Shift to Electrification

A study of Total Cost of Ownership for the two most common charging strategies

Master's Thesis in the Quality and Operations Management Programme

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David Larsson   Anton Persson

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Abstract

In recent years a major shift to battery electric buses has started all over the world, especially in the city bus applications. The major driving factors behind this rapid shift is an increased awareness of toxic pollution, congestion and carbon footprint. Currently, the two main charging strategies used in commercial operations are opportunity charge and overnight charge. This thesis presents an analysis of the Total Cost of Ownership (TCO) for an electric bus fleet operating on different bus routes using either opportunity charging or overnight charging. The purpose of this thesis was to achieve a greater understanding of opportunity charging and overnight charging when it comes to the TCO, and eventually provide a better understanding of what operating conditions that are favorable for each charging strategy and why. This was done through a multiple case study using real route data and schedules from four bus routes located in Sweden. A simulation tool developed in a project mainly funded by Energimyndigheten was utilized in combination with a simulation tool developed in conjunction with this thesis. The EAEB tool incorporates the scheduling of the buses, allowing for a dynamic way to analyze how various parameters influence the operating schedule, and in turn what implications this have on the TCO.

The findings show that opportunity charge achieved the lowest TCO on all the routes but depending on what assumptions that were made and what route that was analyzed, the difference in TCO between the two charging strategies varied between 0,83 % and 9,60 %. The greatest cost category for both charging strategies was the driver cost. Reducing the charge time for the opportunity charging proved to be a successful strategy, reducing both the driver time and number of required vehicles and chargers. This thesis found that it was possible to reduce the TCO with up to 11,73 % when the charge time decreased from 10 min to 3 min. It was discovered that the route characteristics played a vital role in determining to what extent the total driver cost could be reduced. The route with the lowest TCO was characterized by a high number of daily trips, high trip frequency, high trip duration and intermediate trip length. Furthermore, it was discovered that a uniform daily demand was an important precondition to achieve a high usage rate and thereby a low depreciation cost. This was particularly important for overnight charge to accomplish a similar TCO of opportunity charge. Moreover, it was discovered that an increased auxiliary load had a major impact on the TCO. A shift from 6 kW to 14 kW would on average result in a 3,23 % increase in TCO for opportunity charge, and a 6,58 % increase for overnight charge. Hence, it could be concluded that routes with hot or ambient cold conditions are particularly adverse for overnight charge due to the larger battery size.

Keywords: Electric buses, BEB, BEV, Total Cost of Ownership, TCO, Opportunity Charge, Overnight Charge, Public transportation, Route simulation

Glossary

Demand – In the context of operating conditions, demand refers to passenger transport demand

DOD – Depth of Discharge, here defined as the difference between the upper SOC value and lower SOC value

EAEB – A project that mainly was funded by Energimyndigheten and managed by RISE Viktoria AB, where a tool used in this thesis was developed.

Operating conditions – the conditions of the bus route, e.g. weather, topography, route characteristics

Opportunity charging – Fast charging alongside the route, in this thesis limited to end-station charging

Overnight charging – Slow charging in depot during the night

Route characteristics – The four dimensions that characterizes the route – trip frequency, trip duration, daily number of trips and trip length.

SOC – State of Charge, i.e. the energy level in the battery

TCO – Total Cost of Ownership, measured as total annual cost, cost per km, or cost per hour

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1 Introduction

In the following chapter, the background of this master's thesis will be introduced, followed by aim and purpose, objectives and research questions and lastly demarcations.

1.1 Background

Until now, fully electric buses were something that mostly was a topic for smaller projects on limited routes, but in recent years a major shift to battery electric buses has started all over the world, especially in the city bus applications. One example of this is in Amsterdam, where 100 electric buses have been operated in the Schiphol area since April 2018 (VDL 2018a).

The driving factors behind the rapid shift to electric city buses is a rising awareness of toxic air pollution, congestion and carbon footprint (Transport & Environment 2018). Additionally, current mobility problems like car dependency, traffic space consumption and unsuitability to accommodate passenger flows in a sustainable way has actuated the market to investigate new ways of transportation (Corazza, Guida, Musso & Tozz 2016). Furthermore, macro-economic factors like instability in oil prices have compelled policy makers to urge the undertaking of alternative technologies to substitute the oil-dependent mobility (Mahmoud, Garnett, Ferguson & Kanaroglou 2016).

