{chargers_j};\, 0.85 * CAP * Q_{battery_b}\} \qquad \forall \quad n,\ j,\ b \tag{2.5}$$

Due to min operator in Eq. (2.5), the formulated optimization model is a Mixed Integer NonLinear Programming (MINLP) model. Then it's preferable to linearize Eq. (2.5), because solving MINLP problem is much more computationally challenging than solving a Mixed Integer Linear Programming (MILP) problem. To formulate a linear model, Eqs. (2.6) and (2.7) are added as constraints.

$$\gamma_{n,j,b} \leq CP * t_1 * Q_{chargers_j} \qquad \forall \quad n,\ j,\ b \tag{2.6}$$

$$\gamma_{n,j,b} \leq 0.85 * CAP * Q_{battery_b} \qquad \forall \quad n,\ j,\ b \tag{2.7}$$

Finally, for the stops at the end of routes, we assume that charging is required for the upcoming trip (see Eq. (2.8)). The charging process takes place during break time in the schedule between bus trips (t_2) at the terminal station j with charging power (CP).

$$\text{END POINT} \qquad e_{n,j,b} = e_{n,j-1,b} + CP * t_2 * Q_{chargers_j} \qquad \forall \quad n,\ j,\ b \tag{2.8}$$

The subsets of the start, end, and midway stops vary between routes depending on the direction of the route (i.e. outgoing or incoming), because the stops are placed at different locations depending on the direction (e.g. across the road or in a totally different place if the outbound and inbound routes have different paths). Each bus stop is given a unique identifying code, in accordance with Santiago Public Transport Authority's bus schedules. Bus stops that are used by multiple routes are associated with every route they are a part of.

Additionally, boundary constraints for the upper and lower limits of the battery are applied under all circumstances during the route, in order to not to exceed the upper voltage limit of the battery during the fast charging process and not accelerate the aging processes.

EN ROUTE:

$$e_{n,j-1,b} - C_{n,j,b} \geq 0.2 * CAP * Q_{battery_b} \qquad \forall \quad n,\ j,\ b \tag{2.9}$$

$$e_{n,j-1,b} - C_{n,j,b} \leq 0.85 * CAP * Q_{battery_b} \qquad \forall \quad n,\ j,\ b \tag{2.10}$$

AT TERMINAL STATION:

$$e_{n,j,b} \geq 0.2 * CAP * Q_{battery_b} \qquad \forall \quad n,\ j,\ b \tag{2.11}$$

$$e_{n,j,b} \leq 0.85 * CAP * Q_{battery_b} \qquad \forall \quad n,\ j,\ b \tag{2.12}$$

The variables of the optimization model are the following:

$Q_{battery_b}$:	number of elemental cell required by the bus line b	integer
$Q_{charger_j}$:	Charging station build at stop j	binary {0,1}
$e_{n,j,b}$:	Current bus energy level of bus line b in trip n at stop j after charging	Continuous (kWh)

The following tables present the list of sets and the parameters used in the optimization model:

Table 2.1 – List of sets used for the optimization model

Sets	**Description**	**Range**
b	bus line	$\in [1, 17]$
j	Bus stop (unique identifying code for each bus stop)	$\in [1, N_{stops}]$
n	number of trips	$\in [1, x]$

Table 2.2 – Parameters used for the optimization model

Parameter	**Description**	**Unit**
$P_{battery}$	Purchase cost of battery with capacity	[€/kWh]
$P_{charger}$	Purchase cost of Chargers	[€]
N_{buses}	Total number of electrified buses	
$P_{electrification}$	Unit cost of electrification	[€]
$C_{n,j,b}$	Bus energy consumption of line bus b in trip n, to travel to stop j from stop j-1	[kWh]
CAP	Battery capacity	[kWh]
CP	Charging power	[kW]
t_1	Waiting time at bus stop	[h]
t_2	Break time between bus trips at the terminal station	[h]

2.2 Energy Consumption Model

The following section provides an explanation of the energy consumption simulation model of an electric bus developed in this thesis, which takes into account the main technical features of the powertrain system and the geographical characteristics of the bus system routes of the city of Santiago, Chile.

2.2.1 Overview of Energy Consumption Simulation Model

The optimal placement of charging infrastructure arises by efficiently replenishing the energy the bus consumes. As such, it's crucial to accurately capture and record a route's particular energy consumption. A simulation model of the electric bus powertrain was developed to determine the energy consumption of each route. Said model takes into account the operating route, bus configuration and auxiliary power consumption. Specifically, a database with the information of distances and gradient angle of the bus routes was elaborated to be used in the simulation. Secondly, the bus configuration data is previously defined in an initialization file, before starting the simulation. This file includes the weight of the bus, resistance coefficients for dynamic of vehicle motion and efficiencies of powertrain components, such as: the battery, electric engine, gearbox, traction converter and regenerative braking. Finally, the consumption of auxiliaries is added, which depends on weather conditions and includes HVAC system (heating, ventilation and air-conditioning), the steering support, the compressor and other devices. The bus energy consumption model was developed using a backward approach [14] – [6] and implemented using the MATLAB/Simulink software platform.

The simulation/method starts with a specific driving cycle, which is used to calculate total tractive force at the wheels as a function of speed, considering the limitations of the torque-speed curve of the motor. From the multiplication of this total force with the actual bus speed, the instantaneous power at the wheels is computed. Then, taking into account the transmission losses and auxiliary consumption, and integrating the total simulation period, the total energy consumption is computed.

2.2.2 Database of Routes

The data collection of the features of the routes is necessary to develop a real and accurate simulation model of energy consumed by an electric bus, because of the great influence of the bus routes' geographical characteristics on the energy consumption. The database includes inclination angle of the road for each bus stop and the distance between each bus stop and the first bus station on the route. The information of the locations of the bus stops was collected from the Google Earth Pro software mapping service in KML file format. Then, elevation data from NASA Shuttle Radar Topography Mission (SRTM) is added to this file [12]. Afterwards, the KML file format is converted to CSV, through the TCX converter program, to calculate the inclination angle of the road. Specifically, the CSV file is modified by adding the columns: slope, inclination angle of the road expressed in radians and inclination angle of the road expressed in degrees, to finally obtain a XLSX spreadsheet that is used by the energy consumption model. The elevation difference Δh and the distance d between two consecutive stops are used to calculate α, such that $\alpha = (tan)^{-1}(\Delta h/d)$. The procedure is performed for each route of each bus line (outbound and inbound trip). Finally, it is necessary to verify that in each spreadsheet generated in Excel, the altitude values are within a permitted range and not show discontinuity, since Google Earth Pro software sometimes delivers out-of-normal values of GPS coordinates, such as outliers or high peaks. The data is filtered to eliminate the outliers or high peaks and these errors are corrected to get more continuous elevation profiles.

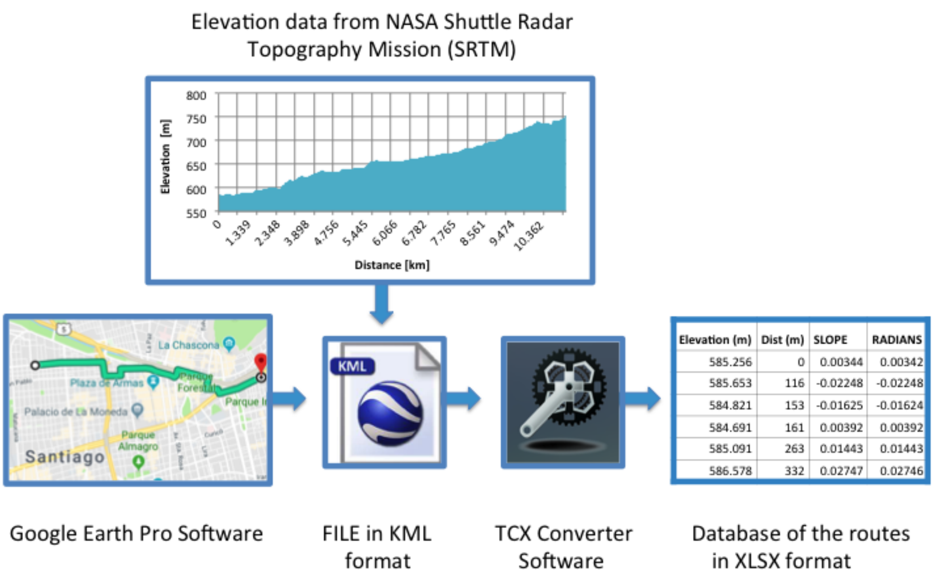


Figure 2.1 – Schematic representation of the data collection

2.2.3 Model Description

The simulation model is divided into 2 concatenated systems (see Fig. 2.2 and 2.3). The first system calculates the speed and force required at the wheel. The model inputs are the speed of the driving cycle, the slope of the road and the distance between each bus stop and the first bus station on the route. The driving speed profile used as a reference is the Santiago driving cycle, which was provided by the Vehicle Control and Certification Center (3CV). The database was explained in the previous subsection 2.2.2

The actual bus speed is calculated using a PID controller and summing up all driving resistances. Specifically, the input into the control loop is the reference speed of the Santiago driving cycle, which is compared with the actual bus speed and the error is sent to a classical PID controller. The output of the regulator is saturated with the maximum torque values given by the torque-speed curve of the motor. To calculate the total force needed at the wheel, multiply the resulting torque by the product of transmission efficiency times reduction over wheel radius. The total force at the wheel through the following equation:

$$F_{Total}(c) = F_{roll} + F_{drag} + F_{climb} + F_{accel} \tag{2.13}$$

The total tractive force F_{Total} includes aerodynamic drag resistance, rolling resistance, climbing resistance and acceleration resistance. Each of the resistive forces are described below and the values of each parameter are detailed in Table 2.3

- Rolling resistance (F_{roll}), the force that is produced by the deformation of the tire with the ground.

$$F_{roll} = C_{rr} * m * g * cos(\alpha) \tag{2.14}$$

Where C_{rr} is the coefficient of rolling resistance, m is the bus weight with average load [kg], g is the gravitational acceleration $[m/s^2]$ and α is the inclination angle of the road, expressed in radian [rad].

- Aerodynamic drag resistance (F_{drag}), the force that is produced by friction with the air as the bus advances.

$$F_{drag} = \frac{1}{2} * C_{drag} * \rho_a * A_f * v^2 \tag{2.15}$$

Where C_{drag} is the drag coefficient, ρ_a is the air density $[kg/m^3]$, A_f is the front area of the bus $[m^2]$ and v is the bus speed $[m/s]$.

- Climbing resistance (F_{climb}), the force that is produced by the weight of the bus when faced with a slope.

$$F_{climb} = m * g * sin(\alpha) \tag{2.16}$$

Where m is the bus weight with average load [kg], g is the gravitational acceleration [m/s^2] and α is the inclination angle of the road, expressed in radians[rad].

- Acceleration resistance (F_{accel}), the force that is produced by the acceleration of the vehicle.

$$F_{accel} = m * a \tag{2.17}$$

Where m is the bus weight with average load [kg], and a is the bus's acceleration [m/s^2]

Finally, the actual speed is calculated from the integral of the force at the wheel.

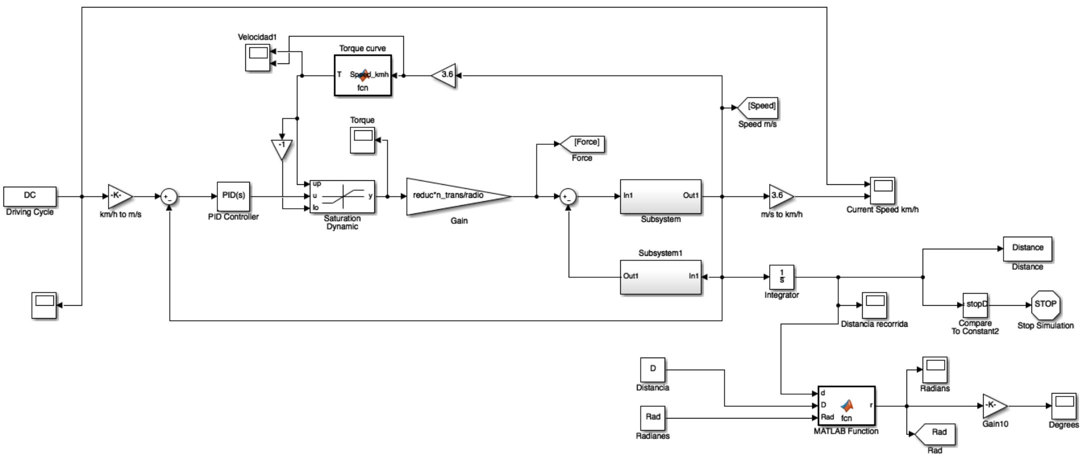


Figure 2.2 – System 1 of the Energy consumption model

The second system of the simulation model calculates the energy consumption. The inputs of the second model are: the actual speed and the resultant force from the first system. The output is the energy consumed during the full course of its route.

In each instant of time during the simulation, the speed is multiplied by the force at the wheel to compute the necessary instantaneous power at the wheel to complete the Santiago driving cycle. Depending on the sign of the instantaneous power, when it is positive (power consumed), it is divided, and when negative (power generated), it is multiplied; by the efficiency of the gearbox, electric engine and traction converter. Furthermore, the regeneration factor is considered when the bus is braking, which determines how much of the kinetic energy can be regenerated. Then it is necessary to add the efficiency of regenerative braking to the power generated. The efficiency of regenerative braking takes into account the fact that not all of the kinetic energy can be recovered due to losses and limitations of the maximum power for recharging the battery [5]. Then, before considering the efficiency of the battery system, the consumption of the auxiliary components (such as air-conditioning and heating, the steering support, the compressor, operating doors, lighting and other devices.) is added to the total instantaneous power. Finally, these power terms are integrated over the entire driving cycle to determine total energy consumption.

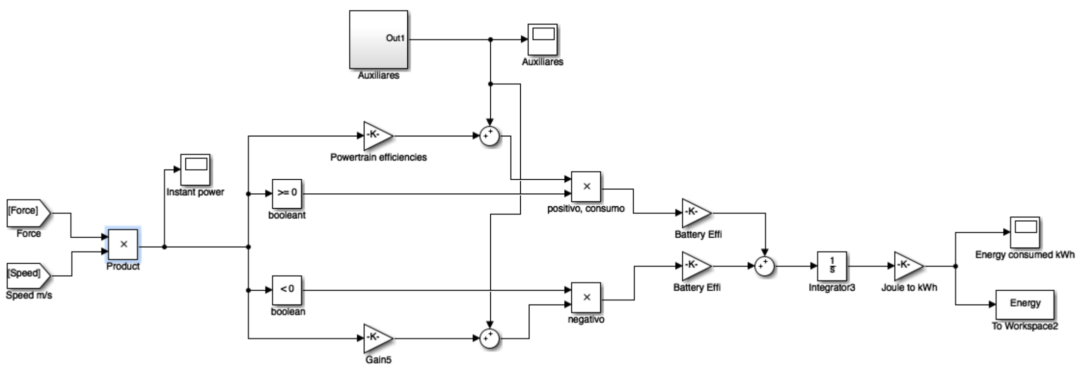


Figure 2.3 – System 2 of the Energy consumption model

Table 2.3 – Technical specifications of the electrified reference bus

Parameter	**Unit**	**Value**
Vehicle mass (total)	[kg]	11400
Vehicle mass with typical load	[kg]	15000
Vehicle mass with maximum load	[kg]	18000
Length	[m]	12.3
Width	[m]	2.5
Height	[m]	3.1
Frontal Area	$[m^2]$	7.75
Rolling resistance coefficient		0.007
Gravitational acceleration	$[m/s^2]$	9.81
Drag coefficient		0.65
Air density	$[kg/m^3]$	1.3
Tires diameter	[m]	1.04
Differential reduction		6

For the optimization model described in the previous section, an energy consumption matrix is required. This matrix includes the sequential energy consumption between every stop on each bus line. Thus, the total energy consumption for each route is calculated in sections, taking the distance between contiguous stops as the basis for each individual section, i.e. the distance between stop j and stop j+1. In this way, the energy consumption of each sub-section of the route is calculated and then the energy consumption matrix is built using these values.

2.3 Assumptions and operational conditions

This section presents raw data and the relevant technical considerations for the optimization model. The first part describes the operational characteristics of the bus lines considered, which are currently operated using conventional diesel buses. The second part focuses on the chosen charging system and the features of the battery considered.

2.3.1 Bus Network

In this study, representative bus lines of the Santiago bus system were identified. The bus operator chosen was the company "METBUS" and bus lines 501 to 518 were selected to make up a total of 17 lines, with 11 terminal stations, a total network of 1001.77 km and 651 buses. In addition, the different bus lines share several intersections, such as some bus stops and also the terminal stations, as can be seen in the figure 2.4. For each bus line, two service trips are simulated corresponding to the outbound and inbound trip between different terminal stations. Furthermore, in this analysis, it is assumed that each vehicle can operate only on a limited number of bus lines, in order to not oversize the number of batteries on each bus line, thus minimizing total investment costs while also maintaining a stable bus operation that runs smoothly even under demanding conditions. The dataset of a workday is chosen in order to meet the requirements of the maximum demand.