Buses has the potential to serve as a more sustainable travel option due to a great environmental and safety performance, and high passenger capacity. Even with modest levels of passenger occupancy, buses can achieve low levels of fuel consumption, contributing to a reduction of CO2 and other GHG emissions (Corazza et al. 2016). In addition to technological changes in terms of new vehicles technologies, the transport industry is also experiencing techno societal changes (VTT 2014). There are indications that consumer preferences are shifting from a desire to own the means of transport towards shared services and an emphasis of simpler transport alternatives. Hence, traffic systems are undergoing a shift to an increasing number of clean vehicles with shared use and ICT services (VTT 2014).

According to Transport & Environment (2018), urban buses is expected to be the first transport mode to reach zero emission by using electric drivetrains. Commercial bus fleets are especially suitable for electrification due to the characteristics of the public transport networks. The operation is planned in advance, with fixed routes and schedules making it easier to plan for electric buses and deciding where to place the charging stations (Wang, Huang, Jiuping & Barclay 2017). The buses operate at low speeds with frequent stops and a high mileage per vehicle, meaning that the high investment costs of the electric drivetrain can be compensated by the reduced operational costs (Rogge, Hurk, Larsen & Sauer 2018).

There are mainly two different charging strategies when it comes to electric buses, i.e. opportunity charging and overnight charging. The characteristics of these two strategies differ, especially when it comes to the infrastructure and batteries. In the case with opportunity charging, the charging infrastructure is placed at bus stops, while in the case with overnight charging the infrastructure is located in the depot (Rogge et al. 2018). As the two strategies has different requirements on e.g. batteries, which according to Karlsson (2016) is a significant cost driver, the choice of charging alternative will affect the Total cost of ownership (TCO) for the operator.

Several studies have been made that investigates the lifecycle costs and TCO of electric buses. Lajunen (2018) recently evaluated the lifecycle costs and charging requirements of electric buses using different charging methods in diverse operating conditions, and eventually comparing the result with diesel buses. Pihlatie, Kukkonen, Halmeaho, Karvonen and Nylund (2014) presented a TCO model that can be utilized in investigating what charging infrastructure and vehicles concepts that are most economically feasible in city bus traffic. Additionally, Mahmoud et al. (2016) presents an assessment of electric buses and digs deeper into the operational context and energy profiles. However, a more in-depth evaluation of the TCO of electric buses is needed, especially with consideration to different charging strategies and integration of bus schedule and traffic planning. Current TCO models and solution approaches have been somewhat limited in their scope when it comes to investigating the relationship between technical requirements and operational conditions. Charging requirements is mostly seen as uncoupled input to the problem, and charging optimization is seldom considered (Rogge et al. 2018). Rothgang, Rogge, Becker and Sauer (2015) concluded that the battery system design and choice of charging concept is highly influenced by the local operating conditions and requirements. However, it can be quite a challenge to integrate all technical and economic aspects in the analysis while making a fair comparison of different charging concepts (Lajunen 2018).

Wang and González (2013), and Mahmoud et al. (2016) concluded that operational context and energy profiles are important factors when it comes to the success of the implementation. Regarding the operational context, current studies have often assumed that the driver time is constant and hence the relationship between technical requirements and driver scheduling have not been investigated in-depth. This relationship is of interest since driver costs and capital cost of vehicles are the main costs related to the operating bus system (Pihlatie et al. 2014). Further, Wang et al. (2017) accentuates the importance of making planning and operational decisions concurrently to accomplish overall cost effectiveness.

This master's thesis analyzed the operational context and bus schedule in combination with the technical requirements of the bus system with the purpose to investigates the TCO of overnight and opportunity charged buses. A simulation tool developed in the EAEB project was used to simulate an electric bus system on four different commercial bus routes located in Sweden, using real trip data and schedules.

1.2 Aim and purpose

Different charging strategies are likely to provide different TCO in different operating conditions, depending on e.g. length of the line, number of stops, duration, scheduling and weather conditions. Hence, the purpose with this master's thesis was to achieve a greater understanding of opportunity charging and overnight charging when it comes to the TCO. The master's thesis should eventually provide a better understanding of what operating conditions that are favorable for each charging strategy and why.