The routes of the bus lines differ greatly in terms of total distance and the variability of the slope throughout the route. Specifically, the route length, inclination angle and the number of bus stops vary significantly, ranging between 11 and 32 km, -6° and 8° and 34 to 123 stops, respectively. Information on the topology of the bus network is used for the installation of fast charging stations in some shared stops, in order to take advantage of the cost synergies. Assuming that any potential crossover uses of the charging infrastructure create cost savings, the simulation model incorporates route specific data, whether in reference to the intersections of bus lines or grid accessibility. The selection includes bus routes that cross the city from west to east, connecting extreme points around the city center, as shown in the figure 2.4

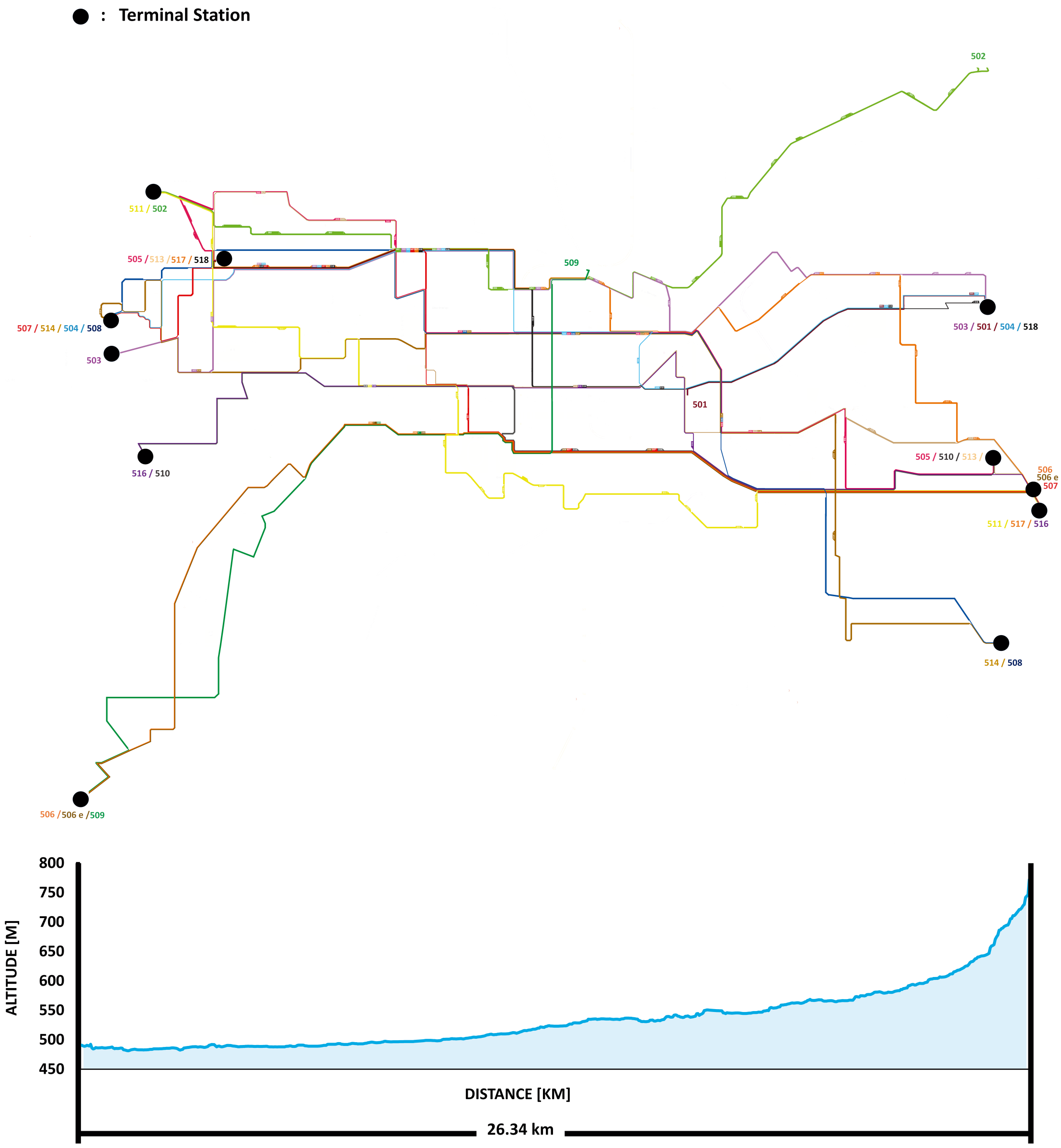


Figure 2.4 – Bus network

The operational schedule of each line has already been pre-determined and an upper limit of three minutes is set for the charging process en route. For the rest of the stops, it is assumed that the dwell time (at each bus stop) is 20s (charging time 15s) and the waiting time at each traffic light will also be 15s. Dwelling times at the terminal station should range between 15 and 20 min. Daily operating hours are up to 18 hours (5:30 am-11:30 pm). The table 2.4 shows the number of trips per day, the number of buses per bus line, and the total distance of each bus route's round trip.

Table 2.4 – Bus lines overview

BUS LINE	**No. of buses per bus line**	**No. of trips per service trip in one day**	**Driving distance OUTBOUND trip (km)**	**Driving distance INBOUND trip (km)**	**TOTAL KM per ROUND TRIP**
501	26	**179**	10.91	10.63	21.54
502	55	**196**	29.72	29.28	59
503	59	**186**	28.41	29.26	57.67
504	45	**128**	30.53	29.93	60.46
505	72	**189**	33.67	33.82	67.49
506	58	**190**	32.92	32.64	65.56
506e	25	**40**	32.84	32.64	65.48
507	43	**139**	31.19	31.25	62.44
508	59	**169**	33.45	33.25	66.7
509	20	**106**	23.66	24.24	47.9
510	23	**93**	28.06	26.94	55
511	24	**91**	35.2	32.99	68.19
513	48	**144**	32.29	31.39	63.68
514	43	**135**	37.36	37.63	74.99
516	52	**191**	29.04	28.92	57.96
517	28	**85**	30.75	30.42	61.17
518	35	**141**	23.37	23.17	46.54
TOTAL	715	2402	503.37	498.4	1001.77
MEAN	42.05	141.29	29.61	29.31	58.92

2.4 Clustering of bus lines

To develop an analysis of the different bus lines to electrify and get a better comprehension of the results of the optimization model, it was chosen to carry out a classification based on the characteristics of the routes. The attributes used to carry out the clustering were the average speed and the angle of inclination accumulated during an ascent trip. The information of the routes and the clusters are presented in the following tables.

BUS LINE	Outbound time [min]	Outbound Distance [km]	Outbound time [h]	Average Speed [km/hr]	Accumulated inclination angle in ascent trip
501	54	10.91	0.9	12.12	38.89
502	118	29.72	1.97	15.11	54.474
503	125	28.41	2.08	13.64	66.682
504	127	30.53	2.12	14.42	65.63
505	130	33.67	2.17	15.54	57.985
506	121	32.92	2.02	16.32	50.691
506e	111	32.84	1.85	17.75	38.295
507	124	31.19	2.07	15.09	63.5
508	134	33.45	2.23	14.98	46.587
509	106	23.66	1.77	13.39	31.035
510	117	28.06	1.95	14.39	43.525
511	139	35.2	2.32	15.19	57.329
513	134	32.29	2.23	14.46	55.906
514	151	37.36	2.52	14.85	54.393
516	123	29.04	2.05	14.17	66.83
517	129	30.75	2.15	14.3	84.376
518	111	23.37	1.85	12.63	54.857

Table 2.5 – Average speed in ascent trip, grouped by cluster

AVERAGE SPEED	**[km/h]**	14.61					
LOW	501	503	509	518			
MIDDLE	504	508	510	513	514	516	517
HIGH	502	505	506	506e	507	511	

Table 2.6 – Accumulated inclination angle in ascent trip, grouped by cluster

ACCUMULATED INCLINATION ANGLE	[°]	54						
MINIMUM	501	506	506e	508	509	510		
MIDDLE	502	514	518					
MAXIMUM	503	504	505	507	511	513	516	517

From the results of the clustering, the bus lines 505, 507 and 511 would be expected to consume more energy during the inbound trip. However, in a roundtrip, it will not necessarily be the same bus lines that consume more energy, because it also depends on the characteristics of the return route, in terms of the length of the route and if they can regenerate enough energy in the descent.

2.5 Charging Strategy and Battery System

The trade-off between the battery capacity and the amount of installed charging infrastructure is crucial to determine the electrification costs. With regards to the charging process, this study has determined that the use of both types of charging systems is preferable, the opportunity charge and the depot charge, in order to take better advantage of the dwell times of the buses. This mixing of the two charging forms will also allow for charging between the end and the beginning of routes, thus not overshooting the ideal number of battery modules. The opportunity charge can take place during the day at bus stops along the route as well as at the terminal stops. In this system, the fast charging process is performed using an inverted pantograph. In a complementary way, depot charge will be used during the night at the terminal stations with slow charges, with a charging power of 50 kW in order to recharge completely the remaining energy deficit accumulated during the day. Therefore, at the end of the shift the bus battery is charged to 100% state of charge (SOC).

In this model, a lithium-ion based battery is selected, because of its high specific power and energy densities. Specifically, in this study a lithium-titanate battery (LTO) was chosen, due to the high charging power used during fast charging process. The required capacity of the battery is calculated based on the energy consumption of the different routes under extreme operating conditions, the availability of the charging infrastructure and spatial restrictions in the soon-to-be transformed vehicles. Additionally, in order to avoid an accelerated degradation of the batteries, the battery capacity must be such that the battery's state of charge (SOC) never dips below 20%, when running at entire operating range. Then, during the day, the fast charging process will be limited to the threshold of 85% SOC so as not to accelerate the fading process and at the depot, the overnight charge will be made above this limit up to 100%, with low power. The variation of battery capacity will be limited to a maximum of three different sizes, depending on the distance covered by buses on each trip, in order to guarantee operational flexibility and limit technical complexity. Due to requiring the same battery capacity for each bus line would be detrimental to the project, inevitably incurring unnecessarily high costs for unneeded size. However, to precisely determine the individual capacity of each bus line according to its respective energy consumption would limit the flexibility of the implementation of the electrification project. Furthermore, all buses which are operated on the same bus line have an identical battery system and the battery of each bus is fully charged at the beginning of the each day, which means that the SOC is 100%.

Table 2.7 – Battery technical specifications

	High-power battery
Cell chemistry	Titanium oxide
Cell capacity (Ah)	30
Cell nominal voltage (V)	2.1
Cell weight (kg)	0.75
Cycle life	10000

2.5.1 Battery Design

The battery system design depends on the charging strategy used and therefore on the needed energy content of the battery. Also, the battery system must be sized in line with the maximum and minimum voltage requirements of the electric engine, in order to provide the necessary driving power during a service trip. Different topologies can be constructed depending on the desired output voltage and the cells which are chosen [22]. Most contemporary battery systems have a straightforward serial connection. However, there are also reasons to favor a more complex topology that connects smaller cells in parallel either on cell (parallel-series connection) or consists of more than one pack [19]. When cells are connected in parallel, the redundancy is enhanced because the failure or flaw in one cell does not necessarily bring the whole system down. Further, when two independent packs are used, normal operations can continue in spite of a failure, such as overheating in one of the two systems. The usage of two independent packs can be done either by directly connecting identical packs in parallel, or by using dc-to-dc converters to connect them at a common dc-link. The latter connection offers further flexibility in the powertrain design at the cost of a higher complexity due to the additional power electronics and control effort. In this case, the packs are connected directly in parallel to limit the complexity and make an easy installation of the packs inside of the bus. The configuration in which the cells are connected internally will determine the necessary voltage level in the system. If the topology without a DC-link is used, the battery voltage sets the voltage level of the traction inverter at the same time. In this project the battery system must have a voltage range between 450V and 700V. The battery system is designed to store the energy needed to maintain stable bus operations even under demanding conditions. Thus, the design selected could be one with 1 pack or 2 packs in parallel, depending on the bus line. This keeps costs low, and limits the complexity of installing batteries on the buses.

2.6 Cost Parameters

The following cost parameters used in this study are based on the values presented in recent literature. The cost of the battery system in electric buses varies significantly depending on the chemical composition of the battery and battery's energy capacity. In addition, it is not reasonable to assume that the purchase costs of batteries will continue to decrease enormously in the future, as has occurred in recent years, since the price of batteries is expected to stabilize. However, the installation of fast charging infrastructure will decrease in the future, as technologies mature and diffusion increases. The costs are specific for the case study but averaged to hide traceable information from the battery manufacturers. The cost of the components related to the electric motor, control drivers and other electronics are not given, because it's private information belonging to the Reborn Electric company. Table 2.8 shows the chosen cost parameters for this evaluation.

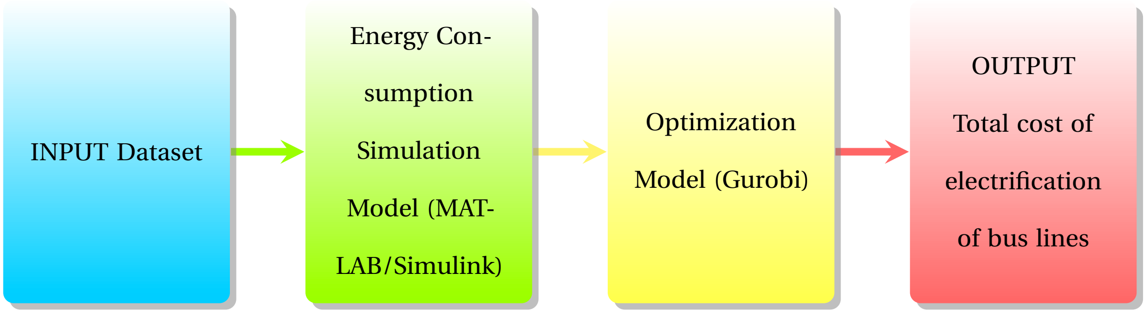
Table 2.8 – Cost parameters

Parameter	**Value**
Purchase cost of electric bus (without battery)(€)	350000
Reference service life of buses (years)	10
High–Power battery cost (€/kW)	250
Fast charging device cost (P>200 kW) (€)	250000
Overnight charging device cost (P<= 50 kW) (€)	20000
Service life of charging devices (years)	20

2.7 Structure of the simulation process

Figure 2.5 provides a schematic representation of the structure and linkages of the model components developed in this thesis.The structure of the model can be split into four main steps . First, (i) the input dataset, which collects information on bus configuration data, the driving cycle and route characteristics. Important route characteristics include the road's angle of incline at each bus stop, the distance between each bus stop and the first bus station on the route. Second, (ii) the energy consumption model, which calculates energy consumption for each sub-section of the route. Then, the energy consumption matrix, which includes the sequential energy consumption between every stop on each bus line, is built. Third, (iii) the optimization model, which finds the minimum total costs for the 2 reference cases considered. Lastly, (iv) the sensitivity analysis, which uses the results from the 2 reference cases to analyses certain parameters for their sensitivity.

Figure 2.5 – Flowchart of the simulation process


INPUT Dataset
Energy Consumption Simulation Model (MATLAB/Simulink)
Optimization Model (Gurobi)
OUTPUT
Total cost of electrification of bus lines

3 Results and Sensitivity Analysis

This chapter focuses on presenting and analyzing the main results regarding how to electrify certain bus lines with a fast charging infrastructure. For this, 2 reference cases were used to make a reasonable comparison of which option is more profitable in terms of the investment costs required for the charging infrastructure and the battery system. Secondly, a sensitivity analysis is presented to analyse different scenarios considered for the 2 reference cases, together with the respective results of the different simulations.

3.1 Assumptions

The following assumptions are presented in the previous chapter and are made throughout the entire study:

- All buses start the working day with 100% battery capacity.
- The battery system has a built in added safety margin which guarantees a SOC of more than 25% throughout the route. This lasts until the bus arrives at the terminal station for its scheduled break for charging between bus trips.

- With regards to the fast charging process, the charging time at bus stops is 3 minutes and 20 minutes at the terminal station.
- The standard solution adds one fast charger to each terminal to the base number suggested by the solver. The extra serves as a backup reserve in case of the failure of another charger, to avoid interruptions to the bus schedule.
- Slow charging is exclusively carried out at night after the end of a shift . This nighttime charging at the terminal station is carried out at a charging power of 50 kW. The bus battery is charged to 100% by the end of this nighttime charging session.
- In accordance with the operational schedule, every bus line parks half its bus fleet in one of the two terminal stations, with the exception of lines 501, 502 and 509.
- The bus line 501 is the only line that goes through the charging process after each round trip, due to the short length of its route and its high operational frequency.
- All buses are identical and are operated by the same bus company.

3.2 Reference Cases

In this study, 2 reference cases are considered in order to determine the most economically convenient solution which both complies with the technical requirements and the bus network's operational schedule. First, option A entails using opportunity charging along the route, and pairing this with a charging session at the terminal station each time a bus finishes an inbound or outbound service trip. Secondly, option B involves charging en route as well, but accompanies this with charging at only one of the two terminal stations reached each time the bus makes a roundtrip. Table 3.1 shows the values of the parameters adopted for both options.

Table 3.1 – Simulation parameters

Parameter	**Value**
Price of battery (€)	250
Price of Fast charging devices (€)	250000
Auxiliary Consumption (kW)	6
Charging Power of Fast charger (kW)	400

3.2.1 OPTION A: Opportunity charge at each terminal

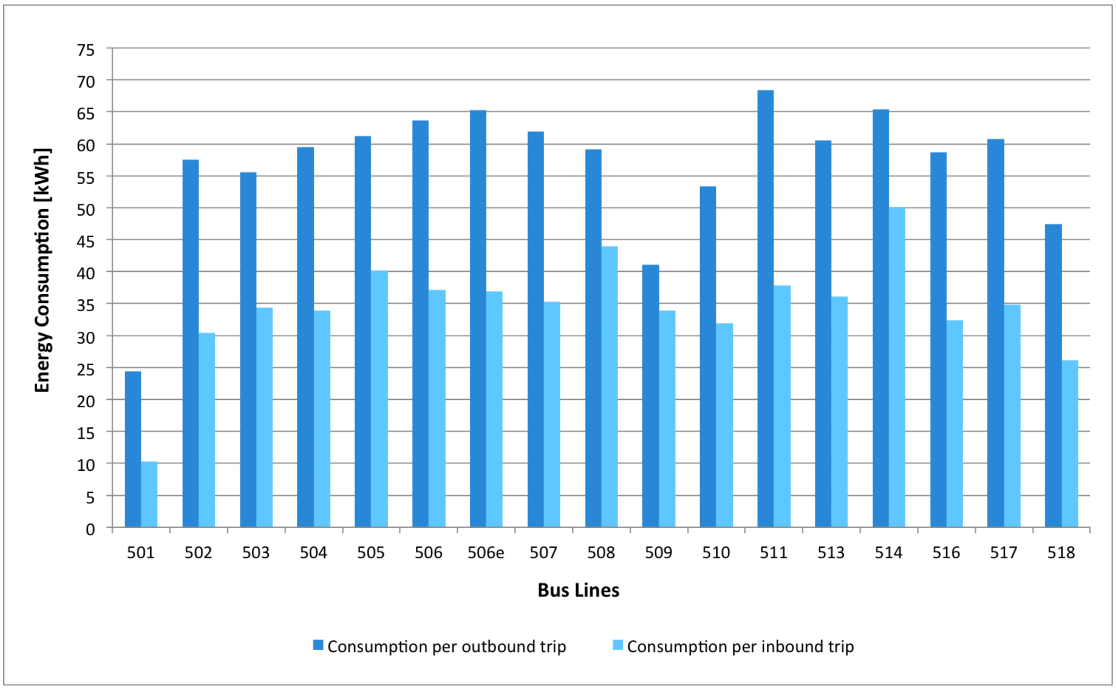


Figure 3.1 – Energy Consumption per outbound and inbound trip for each bus line in the reference case of option A

The above graph gives the energy consumption of one bus from each bus line, per outbound and inbound trip respectively. These results were calculated using the energy consumption simulation model, which was explained in the chapter 2. The bus weight considered for this option is 15 tons. The energy consumption of the outbound routes varies between 24 kWh and 68 kWh, with an average consumption of 56.68 kWh. Bus line 511 has the highest energy consumption, at 68 kWh.

The results for option A are presented in the table 3.2. For the electrification of bus lines 501 - 518, a total number of 42 charging stations are required. The charging points are located at each terminal station as well as at terminal stops. Only one charger is located en route and is used by 3 bus lines: 502, 503 and 517. This charging station is also the terminal stop of bus line 509 (see Fig. 3.2).

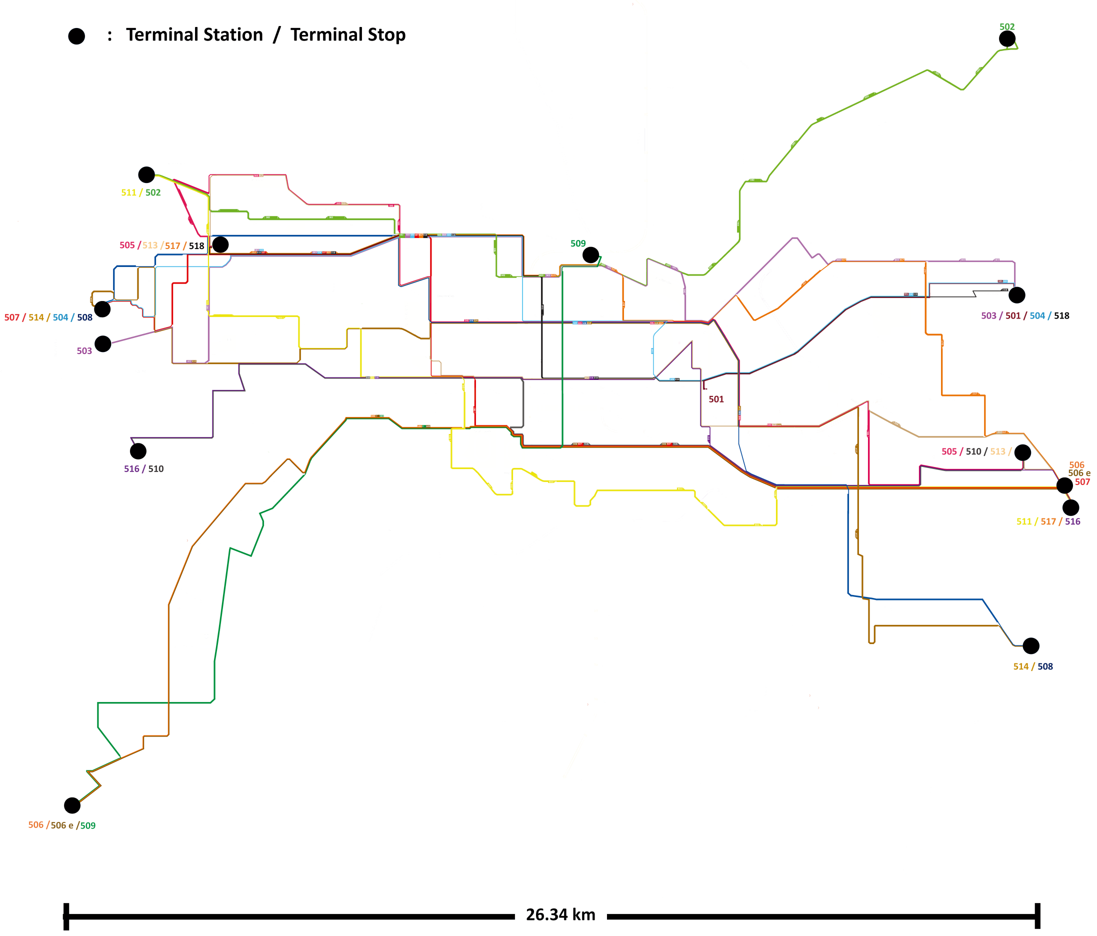


Figure 3.2 – Bus network and charging stations for the reference case of the option A

The design of the battery system modules was chosen with an eye towards size, looking to equip buses with the smallest possible batteries. This focus on size was important in order to guarantee operational flexibility and limit the technical complexity of the implementation of the electrification project. In this way, it's easy to classify the bus lines into 2 clusters: 1 modular pack of 30 modules in a series of : 5p10s and 2 modular packs in parallel, each modular pack of 30 modules in series of : 3p10s. This battery design follows the logic of the groupings being based on average speed, because the bus lines with low speed have the smallest battery size. However, the grouping around the angle of incline does not correlate to battery design since the fast charger is located on the route.

Table 3.2 – Solution of the reference case of option A

Bus Line	**Energy Consumption per Outbound trip (kWh)**	**Energy Consumption per Inbound trip (kWh)**	**Battery Design**	**Useful Lifetime (years)**
501	24.349	10.254	1 pack 5p	3.91
502	57.497	30.398	1 pack 5p	3.42
503	55.512	34.399	1 pack 5p	3.91
504	59.536	33.877	2 packs 3p	4.57
505	61.218	40.139	2 packs 3p	4.57
506	63.668	37.182	2 packs 3p	3.42
506e	65.239	36.953	2 packs 3p	6.85
507	61.945	35.321	2 packs 3p	3.42
508	59.149	44.003	2 packs 3p	4.57
509	41.028	33.93	1 pack 5p	2.49
510	53.342	31.959	1 pack 5p	3.04
511	68.368	37.778	2 packs 3p	3.42
513	60.571	36.126	2 packs 3p	4.57
514	65.389	50.149	2 packs 3p	3.91
516	58.665	32.358	2 packs 3p	3.42
517	60.801	34.824	1 pack 5p	3.91
518	47.439	26.154	1 pack 5p	3.04

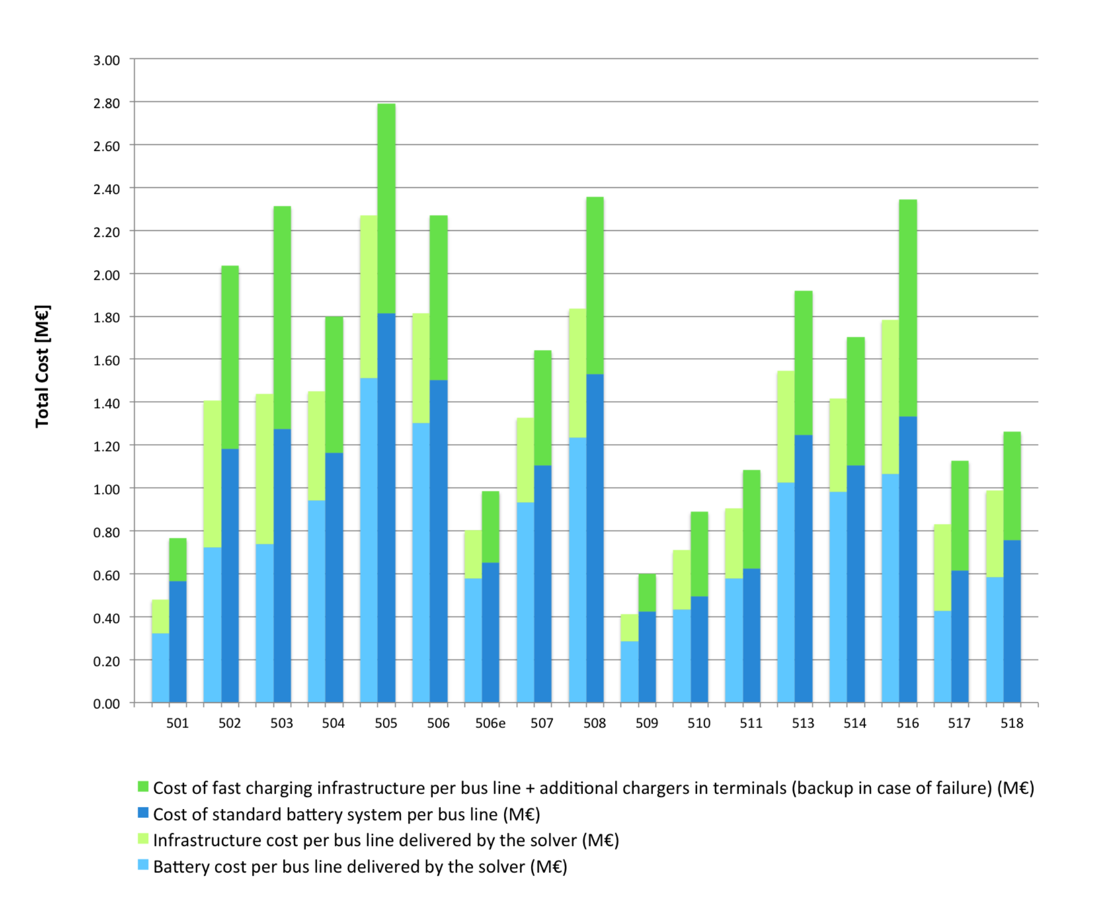


Figure 3.3 – Electrification costs per fleet and bus line for the reference case of the option A

Figure 3.3 shows the initial electrification cost as calculated by the solver, along with the cost as calculated when considering a standard battery design. System cost includes the battery system as well as the fast charging infrastructure for each bus line. The total electrification cost of each bus line's fleet varies considerably, mainly as a result of differing numbers of operating buses. Bus lines 505, 506, 508 and 516 present the highest total cost of electrification, due to the high number of operating buses. The infrastructure costs are allocated in proportion to the number of bus lines which utilize a fast charging station. The highest costs for charging infrastructure per bus line are incurred for bus lines 503 and 517, respectively. This is because the number of buses needed for these lines is not too high when compared with the cost of a fast charging device. As was mentioned in the assumptions, there is difference in the charging infrastructure cost between the solution given by the solver and the final solution chosen. This is due to these additional back-up chargers at the terminal stations.

The total fast charging infrastructure for the simulated bus network of 1001.77 km operated by 651 buses amounts to 10.5 million €, compared to a battery cost of 17.39 million €. Therefore, the charging infrastructure for the electrification of the bus network amounts to around 10,481 € per bus route km. In addition, with this solution is necessary to install 41 slow chargers, which are distributed in the terminal stations in proportion to the number of operating buses. The total cost of the slow chargers is 0.44 million €, then the total initial investment cost is 28.71 million €.

3.2.2 OPTION B: charging after every round trip

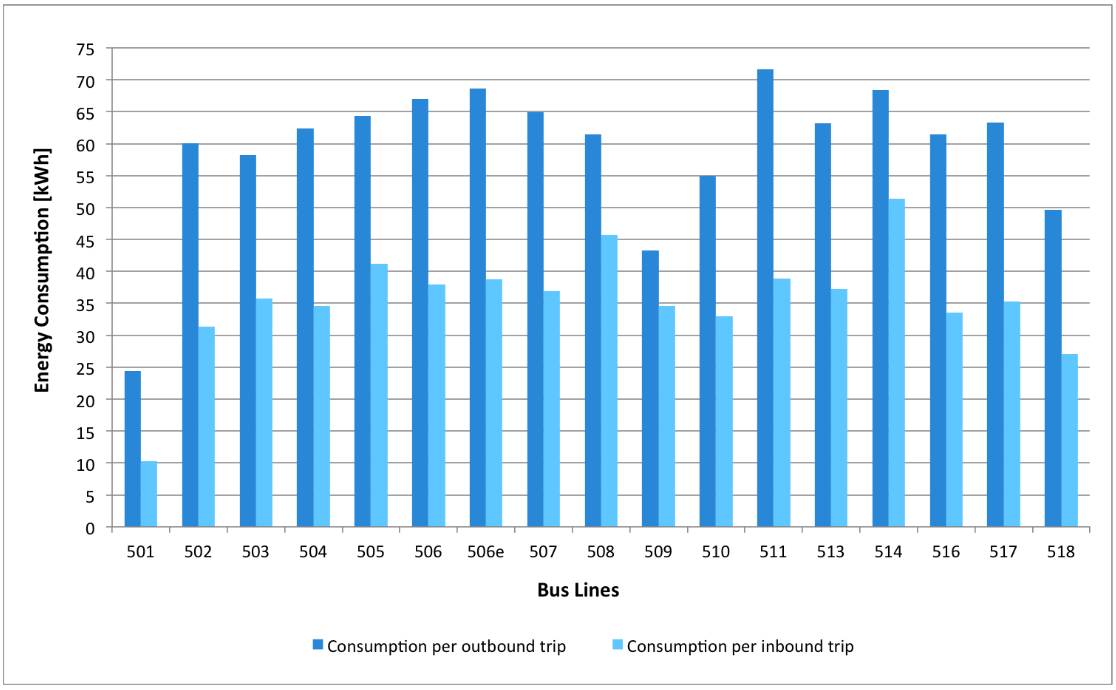


Figure 3.4 – Energy consumption per outbound and inbound trip for each bus line in the reference case of option B

In this case, the bus weight used to calculate the energy consumption was 16 tons. Because the charging process is carried out after every round trip, a larger battery system is necessary, which implies a higher overall system weight. The energy consumption of the outbound routes varies between 25 kWh and 72 kWh, with an average consumption of 59.32 kWh. As expected, as in the previous case, the bus line with the highest energy consumption on its outbound trip is 511, at 72 kWh. However, for round trips, the bus line with the highest energy consumption is 514, since the route of the incoming trip does not allow for enough regeneration of energy in comparison with line 511.

The results for option B are presented in table 3.3. For the electrification of bus lines 501 - 518 a total number of 23 charging stations are required. Almost all of the fast charging points are located at terminal stations on the western side of the city, with only three fast chargers placed at just one terminal station on the eastern side of the city (see Fig. 3.5). There aren't charges en route, due to the charging constraints on each round trip and the high cost of fast charging devices.

Table 3.3 – Solution of the reference case of Option B

Bus Line	Energy Consumption per Outbound trip (kWh)	Energy Consumption per Inbound trip (kWh)	Battery Design	Useful Lifetime (years)
501	24.349	10.254	2 packs 4p	5.48
502	60.118	31.371	2 packs 4p	6.85
503	58.186	35.701	2 packs 5p	6.85
504	62.411	34.628	2 packs 5p	9.13
505	64.384	41.221	2 packs 5p	9.13
506	67.001	37.999	2 packs 5p	6.85
506e	68.626	38.767	2 packs 5p	13.70
507	64.903	36.946	2 packs 5p	6.85
508	61.402	45.731	2 packs 5p	9.13
509	43.239	34.585	2 packs 4p	4.57
510	54.914	32.923	2 packs 4p	5.48
511	71.632	38.898	2 packs 5p	3.42
513	63.221	37.227	2 packs 5p	9.13
514	68.440	51.430	2 packs 6p	3.42
516	61.432	33.543	2 packs 5p	6.85
517	63.270	35.292	2 packs 5p	6.85
518	49.635	27.057	2 packs 4p	5.48

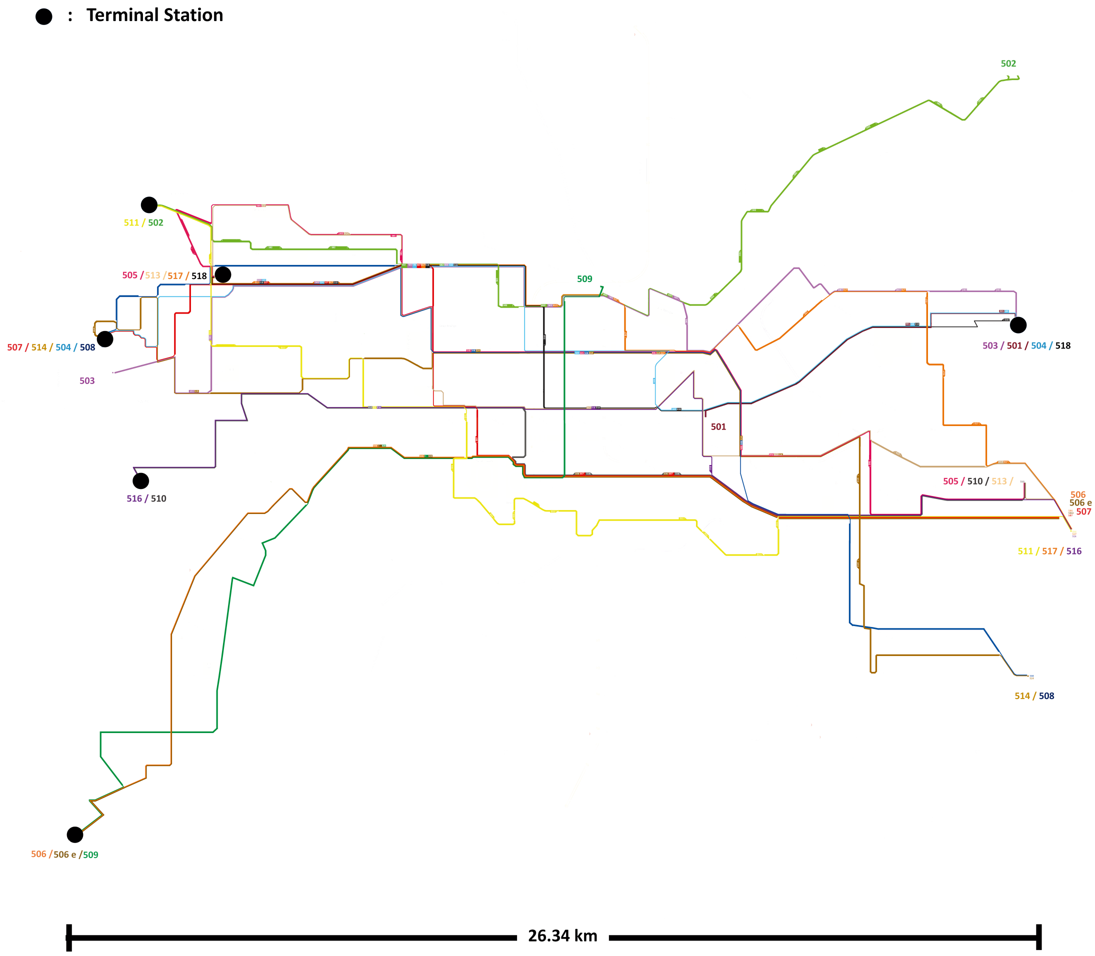


Figure 3.5 – Bus network and charging stations for the reference case of the option B

The design of the battery system modules was selected with an eye towards guaranteeing a reliable energy supply over the course of a round trip. This is crucial in order to preserve operational flexibility and avoid unnecessary technical complexity in implementing the electrification project. Therefore, stable bus operations are kept at normal consumption rates during a round trip. The clusters for this option are 3: 2 modular packs in parallel, each modular pack of 30 modules in series of: 4p10s, 2 modular packs in parallel, each modular pack of 30 modules in series of: 5p10s and 2 modular packs in parallel, each modular pack of 30 modules in series of: 6p10s (see Table 3.3).

There is not a strong relationship between battery design and either type of clustering. In the case of clustering based on average speed, bus line 502, with a high average speed, requires the smallest battery size with 2 modular packs in parallel with an elemental cell of 5p. The cluster based on the accumulated angle of incline for bus lines 506, 506e and 508, which have a low overall angle of incline, requires the mean battery design with 2 modular packs in parallel with an elemental cell of 5p.

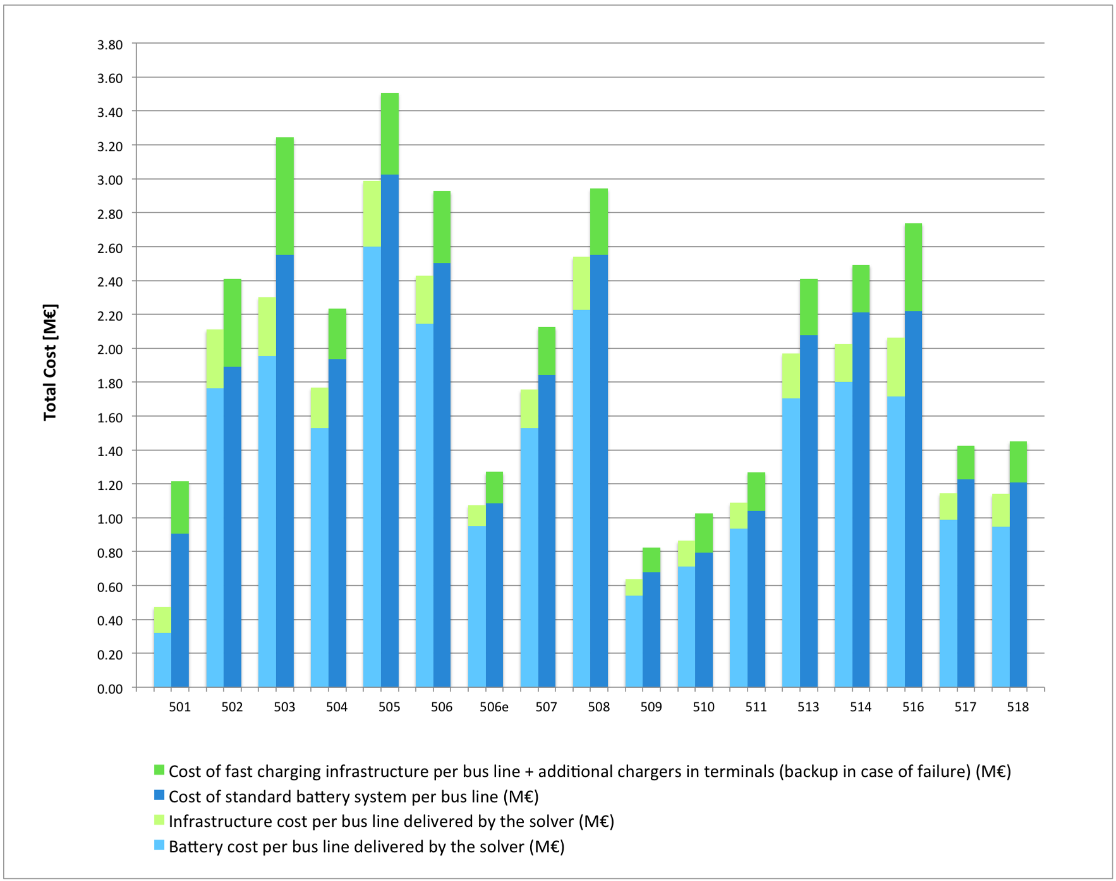


Figure 3.6 – Electrification costs per fleet and bus line for the reference case of the option B

Figure 3.6 presents the initial electrification cost including the battery system and the fast charging infrastructure per bus line. In this case, the number of fast charging devices is less than in option A, resulting in lower infrastructure costs than in the first case. However, battery cost per bus line are higher than option A, due to the large capacity required and the high number of operating buses. Therefore, total investment cost are also higher than in option A. With this solution, the bus lines 503, 505, 506 and 508 present the highest total cost for electrification, due to the high number of operating buses.