1.3 Objectives and research questions

To be able to understand the drivers that affect the TCO for the different charging strategies, a greater understanding of the TCO is necessary. The objective with the first research question is to gather information needed for the calculations in this study, hence the first research question was stated as:

RQ 1 – What parameters to include in the TCO calculation for an electric bus system?

Furthermore, to be able to understand which parameters, e.g. operating conditions and costs, that have the greatest impact on the TCO, the second research questions was stated as:

RQ2 – What parameters seems to have greatest impact on the TCO for each charging strategy?

When knowing what parameters that has the greatest impact on the TCO, it is possible to investigate what operating conditions that seems to be most favourable for opportunity charging and overnight charging. Hence, the third research question was stated as:

RQ3 – What operating conditions seems to be most favourable for each charging strategy?

Moreover, to get a better understanding of how the TCO differs between opportunity charging and overnight charging, the fourth research question was stated as:

RQ4 – How does the TCO differ between the two charging strategies?

1.4 Demarcations

This master's thesis was delimited to electric city buses as today's technology is most suited for shorter routes. Only fully electric buses were considered, and no comparison was done between electric buses and buses with internal combustion engine as that comparison already has been done in several other articles. Furthermore, only 12 m electric buses were considered, as the vast majority of electric buses ordered in Europe 2017 were 12 m buses (Baguette 2018). The battery sizes used for the buses in the simulations was not based on sizes available on the market today, instead theoretical values were used.

For charging strategies, this thesis was delimited to include opportunity charging and plug-in charging. As these two strategies was the most common for buses ordered in Europe 2017 (Baguette 2018). Moreover, opportunity charging was delimited to charging with pantograph at end-stations only and depot during the night, and plug-in charging was delimited to overnight charging in depot, with possibility for charging during the days only if the bus schedule allows. The charger sizes used in the simulations was not based on sizes available on the market today, instead theoretical values were used.

The TCO calculation was delimited to a consumer-oriented approach, i.e. only costs that are perceived by the consumers are considered (Lebeau, Lebeau, Macharias & Mierlo 2013). Moreover, this master's thesis did not investigated networks of routes, which can be analyzed to understand e.g. cost synergies of opportunity chargers. However, this did not limit the possibility to achieve the purpose of this thesis.

2 Problem context and literature findings

To be able give an enhanced pre-understanding for the reader, but also for the authors of this report to get enough knowledge about the electric bus system investigated in this thesis, a literature review was performed. The literature that was found to be particular important and useful is presented in this chapter. Hence the chapter consist of theory about electric buses, batteries, charging strategies, energy consumption, and TCO.

2.1 Electric buses

According to Wang et al. (2017) there are currently three main types of electric buses on the market, i.e. hybrid electric buses, HEVs, plug-in hybrid electric buses, PHEVs, and battery electric buses, hereinafter referred to as electric buses. These alternatives are differentiated by design and its different degrees of electrification (Mahmoud et al. 2016). Electric buses are powered solely by an electric motor, and compared to HEVs and PHEVs, electric buses have zero tailpipe emissions, which make them a great alternative in the pursuit for a fossil free public transport sector (Wang et al 2017). As mentioned in 1.4. this thesis was delimited to electric buses, and a configuration of an electric bus is presented in Figure 1, including battery, motor, transmission, final drive and auxiliary devices. Auxiliary devices include e.g. air condition, heating, radio, lighting (Goethem, Koorneef & Spronksman 2013).

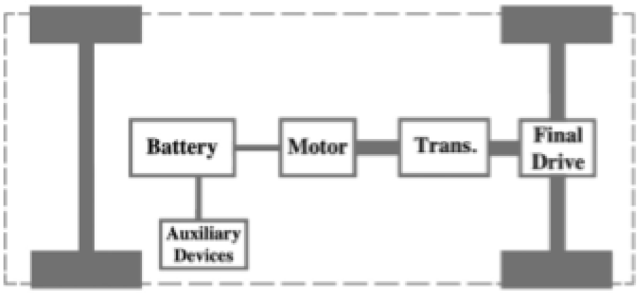


Figure 1 – Electric bus configuration (Mahmoud et al. 2016)

From Bloomberg NEF (2018) it was found that there were around 385 000 electric buses globally 2017, with 99 % of these in China. The Chinese electric bus market is fragmented, however the largest producer in 2016 was Yutong with 19 % of the market followed by BYD with 13 % of the market. When it comes to the European market, BYD was the largest European producer in 2017 with 15 % of the market, followed by Solaris with 12 % and VDL with 9 % (Baguette 2018). In Table 1, data for 12 m electric buses from Yutong, BYD, Solaris and VDL is presented.