The highest costs for charging infrastructure per bus line occur for bus lines 503 and 505, respectively. Because these bus lines are the ones with the highest number of operational buses, so the utilization rate of the charging infrastructure by these bus lines is higher than the other bus lines

The total fast charging infrastructure for the simulated bus network of 1001.77 km operated by 651 buses amounts to 5.75 million €, with a battery cost of 29.76 million €. Therefore, the cost of the charging infrastructure needed for the electrification of the bus network amounts to around 5,740 € per bus route km. Furthermore, with this solution it's necessary to install 94 slow chargers, with 64% of them distributed in the eastern terminal stations. This is because those terminal stations do not have fast charging infrastructure. The total cost of the slow chargers is 1.88 million €, bring the total initial investment cost to 37.39 million €.

The difference between option A and option B is 8,68 million €. The problem with option A is that this solution accelerates the aging process of the battery system, due to the high number of charging process taking place each day. Thus, in the short term to take into account the replacement cost of the battery each bus line, at least in 3 years into the future. On the other hand, the problem with option B is the high initial investment cost, in terms of the battery system. The Reborn electric company has to decide which option is most economically convenient. Because, the battery price has decreased in recent years, but it's expected that in the next years, the battery cost will remain steady.

3.3 Scenario 1: Normal weight and Auxiliary Consumption 6 kW

3.3.1 OPTION A: bus weight 15 ton

I. **Charging Power of 400kW at terminal station:**

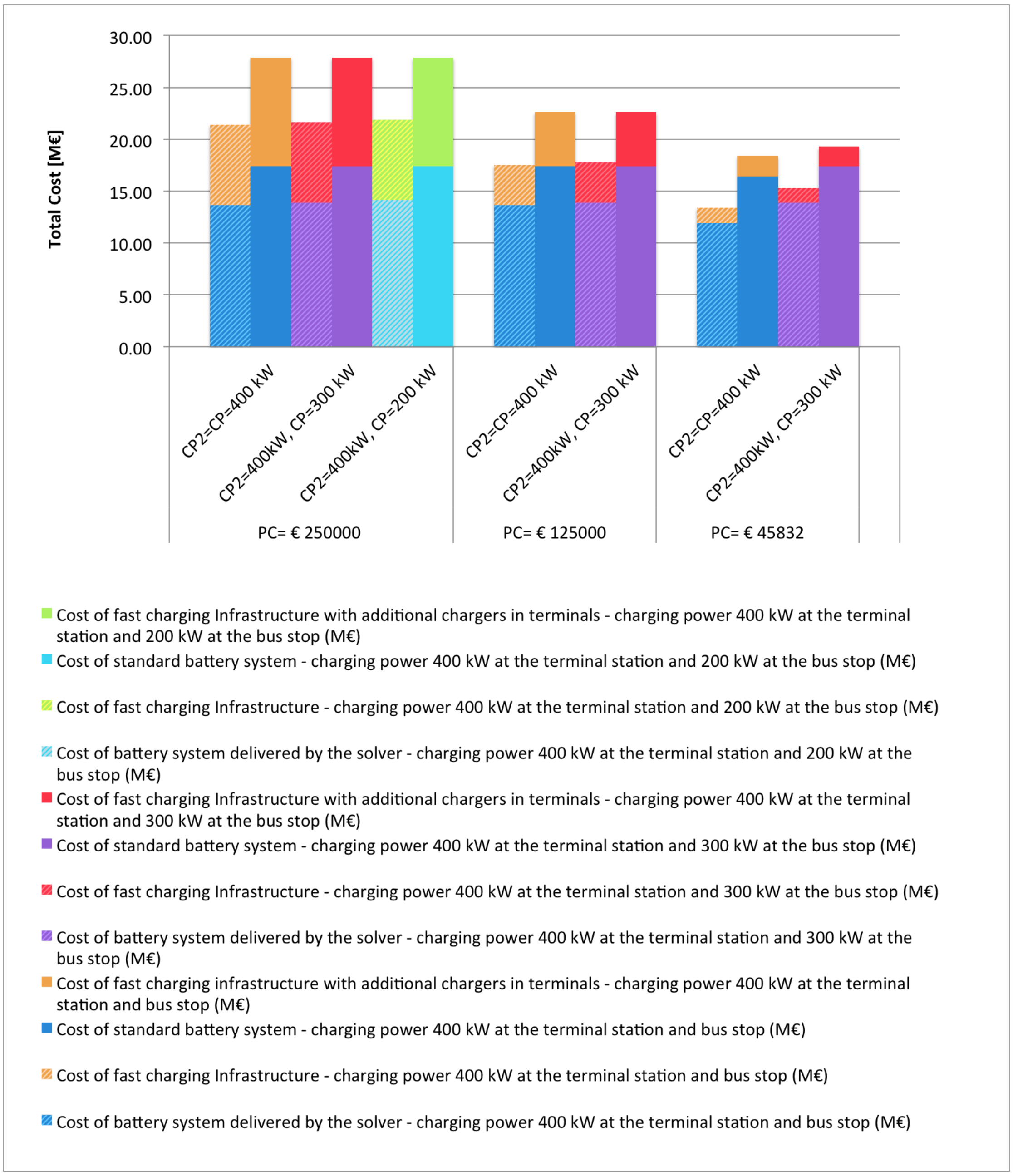


Figure 3.7 – Electrification costs with charging power of 400 kW at the terminal station

The solution delivered by the solver shows an increase in the size of the battery system and therefore in its costs, as the charging power of the fast chargers en route decreases. However, when the price of the fast charging infrastructure is greater than 45832 €, the solution for the standardization of the battery system design does not change, regardless of en-route charging devices charging power. This is due to the fact that the design solution here takes into account a safety margin and operational flexibility in using the same battery system for several bus lines. This allows for flexibility in normal operations and keeps unnecessary technical complexity to a minimum. Therefore, this solution allows for a certain degree of freedom, so that the decrease in the charging power en route does not greatly affect the design already decided upon.

The charging points are located at each of the terminal stations as well as at terminal stops. Due to the high cost of fast charging devices, only one charger is located en route and is used by 3 bus lines, 502, 503 and 517. This charging station is also the terminal stop of bus line 509. When the price of the fast chargers is equal to 45832 €, the one additional charger is located at the bus stop that lines 506, 506e, 507, 510, 511 and 516 share on their outbound route. This result follows, as bus lines 507 and 511 have a high energy consumption and furthermore, energy consumption is higher on these outbound trips, due to the increased angle of incline on the road.

II. **Charging Power lower than 400kW at terminal stations and in bus stops:**

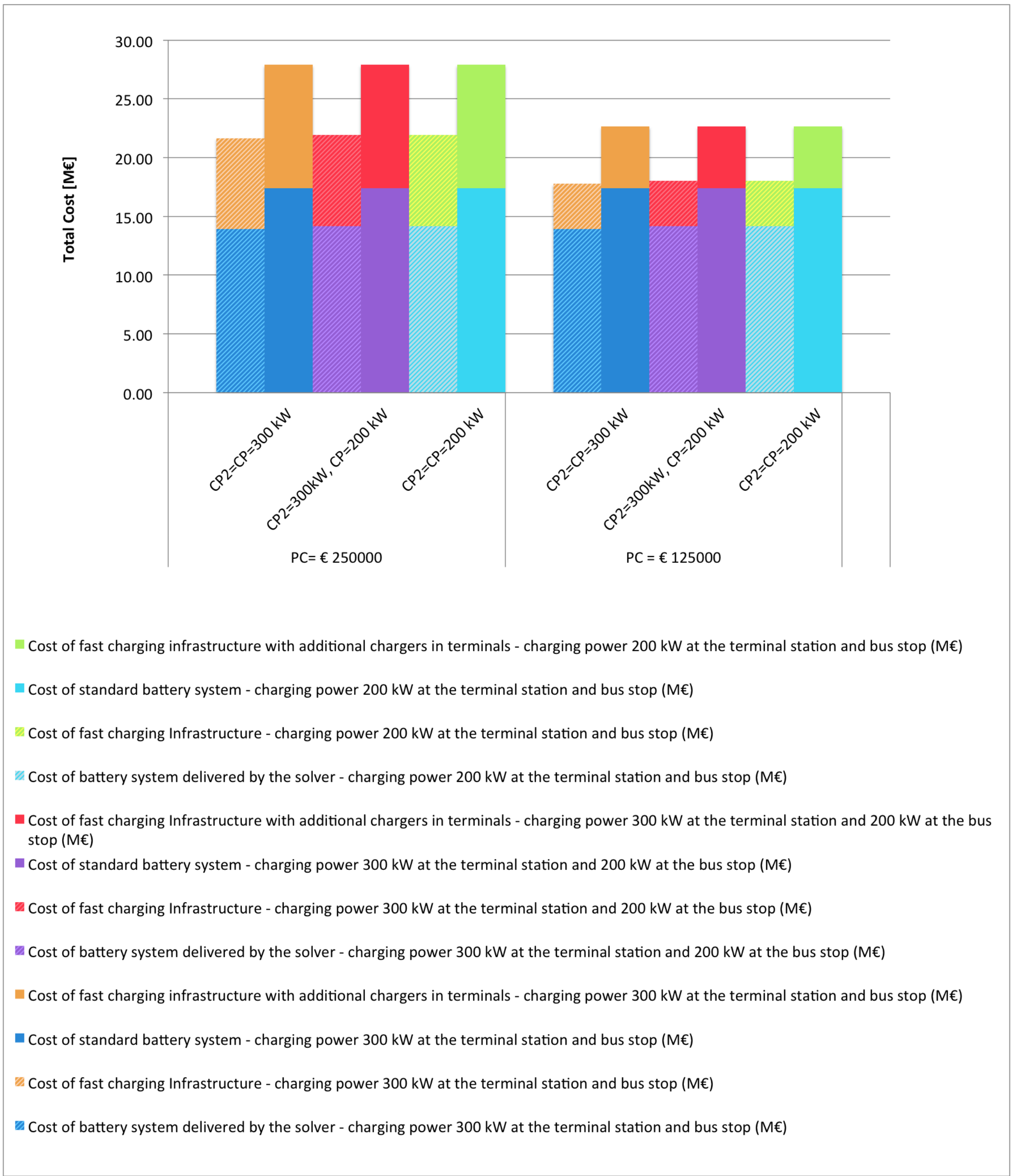


Figure 3.8 – Electrification costs with charging power lower than 400 kW at the terminal station and in bus stops

In this case, the solution given by the solver is the same as in case A above, where the cost of the fast charging infrastructure is between 250000 € and 125000 € and the charging power at bus stops is 300 kW or 200 kW. Specifically, the solver's solution when the charging power both at the terminal station and en route is equal to 300 kW, is the same as in the previous case A when charging power at the terminal station is equal to 400 kW and en route is equal to 300 kW. In the case where charging power at the terminal station is equal to 300 kW or 200 kW and en route is equal to 200 kW, the results are also the same as in the previous case A, where charging power at the terminal station is equal to 400 kW and en route is equal to 200 kW. These results are due to the fact that the energy consumed during the outbound or inbound trip is not too high and therefore it's possible to charge up to 85% of the battery capacity with 300 kW and 200 kW charging power over the course of the break time between trips at the terminal station. Thus, it's not surprising that the solution from the solver is the same as in the previous case A. Consequently, the conclusion for this case is the same as that which was presented in the above case A with a total investment cost of 28.71 million € and battery design (see Table 3.2).

As was explained in reference case A, the battery design is consistent with the grouping based on average speed, but is not correlated with the clustering based on angle of incline.

3.3.2 OPTION B: bus weight 16 ton

I. **Charging Power of 400kW at terminal station:**

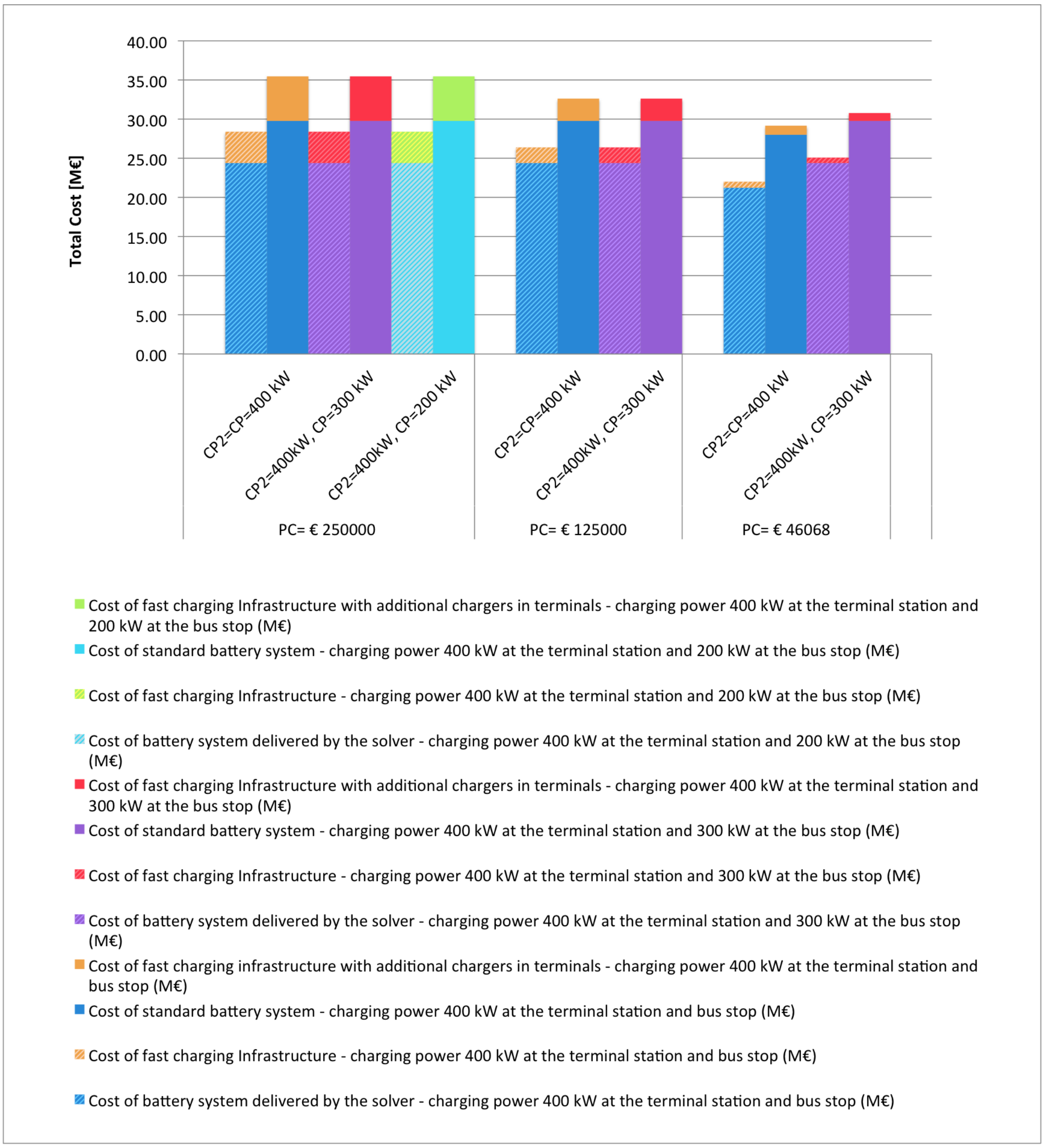


Figure 3.9 – Electrification costs with charging power of 400 kW at the terminal station

The solution delivered by the solver doesn't change when the cost of the fast charging devices is higher than 46068 €. Consequently, the standardization of the battery system design does not change in this instance. This result is consistent, since the number of charging stations selected by the optimization model seeks to use the minimum number of stations to guarantee normal bus operations on a round trip. Almost all of the fast charging points are located at terminal stations on the west side of the city, with only three fast chargers placed at one single terminal station on the eastern side (see Fig. 3.5). There are no charges en route, due to the charging constraints on each round trip and the high cost of fast charging devices.

When the cost of the charging devices is 46068 € and the charging power at the terminal station and bus stop is 400 kW, the optimization model adds 2 chargers along the route. These charging points are located at the bus stop shared by bus lines 506, 506e, 507, 510, 511 and 516 on their outbound route. Specifically, one of these stops is the same as in case A, and the other is the last stop before the route hits an uphill slope on the way to the eastern terminal. Therefore, this result is consistent, since bus lines 507 and 511 have a high energy consumption and, when traveling towards the eastern terminal, the energy consumption of buses is higher, due to the road's greater angle of incline.

II. **Charging Power lower than 400kW at terminal stations and in bus stops:**

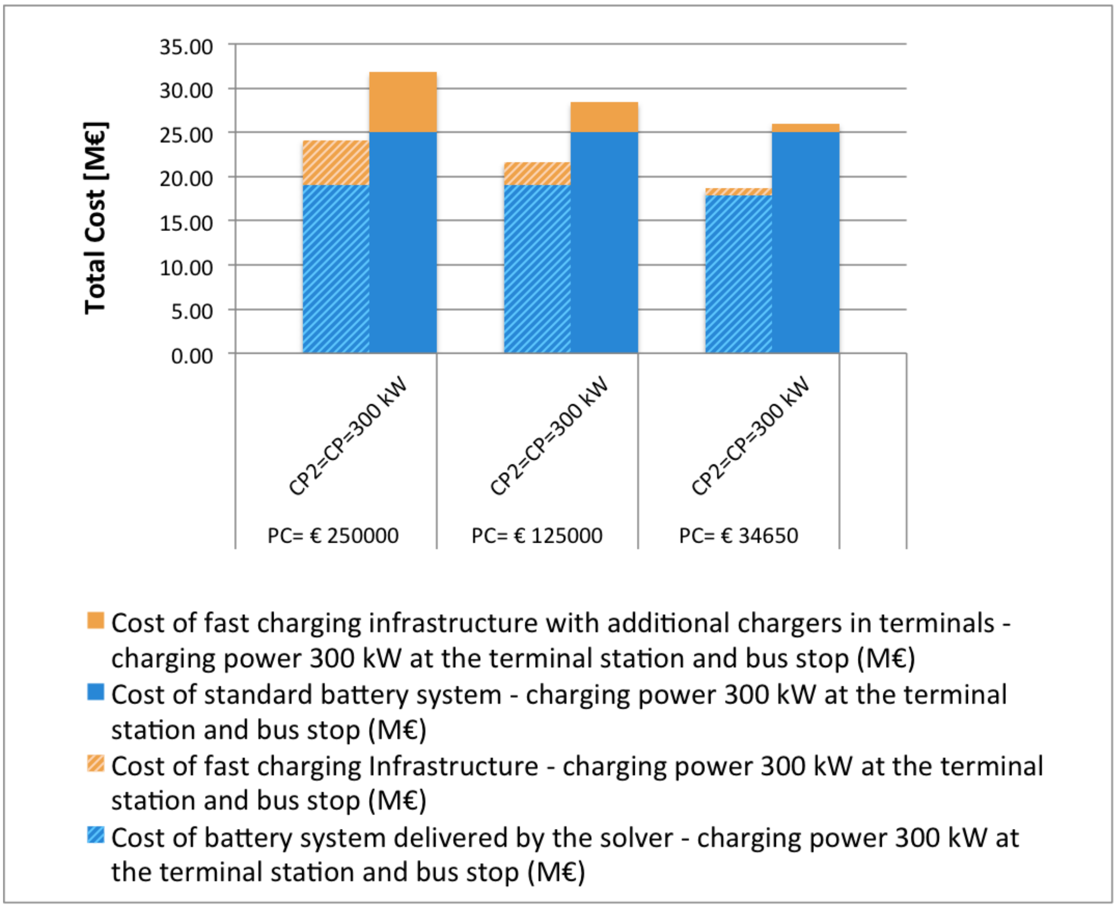


Figure 3.10 – Electrification costs with charging power lower than 400 kW at the terminal station and in bus stops

In this case, due to the charging process taking place after every round trip, it's not feasible to use a charging power of 200 kW at the terminal station. In other words, it's not possible for every bus line to charge its battery up to 85% capacity in just 20 minutes .Therefore in this scenario, only a charging power of 300kW at the terminal station is considered.

The solver gives a different solution than in case B above, because it adds 4 fast chargers along the route. Then, the battery capacity in some bus lines decreases, in turn also decreasing battery cost. These results occur because the charging process is carried out every roundtrip and the charging power in the terminal is 300 kW. So as to not increase battery system costs unnecessarily, it is more convenient to place more chargers mid-route at stops common to the lines with higher energy consumption. Thus, in this scenario, the battery system design changes and its new cost is 25.03 million €. The cost of the fast charging infrastructure is 6.78 million €, making the initial investment in the battery system and fast charging infrastructure 31.81 million €, lower than that in case B above. However, the solution in this case accelerates the aging process of the batteries, making this solution more expensive in the long term than that in case B.

3.4 Scenario 2: Normal weight and Auxiliary Consumption 9 kW

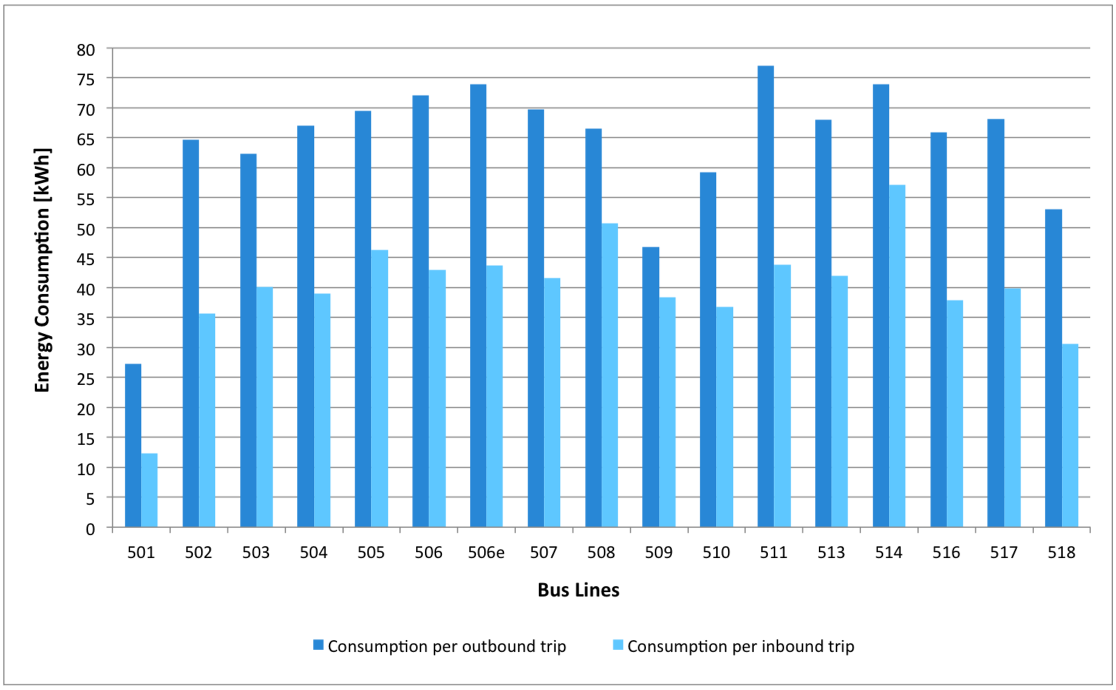


Figure 3.11 – Energy consumption per outbound trip and per inbound trip for each bus line in scenario 2

As illustrated by Figure , the energy consumption is too high, it's not feasible to use a charging power of 200 kW at the terminal station. In 20 minutes, it's not possible to charge up to as high of 85% of the battery capacity for some bus lines. Thus, in this scenario some buses would have to carry a cumulative deficit of energy throughout the day. It might be possible to add more chargers en route to compensate for this deficit, but that would accelerate the aging process even more.

3.4.1 OPTION A: bus weight 16 ton

I. **Charging Power of 400kW at terminal station:**

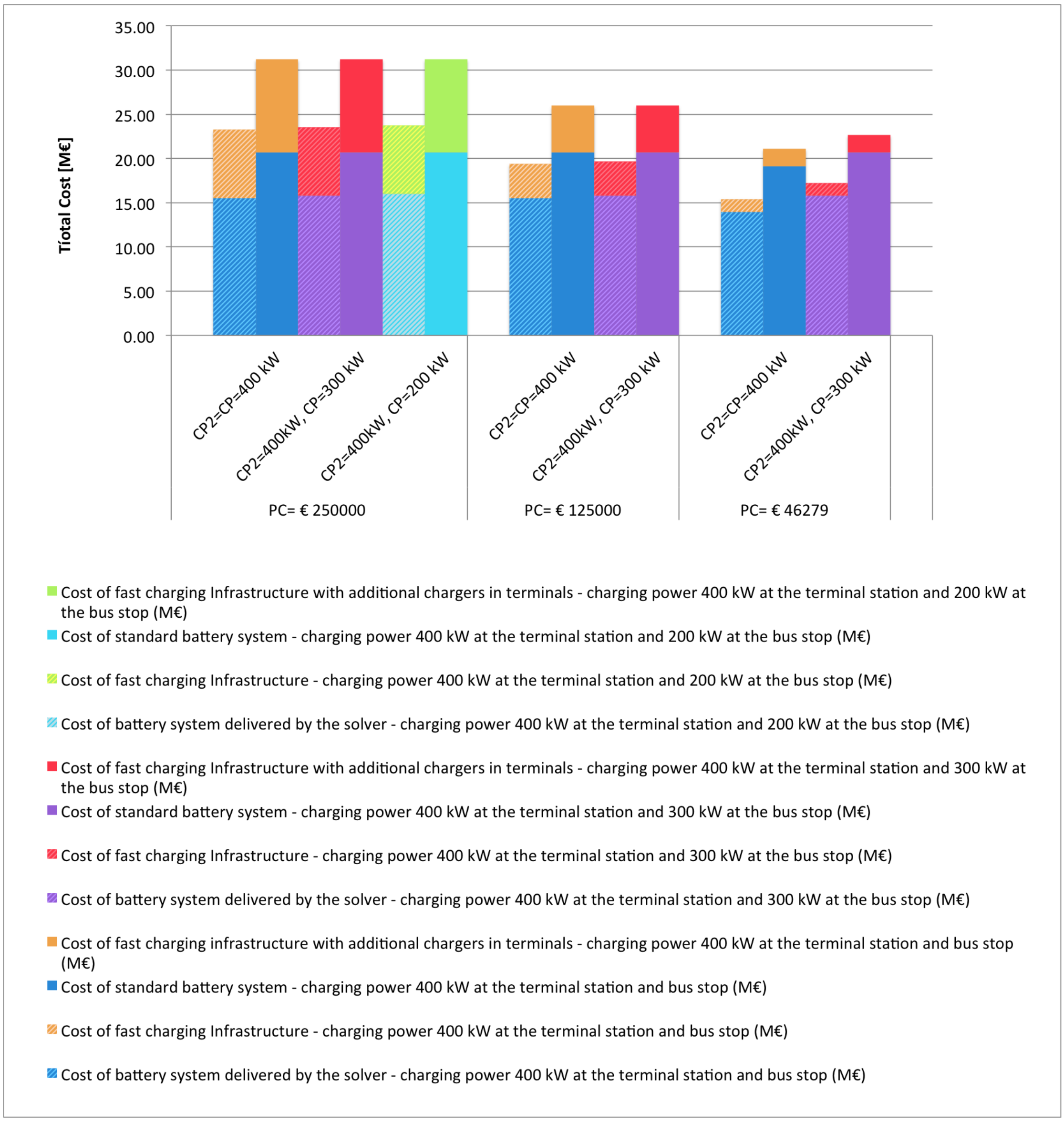


Figure 3.12 – Electrification costs with charging power of 400 kW at the terminal station

In this case, it is expected that with the increase in energy consumption, a larger battery system is necessary. Thus, a new battery system design is required in order to maintain stable bus operations. The solution provided by the solver puts forth a situation where as the battery system size increases, therefore increasing costs as well, the charging power of the fast chargers en route decreases.

The solution for the standardization of the battery system design does not change, regardless of the charging power of the charging devices en route, when the price of the fast charging infrastructure is greater than 46279 €. Operational flexibility, a safety margin and technical simplicity are key considerations in selecting a standardized battery system for several bus lines. This solution allows a certain degree of freedom, because the the required increase in battery system capacity as the power of the en route chargers decreases is not so significant as to call for a different design.

According to the solver, 1 single charger is placed along the route at a stop which is both line 509's terminal stop and also is shared by lines 502, 503 and 517. The remaining chargers are distributed to the other terminal stations. When the price of the fast chargers is equal to 46279 €, only one other charger is added en route. Said charger is located at a stop common to lines 506, 506e, 507, 510, 511 and 516, as in case A 3.3.1-I. This result follows, as the increase in energy consumption causes the model to add another charger en route, at a higher price as compared to the case when the auxiliary consumption is 6 kW. The higher the energy consumption, the more additional fast charging points that are needed on the route. Thus, the price of the fast charging device does not have to decrease as much as in case A 3.3.1-I.

II. **Charging Power lower than 400kW at terminal stations and in bus stops:**

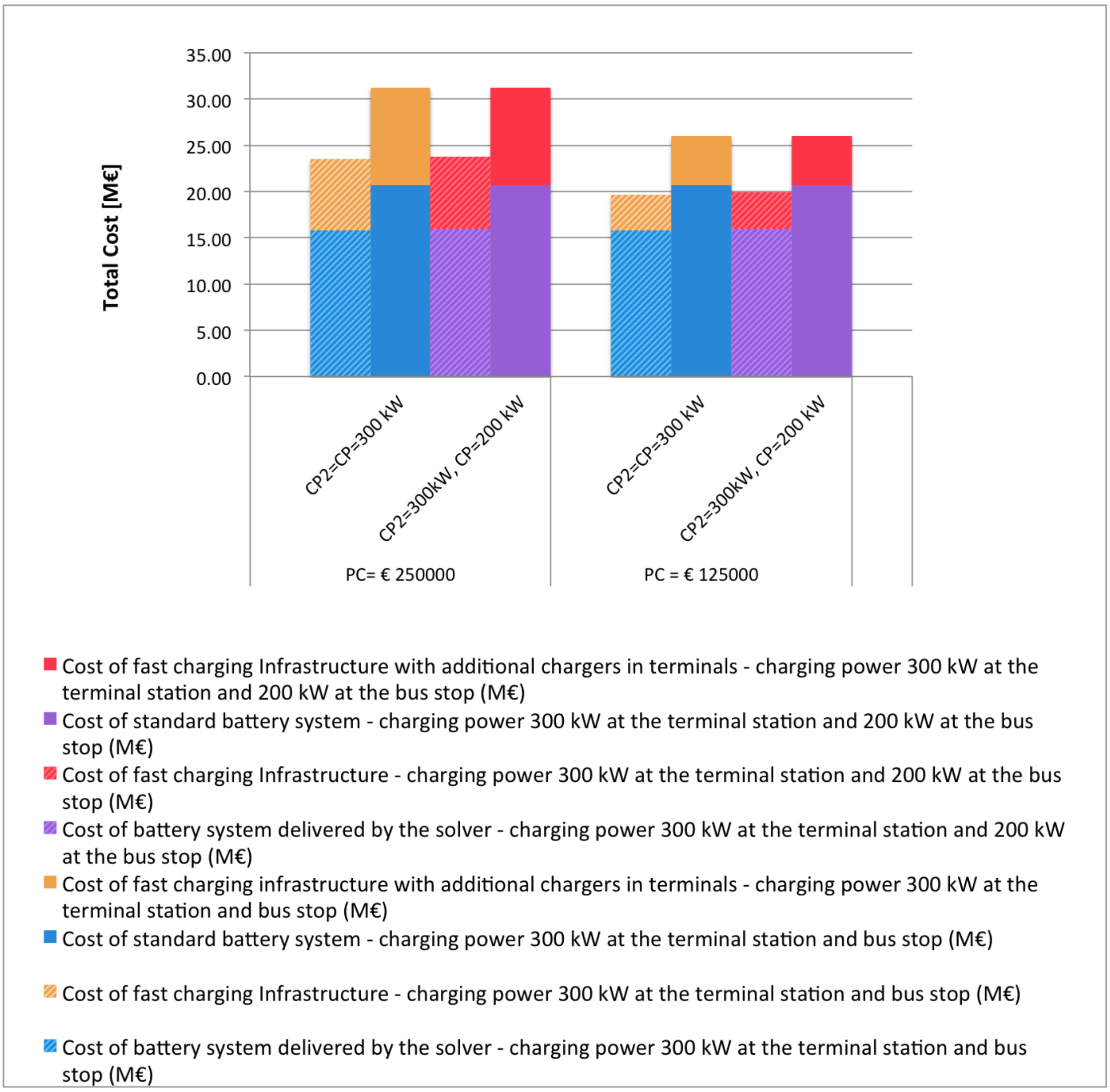


Figure 3.13 – Electrification costs with charging power lower than 400 kW at the terminal station and in bus stops

When the cost of fast charging infrastructure is between 250000 € and 125000 €, and the charging power at bus stop is 300 kW or 200 kW, the solution given by the solver is the same as in case A above. More specifically, when the charging power at both the terminal station and en route is equal to 300 kW, the solution remains the same as in the previous case A when charging power at the terminal station is equal to 400 kW but en route is 300 kW. When terminal station charging power is 300 kW and en route 200 kW, the solution is the same as in case A where terminal station charging power is 400 kW and en route is 200 kW. These results are due to the fact that while the energy consumed over both the inbound and outbound trip is high, it's still possible to charge the battery to up to 85% of its capacity when the charging power is equal to or greater than 300kW over the course of a break between trips at the terminal station. Consequently, the conclusion for this case is the same as that presented for the previous case with a total investment cost of 31.22 million €.

3.4.2 OPTION B: bus weight 16 ton

I. **Charging Power of 400kW at terminal station:**

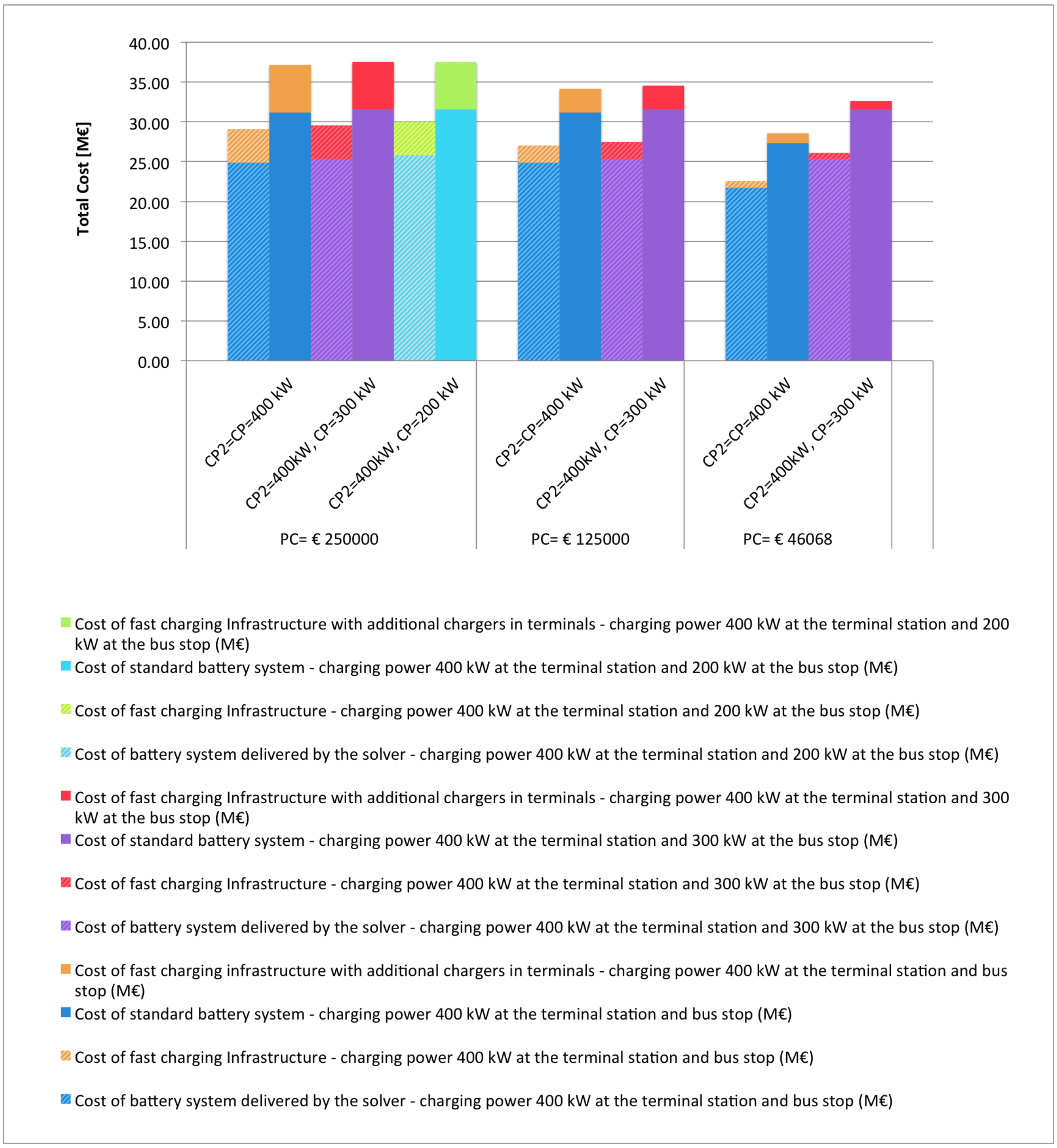


Figure 3.14 – Electrification costs with charging power of 400 kW at the terminal station

In this case, the solution delivered by the solver determines that an increase in the size of the battery system and therefore in its costs, as the charging power of the fast chargers en route decreases. Thus, the required battery capacity is higher than reference case B, due to the increase in energy consumption.