Table 1 - Data for Yutong, BYD, Solaris and VDL 12 m electric buses (Bloomberg NEF 2018, ZeEUS 2017a)

	Yutong NEW E12LF	BYD 12 m Overseas	Solaris Urbino 12 electric	VDL Citea SLF-120 Electric
Charging system	Plug-in	Plug-in	Plug-in / Pantograph	Plug-in / Pantograph
Length	12 m	12 m	12 m	12 m
Gross vehicle weight	19 100 kg	19 000 kg	18 000 - 19 000 kg	19 500 kg
Passenger capacity	75 + 2 (wheelchair)	Up to 95	Up to 90	92
Airco	Fully electric	Yes*	Electric	Electric
Heating	Electric	Electric or diesel	Electric or diesel	Electric or diesel
Range	300 km under SORT	320 km under SORT		
Consumption			0,9 kWh/km under SORT 2	
Battery energy	324 kWh	324 kWh	Up to 240 kWh	85 - 180 kWh
Battery warranty	5 yrs	5 yrs	Up to 5 - 10 yrs	
Charge rate	60 kW	2x 40 kW	Up to 450 kW	Up to 360 kW
Charge time	5,5 h	4 - 4,5 h		5 min - 4,5 h

Here, SORT stands for Standardised On-Road Test cycles, which is an initiative of the UITP Bus Committee (UITP 2017). This initiative aimed to providing the bus sector with a standard when it comes to the comparison of energy consumption between different buses. SORT and the different driving cycles related to the standard will be described more in detail in 2.4.

Electric buses have many advantages according to Wang et al. (2017), however the same authors states that there are concerns when it comes to the driving range for electric buses. The driving range for electric buses is also considered as a key barrier by Mahmoud et al. (2016). Neubauer and Wood (2014) wrote about the fear associated with reaching the maximum driving range for battery electric vehicles, i.e. Range anxiety, and that this can cause drivers to choose other power sources. According to Wang et al. (2017) this range anxiety can be mitigated by using either fast charging technology or by swapping batteries to fully charged batteries during the day. Different charging strategies will require different batteries and different charging equipment. The next part of the report will introduce batteries, while the charging strategies and associated charging equipment will be presented in 2.3.

2.2 Batteries

There are several battery types used in commercial operation and depending on the application, different demands are put on the batteries. In operations using only overnight-charged buses, the buses are commonly only charged once or twice during the daily bus schedule, meaning that the batteries must store a high amount of energy, i.e. having a high specific energy ratio (kWh/kg). In operations using opportunity charging, the batteries are charged often with high currents. In this case, high power batteries (kW/kg) are suitable due to their ability to receive very high currents (Lajunen 2018).

Battery type and capacity has a high impact on the performance of the bus (Lajunen & Lipman 2016). A downside with overnight charged buses is that a high daily driving distance demands a high battery capacity, which in turn affects the weight, energy consumption and passenger capacity of the bus. Meaning that overnight-charged buses can be less suitable for longer distances (Pihlatie et al. 2014). Opportunity charged buses demands less battery capacity compared to overnight charged buses, meaning less weight and energy consumption. Additionally, operating conditions can have a big impact on the battery dimensioning. In more extreme weather conditions, the batteries must be dimensioned to support the cabin thermal management while simultaneously ensuring adequate operating range, thus increasing the required battery capacity (Jaguemont, Boulon & Dubé 2016).

The lifetime of batteries is a complex question and it depends on several different parameters concerning battery system design (Pihlatie et al. 2014). Battery design parameters such as cell material, quality of manufacturing, thermal and electrical management of battery pack and depth-of-discharge (DOD) are some of the parameters that must be considered when calculating the battery lifetime (Pihlatie et al. 2014). Battery degradation in lithium-ion batteries can occur during both storage and cycling due to chemical and mechanical processes, which eventually leads to capacity fade and a shortening of the vehicles achievable range (Barré et al. 2013). For example, a large DOD can cause contact loses between certain components on the anode, increasing the chances for power fade. Overcharging the battery can eventually result in the creation of dendrite on the anode, thereby wasting cyclable lithium which leads to capacity fade (Barré et al. 2013).