The solution for the standardization of the battery system design changes when the charging power of the charging devices en route is lower than 400 kW, and the price of the fast charging infrastructure is lower than 46068 €. This is because in this scenario, the energy demands are very high, and thus the design solution must account for this increase. Therefore, a design solution with a standardized battery system is needed when working with high charging power. There is simply less freedom to maneuver in the solution when the chargers en route have a charging power of less than 400 kW. The number of fast charging devices required is 24 when the charger cost is 250000 €. The vast majority of these devices will be located at terminal stations on the west side of the city, with only three placed at a single terminal station on the eastern side of the city, and one along the route. Specifically, in this case, the optimization model always adds one charger en route, due to the increase in energy consumption in comparison to reference case B. This increase in the auxiliary consumption, together with the constraint of needing to carry out charging each round trip, necessitates a battery system with greater capacity. Therefore, in order to ensure sufficient energy supply during a round trip, an increase in the cost of the battery system is necessary. However, the optimization model finds that the optimal solution is to add a charger en route and thus minimize investment costs while also keeping the bus operating normally. The charger added en route is located at a shared bus stop of lines 503, 505, 508, 514 and 517 on their outbound route. This result is consistent, since bus lines 508 and 514 have a high energy consumption on round trips. Further, energy consumption is higher on outbound trips due to the increased inclination angle of the road when the bus is closer to the east terminal station. The optimization model calls for 2 more chargers when the cost of fast charging devices is 46068 €. That price is the same as in the previous case B 3.3.2-I, when 2 chargers were needed en route. However, only one of the chargers in this case would be placed at the same bus stop as in the solution to case B 3.3.2-I.

II. **Charging Power lower than 400kW at terminal stations and in bus stops:**

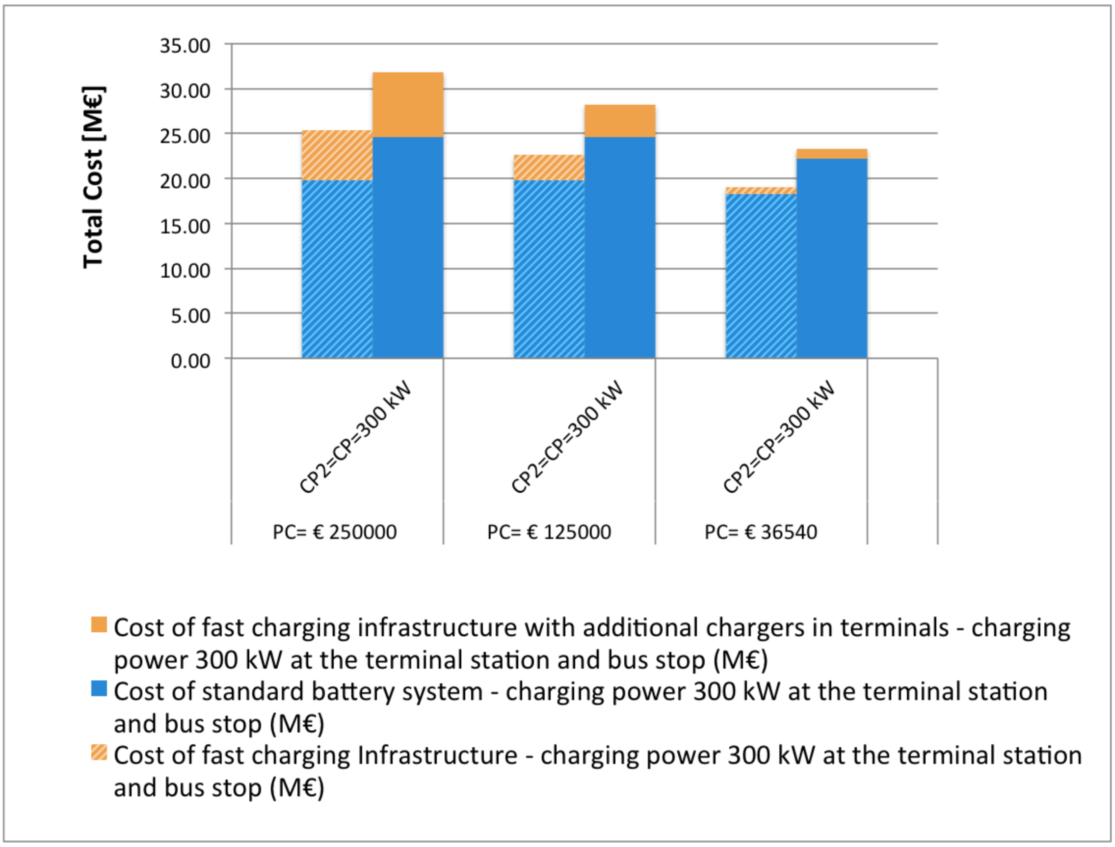


Figure 3.15 – Electrification costs with charging power lower than 400 kW at the terminal station and in bus stops

In this case, due to high energy consumption it is not convenient to use 200 kW to charge en route. This would leave too many fast chargers along the route and excessively increase the number of charge en route per bus line. Therefore, the aging process of the batteries is accelerated more than is ideal, for it would necessitate a replacement of the battery system in less than 2 years. The solution in the long term, therefore, would be very expensive and inefficient. As a result, in this scenario only the 300 kW charging power at both the terminal station and bus stop is considered. The solution given by the solver here is different than case B above, with 5 fast chargers added en route. In this solution the battery capacity in some bus lines decreases and therefore the battery cost decreases as wells. These results arise from the charging power at the terminal being

300 kW, along with a 100 kWh increase in energy consumption for almost every bus line as compared with the B cases (reference case B and case B 3.3.2) . Therefore, it is not possible to replenish the energy consumed during a round trip in solely 20 minutes, unlike as in case B (with a charging power of 400 kW at the terminal station). As a result, the optimization model does not increase the capacity of the battery system, since it would not be reasonable and would involve an unnecessary increase in the cost of the battery.

In this scenario, the battery system design changes and its cost hits 24.61 million € and the fast charger comes to 7.25 million €, bringing the initial investment in these areas to 31.86 million €, lower than the initial investment cost in case B above. However, the solution in this case accelerates the aging process of the batteries too much, making this solution more expensive than case B in the long term.

3.5 Scenario 3: Maximum weight and Auxiliary Consumption 6 kW

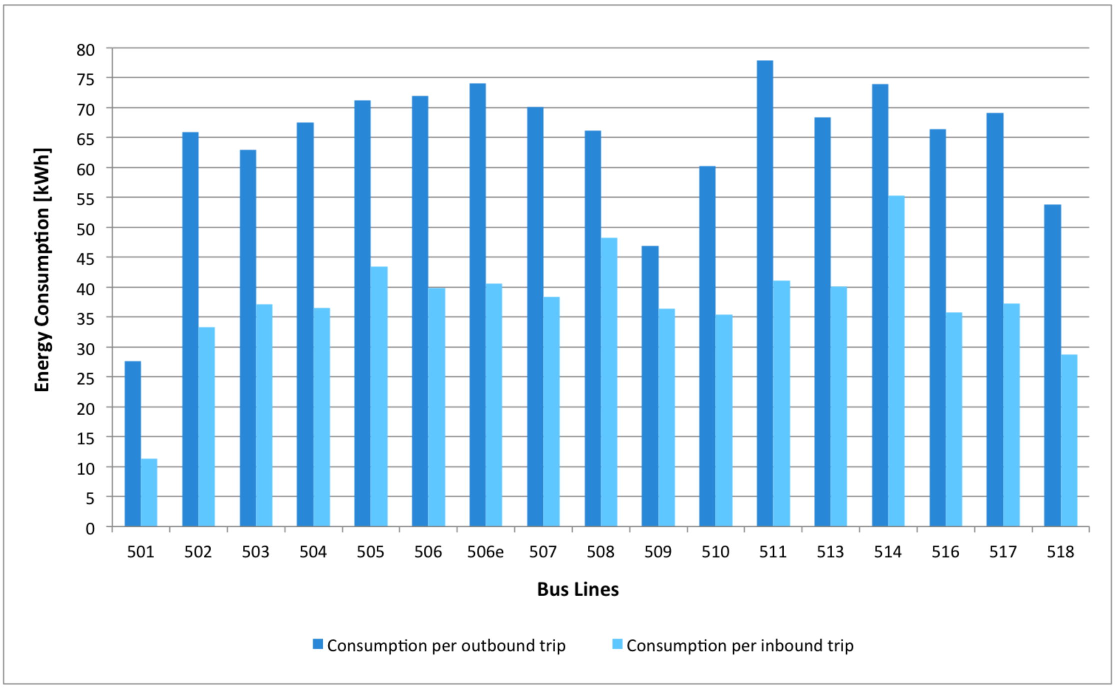


Figure 3.16 – Energy consumption per outbound trip and per inbound trip for each bus line in scenario 3

3.5.1 OPTION A: bus weight 18 ton

I. **Charging Power of 400kW at terminal station:**

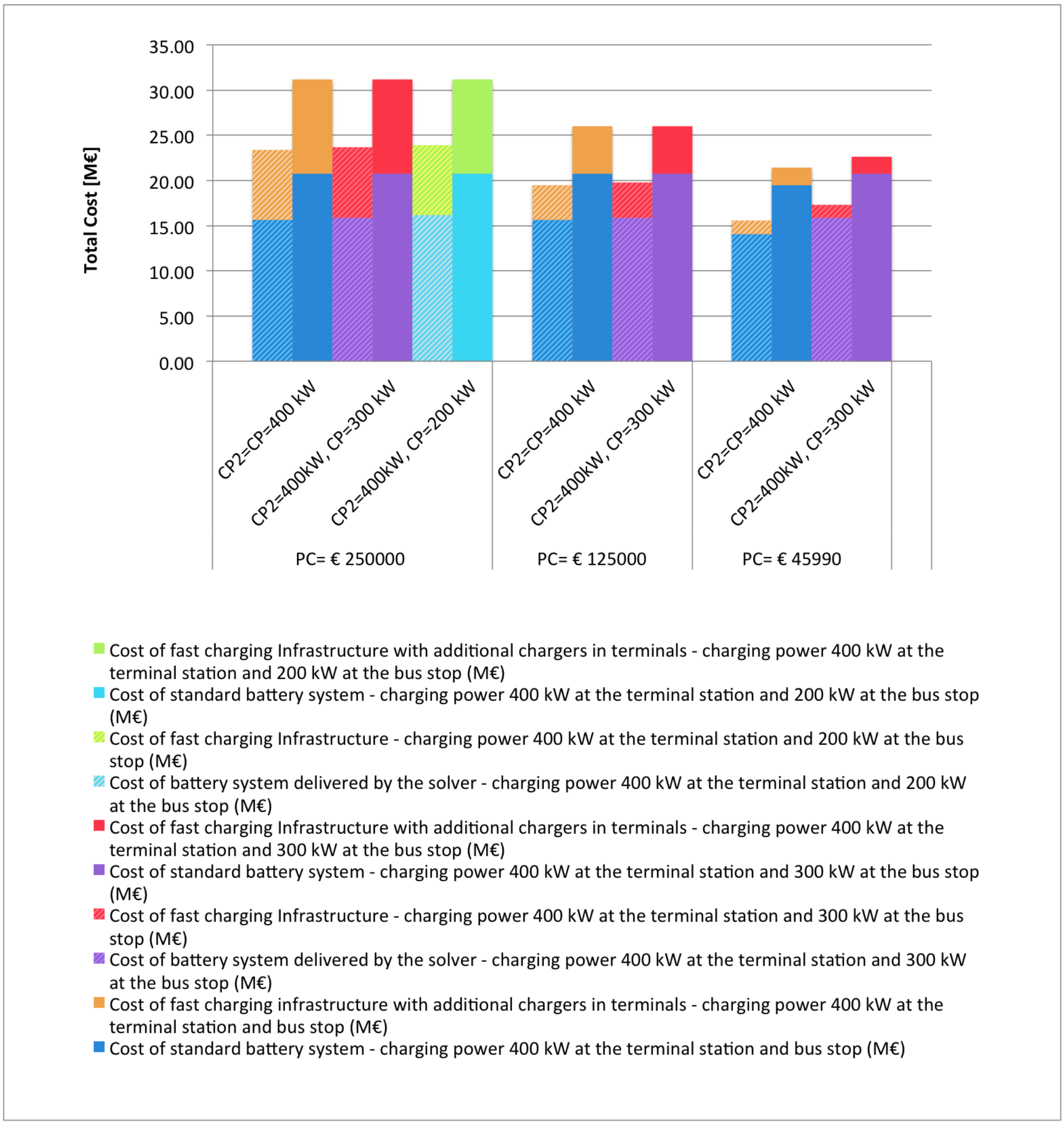


Figure 3.17 – Electrification costs with charging power of 400 kW at the terminal station

Again, the solver's finds that as the charging power along the route decreases, the required battery system capacity goes up and therefore so do costs. In this scenario, the bus weight is 18 tons, so the energy consumption during the ascending inbound trip is greater than in a case with normal weight and auxiliary consumption of 9 kW. However, round trip consumption is lower tan in case A 3.4.1-I., because in the downhill trip, the bus with weight a weight of 18 tons consumes less energy (regenerates more energy), than when the bus weighs 16 ton and carries an auxiliary consumption 9 kW. Therefore, the same design battery system design as in case A is used when the price of the fast charging infrastructure is higher than 45990 €, regardless of the en route charging devices' power. The same battery design as in case A 3.3.1-I. is not used, since it oversizes the capacity (kWh) of some bus lines and therefore increases the total costs unnecessarily.

The fast charging devices are located at each of the terminal stations as well as at terminal stops. Only one charger is located en route and is used by 3 bus lines: 502, 503 and 517. At the same time, this charging station is the terminal stop of bus line 509. Only one other charger is added en route when the price of the fast chargers is equal to 45990 €. Said charger is located at one stop common to lines 506, 506e, 507, 510, 511 and 516, as in the previous cases A (Case A 3.3.1-I and Case A 3.4.1-I). This result follows, since although the energy consumption in the uphill trip is greater than in the previous case A 3.4.1-I, the difference in consumption is not greater than 5 kWh. So, it is logical that the position of the fast charger along the route does not change. It also follows that the price given by the model for the additional charger is lower here tan in case A 3.4.1-I , since total round trip consumption with an 18 tons bus with auxiliary consumption of 6kW is lower than in the case of a bus with normal weight and auxiliary consumption of 9kW.

II. **Charging Power lower than 400kW at terminal stations and in bus stops:**

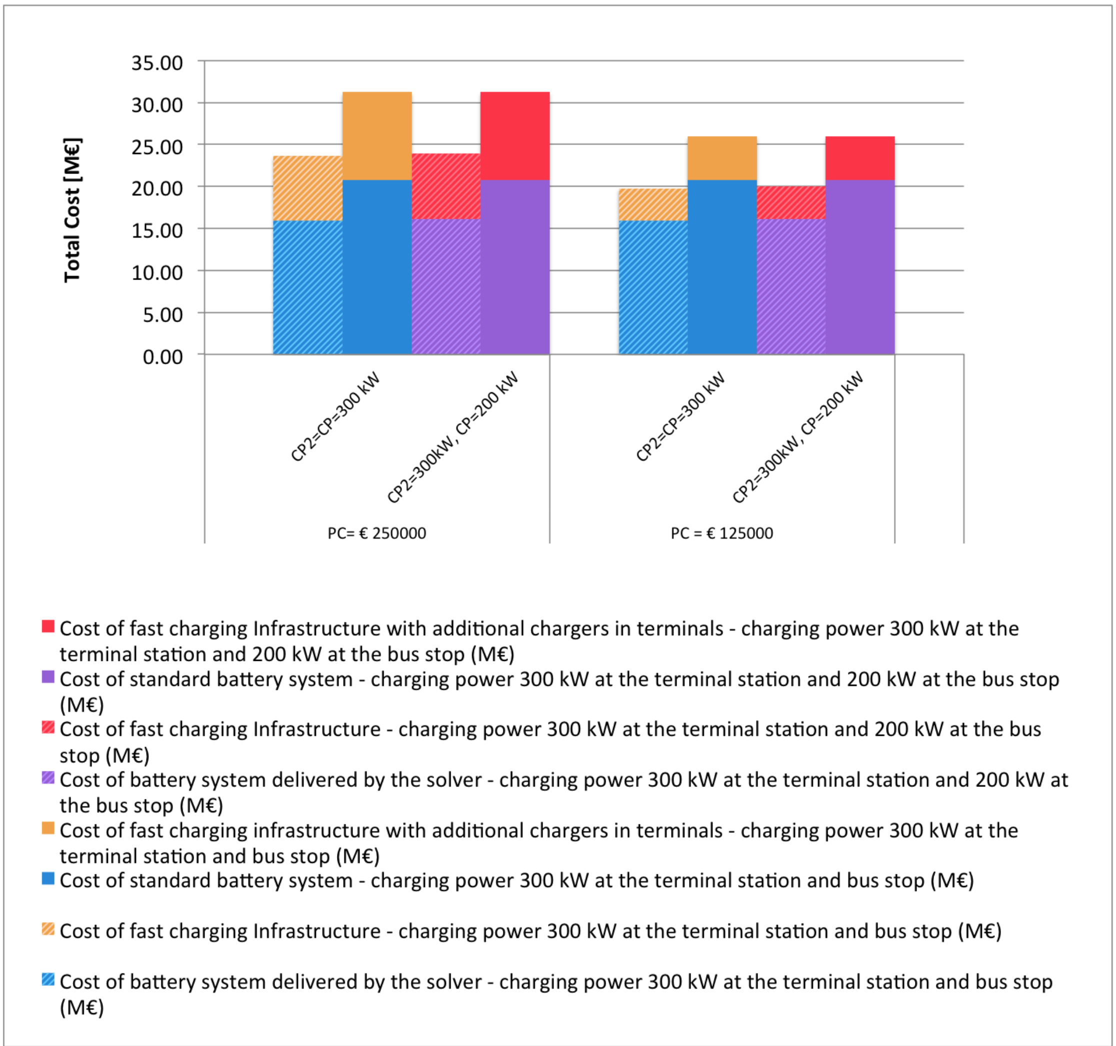


Figure 3.18 – Electrification costs with charging power lower than 400 kW at the terminal station and in bus stops

In this case, when the cost of the fast charging infrastructure is between 250000 € and 125000 €, and the charging power at the bus stop is either 300 kW or 200 kW, the solution found by the solver is the same as in case A above. When the charging power both at the terminal station and en route is equal to 300 kW, the solution is the same as in the previous case A when the charging power at the terminal station was equal to 400 kW but en route was equal to 300 kW. When charging power at the terminal station is 300 kW but en route is 200 kW, the solution is the same as in the previous case A when charging power at the terminal station was 400 kW and en route was 200 kW. These results are due to the fact that the energy consumed on both the inbound and outbound trip is high. Therefore, during the break time between trips at the terminal station, the battery can be charged to up to 85% of its capacity with charging power equal to or greater than 300 kW. Consequently, the conclusion for this case is the same as that which was presented in the previous case, with the same total investment cost 20.72 million €.

3.5.2 OPTION B: bus weight 18 ton

I. **Charging Power of 400kW at terminal station:**

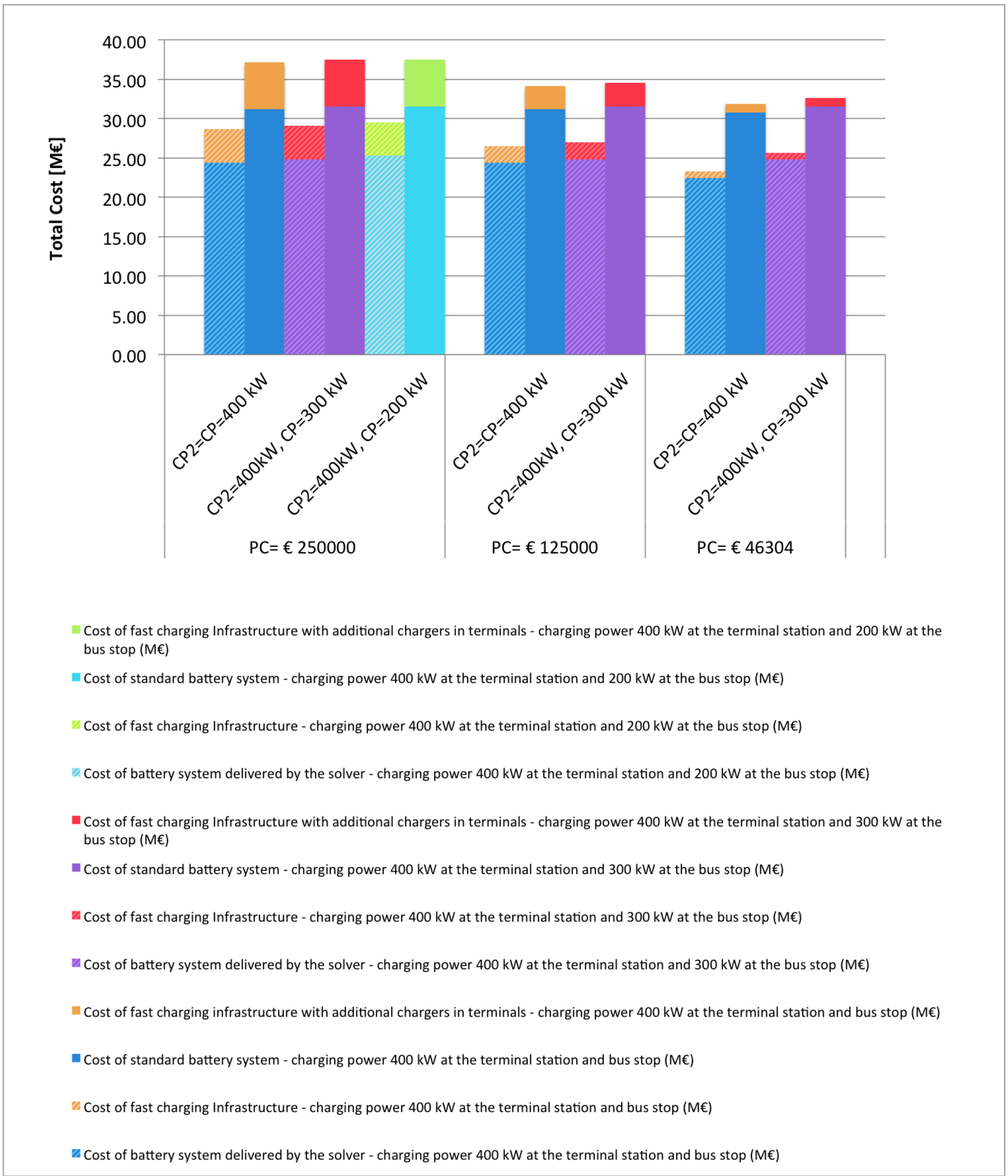


Figure 3.19 – Electrification costs with charging power of 400 kW at the terminal station

In this scenario, the bus weight is 18 tons, so the energy consumption during uphill route (outbound trip) is greater than in cases with normal weight and auxiliary consumption of 9 kW. However, the consumption for a round trip is lower compared with case B 3.4.2-I, because in the downhill trip, the bus with a weight of 18 tons consumes less energy (regenerates more energy) than when the bus weighs 16 tons and the auxiliary consumption is 9 kW. The solver suggests a battery system here with less capacity than in the previous case B 3.4.2-I. However, the size of the battery system also needs to be bigger in this case, leading to an increase in cost. This increase is due to lower charging power in the route-side fast chargers in this arrangement. Specifically, when the charging power at both the terminal station and along the route is 400 kW, the battery cost is 24.4 million €, and when the charging power at the terminal station is 400 kW but en route is 200 kW, the battery costs increase to 25.31 million €.

The solution for the standardization of the battery system design changes in a similar fashion as in the above case B 3.4.2-I, where the mid-route charging devices have a charging power of less than 400 kW, and the price of the fast charging infrastructure is lower than 46304 €. In these conditions, the high energy consumption during the uphill routes constrains the problem in terms of costs. In other words, needing the SOC to have a safety margin of more than 25% and also to minimize costs, the model is sensitive to the decrease in charging power of the route-side fast charger. Thus, the design of the battery system changes when the charging power en route is less than 400 kW, to ensure sufficient energy supply during a round trip.

Therefore, in order to minimize total investment costs, the design of the battery system must work with charging devices that charge at a power of 400 kW at both the terminal stations and bus stops, as in case 3.4.2-I. On the other hand, the battery system design of the cases when the charging power of the chargers en route is lower than 400 kW is not used, since it increases the costs of the battery system and therefore total cost. The design used in case B 3.3.2-Iis not suitable either, since it does not provide the necessary capacity (kWh) for some bus lines and, therefore, is not a feasible solution.

The number of fast charging devices required is the same as in the previous case B 2.1

(24 chargers), with said devices located at the same terminal stations and bus stops. This result is due to the high energy consumption in this scenario. However, the price of the fast charging devices not decrease too much here, as one additional charging station is needed along the route, as in the previous cases B (Case B 3.3.2-Iand Case 3.4.2-I). In those cases, the price drops to 46068 € and adds 2 additional chargers. Here, however, the optimization model adds one additional charger at a higher price than the previous cases B, since the bus of 18 tons consumes more energy when going uphill, and therefore needs to add the additional charger at a higher price than in the other cases.

Another difference in this scenario is that the location of the additional charger is different from that of the others, which is logical since by setting up only one additional charging point, there are more restrictions on the model than in the previous cases. When the price of the bus chargers is equal to 46068 €, 2 additional chargers are needed as in the two B scenarios, but in different locations from those placed previously. One of the chargers is located at the same bus stop as in the case where the price is 46304 €, and the other charger is located on the inbound return trip.

II. **Charging Power lower than 400kW at terminal stations and in bus stops:**

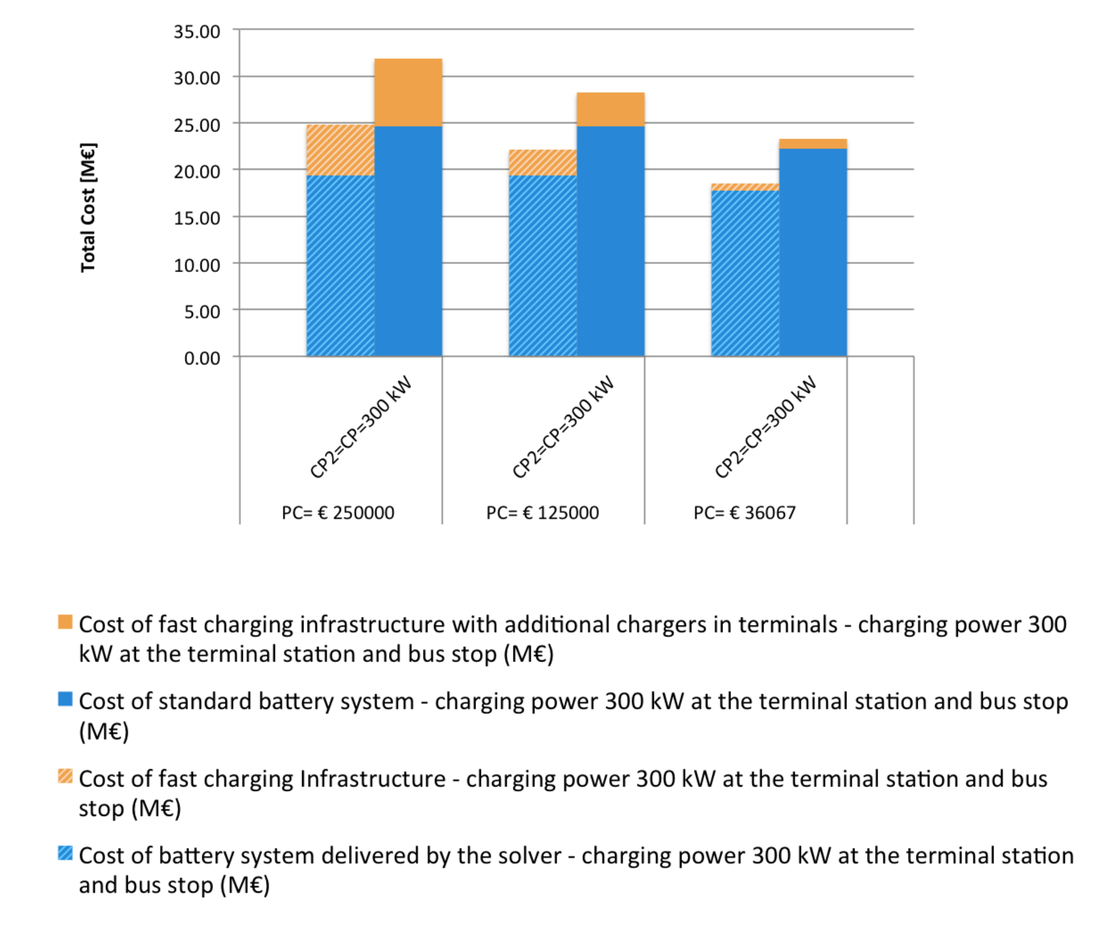


Figure 3.20 – Electrification costs with charging power lower than 400 kW at the terminal station and in bus stops

As mentioned previously, when the bus weight is 18 tons and the auxiliary consumption is 6 kW, the energy consumption on a round trip is lower compared to when the bus weighed 16 tons with an auxiliary consumption of 9 kW. However, the energy consumed in this scenario is also high, so it is not convenient to use 200 kW to charge en route. This would necessitate placing an excess of chargers en route for each bus line, excessively accelerating the batteries? aging process. That would lead to the need to replace the battery system in less than 2 years. Thus, this solution in the long term would be very expensive and inefficient. Therefore, in this scenario only the 300 kW charging power at both the terminal station and bus stop is considered.

The battery capacity for some bus lines decreases, bringing the cost of the battery cost down along with it. These results arise due to the charging power in the terminal being 300 kW, with an increase in energy consumption of more than 100 kWh in almost all bus lines compared to reference cases B and case B 1. Therefore, it is not possible to replenish the energy consumed during a round trip in only 20 minutes, unlike in the previous case B (with a charging power of 400 kW at the terminal station). As a result, the optimization model does not increase the capacity of the battery system, since it would not be reasonable and would pose an unnecessary increase to the cost of the battery. The design of the battery system used in this scenario is the same as that in case B 3.4.2-II, since it minimizes the total investment costs.

The solver adds 5 fast chargers en route, as in case B 3.4.2-II, but in this solution the location of 3 of them changes. Because the energy consumption during the uphill trip (inbound trip) is higher than in the case where the bus weighed 16 tons with an auxiliary of consumption 9 kW, the fast chargers are located at the previous bus stop.

The battery cost is 24.61 million € and the fast charger 7.25 million €, bringing the initial investment with these two elements to 31.86 million €, which is lower than the initial investment cost in case B above. However, the solution in this case excessively accelerates the aging process of the batteries. This makes this solution more expensive in the long term than the previous case B.

3.6 Scenario 4: Maximum weight and Auxiliary Consumption 9 kW

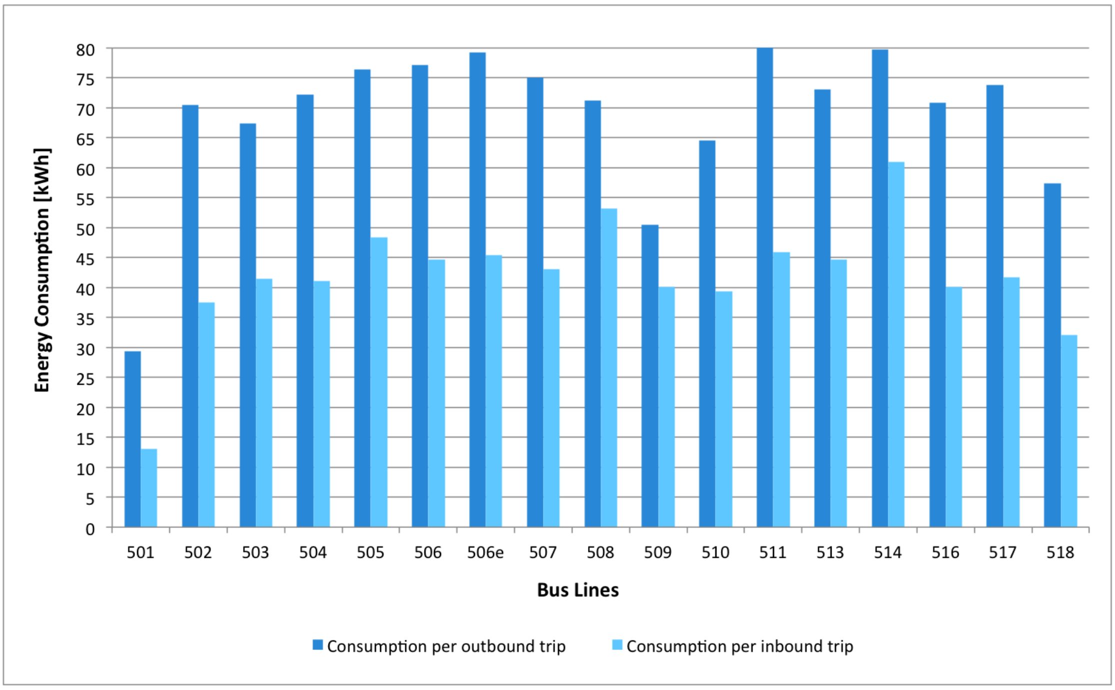


Figure 3.21 – Energy consumption per outbound trip and per inbound trip for each bus line in scenario 4

3.6.1 OPTION A: bus weight 18 ton

I. **Charging Power of 400kW at terminal station:**

Figure 3.22 – Electrification costs with charging power of 400 kW at the terminal station

This is the worst-case scenario, where the bus is at its maximum weight with the maximum auxiliary consumption. In this case, a larger battery system is necessary to maintain regular bus operations under these demanding conditions. The solver determines that an increase in the size of the battery system is necessary, which in turn raises costs, as the charging power of the fast chargers en route decreases. Specifically, when the charging power at both the terminal station and en route is 400 kW, the battery cost is 16.85 million €. When the charging power at the terminal station is 400 kW but en route is 200 kW, the battery cost increases to 17.85 million €. The standard design of the battery system changes when the charging power route-side is less than 400 kW. This is due to more extreme conditions, the higher energy consumption on these routes, which limits the problem in terms of the costs. In other words, to ensure that the SOC carries a safety margin greater than 25%, therein keeping costs low, the model is sensitive to the decrease in the charging power of the fast chargers along the route. Thus, the design of the battery system changes when the charging power en route is lower than 400 kW, to ensure sufficient energy supply during service trips. Therefore, the design for the battery system in this case matches those scenarios where the charging power at both the bus stops and terminal station is 400 kW, because this selection keeps total investment costs to a minimum. However, when the charging power along the route is not 400 kW, a different battery system design is necessary, then the size of the battery and, thus, the total cost would increase unnecessarily. The fast charging infrastructure required in this solution is the same that was obtained in the previous cases A (42 fast charging devices), which are distributed in the bus terminals and terminal bus stop, in proportion of the operating buses. Only another charger is added en route when the price of the fast chargers is equal to 46204 €, said charger is located in different bus stop than previous cases A. However, the charging station is again located at a common bus stop of bus lines: 506, 506e, 507, 510, 511 and 516. In addition, in this case the price at which the model adds an additional charger is lower than when the bus weight is 16ton and auxiliary consumption 9kW.

II. **Charging Power lower than 400kW at terminal stations and in bus stops:**

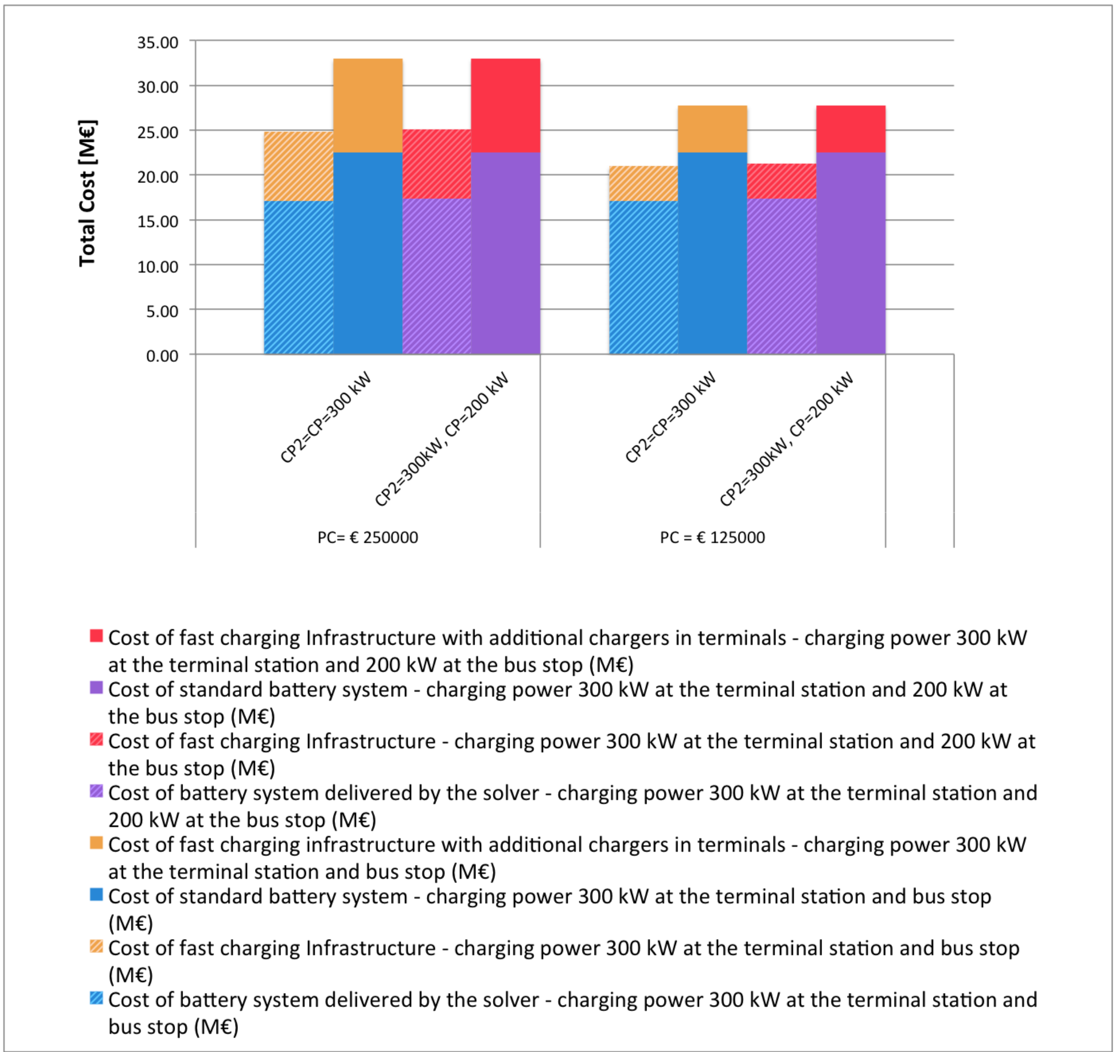


Figure 3.23 – Electrification costs with charging power lower than 400 kW at the terminal station and in bus stops

3.6.2 OPTION B: bus weight 18 ton

I. **Charging Power of 400kW at terminal station:**

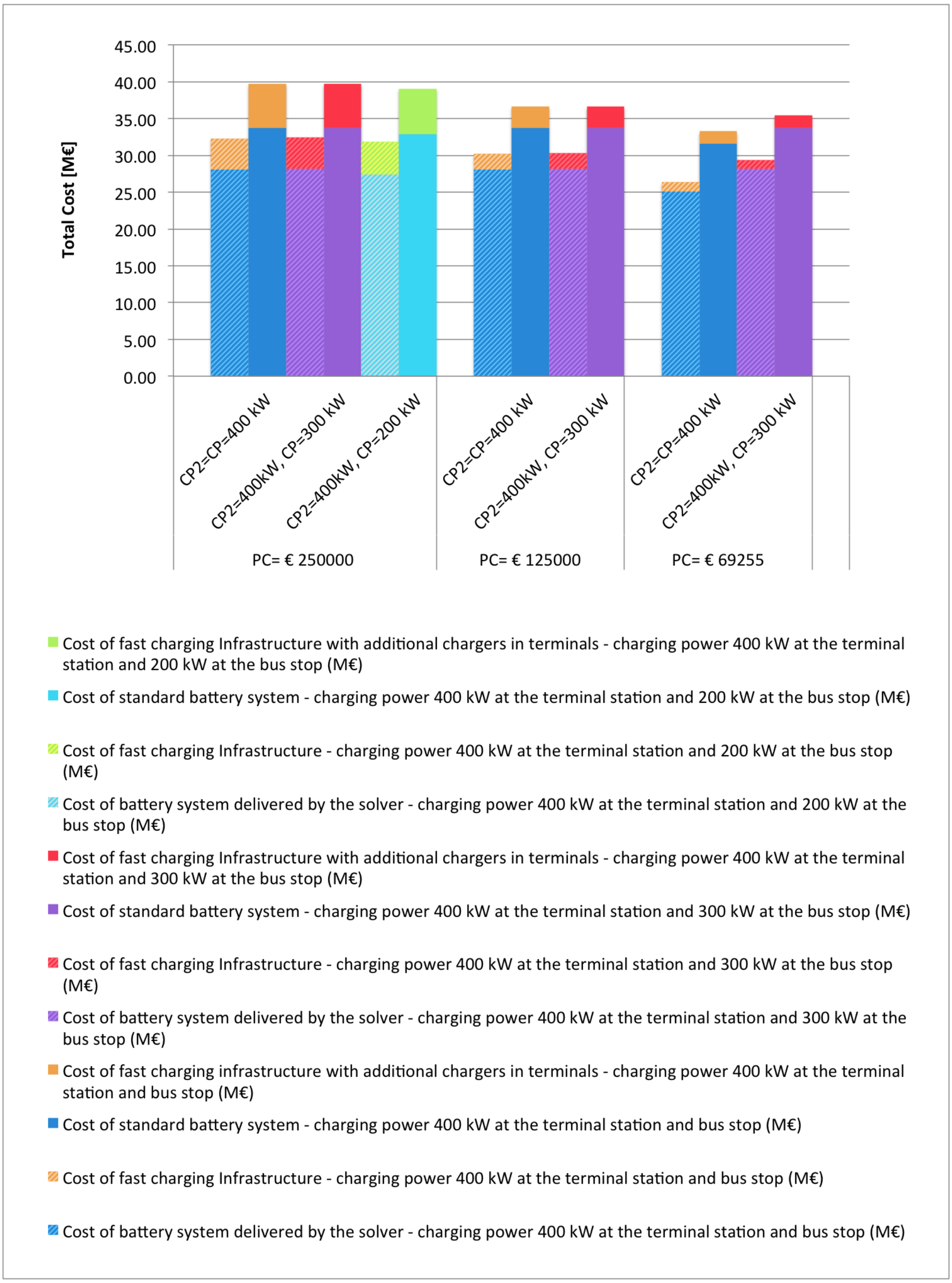


Figure 3.24 – Electrification costs with charging power of 400 kW at the terminal station

This is the worst-case scenario, where the bus is at its maximum weight with the maximum possible auxiliary consumption. Due to these more demanding conditions, a larger battery system is necessary to ensure sufficient energy supply throughout a round trip. The solver suggests that when the fast charger's power goes from 400 kW to 300kW, a small increase in the size of the battery system and therefore in its costs is necessary. Furthermore, in this scenario there is only one charger along the route, which is shared by lines 511 and 514. Thus, change in charging power along the route only affects these two bus lines. The battery cost is 28,05 million € when the charging power at the terminal station and en route is 400 kW and the battery cost increases to 28.16 million € when the charging power at the terminal station is 400 kW but 300 kW en route.

However, when fast charging devices carry a price tag of 250000 € and the charging power at the terminal station is 400 kW and en route 200kW, the battery cost decreases to 27.38 million €, because in this case, the solver adds one additional charger en route. Thus, the battery costs decrease, but the cost of fast charging infrastructure increases in 250000 €. Thus, the total initial investment cost is lower than when the charging power en route is 400 kW or 300 kW. The problem with this solution is that it accelerates the aging process of the battery system too much. Specifically, it is necessary to replace the batteries of bus lines 503 and 507 every 3 years, because the additional charges and the mid-route charging processes here wear them out more quickly. The worst case is with bus line 514, where the battery system must be replaced after 2 years, since during a round trip the bus is charged twice en route. Therefore, the battery design used in the case where the charging power at both the terminal stations and bus stops is 400 kW is suitable here to minimize overall investment costs and keep the batteries from aging too quickly.

The optimization model calls for 23 or 24 fast charging facilities when the charger cost is 250000 €. Out of this total number of chargers, 22 are located at the terminal stations in the same locations as in the previous B cases. The location of the charger en route changes between cases B 3.4.2-I and 3.5.2-I , since the location of the mid-route fast charging device is strongly impacted by the value of the charging power needed. When the conditions are more demanding, the energy consumption is higher, thus restricting your options when it comes to questions of cost or battery charge. The need to minimize costs as well as to provide for a safety margin in the SOC of more than 25%, limits your choices. In this way, the location of fast charging points depends greatly on the amount of injected charging power.

II. **Charging Power lower than 400kW at terminal stations and in bus stops:**

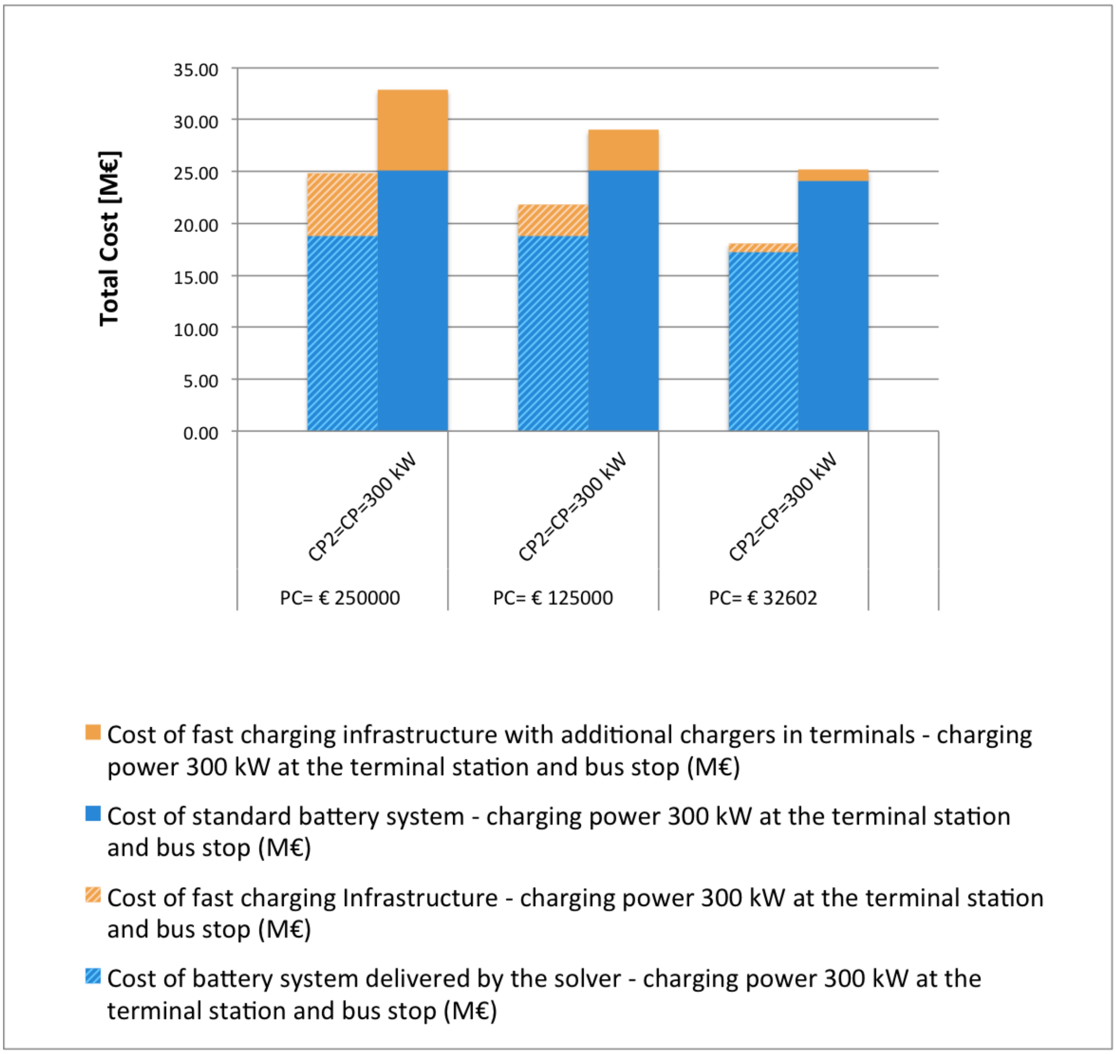


Figure 3.25 – Electrification costs with charging power lower than 400 kW at the terminal station and in bus stops

In this scenario, under such energetically demanding conditions, the charging power of 200 kW can not be used either, due to the reasons already mentioned in cases B 3.4.2-II and 3.5.2-II .

The solution here is different than in case B above, because the solver adds 7 fast chargers en route. Thus the battery capacity in some bus lines decreases along with the battery cost. This occurs due to a charging power in the terminal of 300 kW, and an increase in energy consumption to more than 100 kWh in 14 bus lines. Therefore, it is not possible to replenish the energy consumed during a round trip in 20 minutes, unlike in the previous case B (with a charging power of 400 kW at the terminal station). Thus, the optimization model does not call for an increase in the capacity of the battery system, since it would be unreasonable and involve an unnecessary increase in the cost of the battery. Therefore, in this scenario, the battery system design changes and its cost comes out to 25.13 million €. The fast charger's cost is 7.78 million €, putting the initial investment for the battery system and fast charging infrastructure at 32.91 million €, lower than the initial investment cost in case B above. However, the solution in this case accelerates the aging process of the batteries too much, due to the increase in fast charges along the route. Long term then, this solution is more expensive than the previous case B.

4 Conclusions

In this study, an optimization model for the costs of the electrification of a bus network with fast charging system was developed. This model was then applied to determine the required charging infrastructure and battery capacities to electrify this diesel bus network. The optimization model was implemented using python 3.7, with the optimization package Pyomo 5.5, and the GUROBI solver. The analysis was developed using real-world data from representative bus lines of Santiago bus network. Specifically, the bus lines 501 to 518 were selected to make up a total of 17 lines, with 11 terminal stations, a total network of 1001.77 km and 651 buses. In this study, 2 options (A and B) were used to make a reasonable comparison of which option is more profitable in terms of investment costs and requirements for the charging infrastructure and the battery system. The main conclusions with regards to the results obtained in this study are the following:

The biggest limitation to the electrification of the bus network is still the cost of the batteries. Despite the fact that in recent years, the price of batteries has decreased significantly. The current battery cost based on the technical specifications in terms of capacity and charging power used, is very high, for the electrification of one bus lines as energetically demanding as those of the Santiago bus system.

The fast chargers, although expensive, represent less than 30% of the total cost of electrifying the 17 bus lines, so they do not represent a great limitation in terms of overall costs. However, from the point of view of the Reborn Electric company, the number of fast chargers installed, together with the frequency of charge chosen, still greatly impact the cost of the battery system and overall investment. For the company, therefore, the most convenient solution could be option A, where the cost of the battery system is lower. However, in the short term, the cost of replacing the battery system for certain specific bus lines still needs to be considered when choosing a solution.

Another important factor to consider is the charging power. Specifically, the greater the power injected during the charging process, the more the bus' energy is replenished, lowering the necessary number of battery modules. However, the stability of the electrical distribution system should also be considered in order to avoid concentrating large energy demands in certain areas.

To assess the economic impacts of operational and technology-related constraints, several scenarios were examined. The sensitivity analysis revealed that charging infrastructure and battery capacity requirements depend to a large extent on the assumptions applied in each case. Further, this analysis found that the size of the battery more than compensates for variations of parameters. However, the number of fast chargers en route does not have a great impact on these changes. In addition, for the most demanding energy scenarios, the charging power of the terminal chargers has a great effect on the sizing of the batteries.

The solution for option A is to use 2 battery system designs: 2 modular packs in parallel, each modular pack of 30 modules in series of: 3p10s and 2 modular packs in parallel, each modular pack of 30 modules in series of : 4p10s, which costs 20.72 million €. The selection of this battery system is paired with the installation of 42 fast-charging devices with 400 kW charging power, which are distributed across the different bus terminals and stops, at a cost of 10.5

million €. In addition, for the slow charging process at the end of the operational day, 41 slow chargers of 50 kW are needed, which are distributed to the 11 bus terminals in accordance with the number of operational buses, which use each terminal, with a cost of 0.82 million €. The cost of electrifying 651 buses is 127 million €, therefore, the total initial investment cost is 159.74 €. The advantage of this solution is that it provides greater flexibility in terms of the capacity, weight and design of the battery system. Therefore, it does not significantly increase the cost of the batteries. Furthermore, its weight makes up less than 10% of the maximum weight the bus can bear. However, due to the high number of fast charges that occur in a day, the aging process of the batteries is greatly accelerated. Given this, the short term costs of replacing the battery system in 16 of the 17 bus lines should be considered. That is to say, during the initial phase of implementation and across the 10 years of operation of the project, the total cost of the battery system will be high. Another aspect to consider is the high cost of the fast charging infrastructure. Fast chargers must be installed in every bus terminal in order to meet the energy demands for each day of operation. In addition to the core base of fast chargers, an additional charger is added to each terminal as backup in the event of charger failure. This considerably increases the cost of the fast charging infrastructure. Specifically, the fast charging devices end up representing 30% of the total investment cost.

The solution for option B, where the charging process occurs each time a round trip is made. The selected battery systems are: 2 modular packs in parallel, each modular pack of 30 modules in series of: 5p10s and 2 modular packs in parallel, each modular pack of 30 modules in series of : 6p10s, with a cost of 33.75 million €. The number of fast chargers required is 24, which are distributed to 5 western terminals, 1 eastern terminal and 1 along the route. The fast charging device en route is located at a bus stop shared by lines 511 and 514. The total cost of the charging infrastructure is 6 million €. Additionally, this solution calls for 94 slow chargers of 50 kW, which are distributed to the 11 bus terminals, with the highest concentration at the 4 eastern terminals, where fast chargers are not installed. The total cost of these slow chargers is 1.88 million € and the cost of electrifying 651 buses is 127 million €., bringing the total cost of electrification to 169.33 million €. One of the advantages of this solution is that it decreases the cost of the fast charging infrastructure, because fast chargers are installed in only 6 terminals. Thus, the number of additional chargers needed as backup in case of failure is much smaller than in option A. Specifically, the fast-charging devices make up 15% of the total cost of the investment, half as much as in option A. The second advantage of this solution is that less number of fast charges needed during one operational day. This keep the batteries' aging process from being accelerated too quickly. However, the main problems with this solution are its high initial cost as well as the battery system's high weight. The cost of batteries represents 80% of the total cost of the investment here, and furthermore, the weight of the battery system reduces the weight available for passengers by 20%.

The most convenient solution to keep the cost of the initial investment low is that of option A. Therefore, the selection of this solution is suggested, since it does not require a large initial investment in the battery system nor does it decrease the maximum weight available for passengers, unlike the solution for option B. However, when looking at a time horizon of 10 years, this solution involves the replacement of the battery system on at least 2 occasions for some of the bus lines.

Suggestions:

- It is not recommended to use the same design of the battery system for every bus lines. Basing the design only on the bus line with the highest energy consumption would be more convenient computationally and operationally. However, using the same battery design in every line would raise the total investment cost. The total cost of electrification in this scenario would be 163.63 million € for option A and 172.49 million € for option

B. Thus, the initial total investment would be greater than the results obtained with the optimization model. Finally, it is suggested to use the solution of option A with 2 clusters in order not to oversize the capacity of the battery system in some bus lines and at the same time, to not increase the investment costs too much. The final decision on the design conditions remains open to the company Reborn electric.

- In general, it is not convenient to charge en route, due to the number of trips made by each bus per day, since this accelerates the aging process of the batteries too much. Therefore, the charge along the route is convenient for bus lines whose buses do not make too many trips per day. In the future, it could be convenient to charge en route if the cost of high-power chargers decreases or if the size of the bus fleet of some lines is increased in order to reduce the number of bus trips. However, if the number of buses per line is increased, it would imply a large investment, since new electric buses with the same technical specifications would need to be purchased. Furthermore, these buses would have to be compatible with the requirements of the charging mode, charging power and capacity of the battery system.

- It is suggested that future planning considers the installation of fast chargers in all the bus terminals. This would be a security measure in case of failure of a fast charger in another terminal. In addition, it is recommended to evaluate and modify the operating schedule to avoid queue problems during the slow charging process at the end of each shift. This would keep drivers from waiting longer than necessary because of delays from other buses in starting their loading processes

A An appendix

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