There is a difference between the available and maximum capacity of a battery. The maximum capacity varies depending on temperature and will eventually fade over the batteries lifetime (Lam 2011). The available capacity declines when the battery has been discharged with larger currents. According to (Lam 2011), a battery for electric buses is typically considered to reach the end of its life when the available capacity or maximum power under reference conditions has decreased by 20% of its original value.

The state of charge (SOC), see Figure 2, is a measurement of the level of charge of the battery. A fully charged battery have a SOC value of 100%, and if the battery is fully discharged, the SOC value is equal to 0 % (Jaguemont, Boulon & Dubé 2016). The difference between the upper SOC value and the lower SOC value is called the SOC window. The lower SOC value depends on how much one wants to discharge the battery. Since the battery will lose some capacity over time, the upper SOC value often represents the amount of the original nominal capacity that the battery can maintain at its later stages of the lifecycle (Jaguemont, Boulon & Dubé 2016).

The cycle life of the battery, i.e. the number of cycles before discarding the battery cell, increases rapidly when the SOC window becomes narrower (Pihlatie et al. 2014). The SOC window varies depending on battery type and the operating conditions. Most often, it is a trade-off between range and battery lifetime since a narrow SOC limits the range, but an increased SOC window, hereinafter called DOD, decreases the lifetime of the battery.

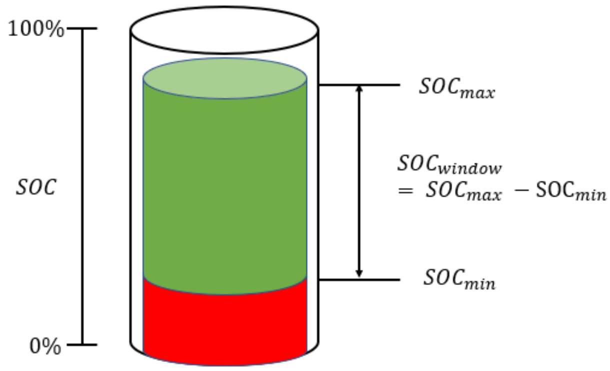


Figure 2 – State of Charge

In the study by Lajunen (2018), the DOD was set 75 % for opportunity charging and 95 % for overnight charging. This resulted in a battery size between 292 and 376 kWh for overnight charged buses with an auxiliary consumption of 6 kW, and between 326 and 391 kWh with an auxiliary consumption of 14 kW. What is included in the auxiliary consumption and what driving condition different auxiliary consumptions corresponds to will be presented in 2.4. Bi, Kleine and Keoleian (2016) chose to have a DOD of 60 % in their study and a battery size of 458 kWh for their overnight charged bus.

Costs and durability of the batteries has quite a large impact on the TCO of electric buses, some studies show that battery capacity can account for up to half of the vehicle's capital cost (Transport & Environment 2018; Lajunen & Lipman 2016). Hence, optimizing battery size according to operation needs is of high priority since over-sizing the battery could have a major impact on the result. Furthermore, the cycle life of the batteries can be quite challenging to model in detail due to the complex relations between battery parameters, and much of the data and information concerning battery life cycles is proprietary to the battery cell manufacturers (Pihlatie et al. 2014). Subsequently, battery lifetime assumptions can be quite a sensitive factor when conducting TCO simulations (Transport & Environment 2018).

Hoke, Brissette, Maksimović, Pratt and Smith (2011) presents an approach for calculating the battery degradation under varying conditions, and that considers effects of temperature, average SOC and cycling DOD. By assuming that these effects are independent from each other, and that the battery is operating under the same conditions throughout its lifetime, one can differentiate a model that calculates the changes in battery cycle life depending on the DOD, see equation (1).

$$CL = \left(\frac{DOD}{145{,}71}\right)^{-\frac{1}{0{,}6844}} \tag{1}$$

For the logic and assumptions behind equation (1), readers are referred to the paper by Hoke et al. (2011). This equation can in turn be used to calculate the economic loss of the battery degradation. In this thesis, the depreciation cost of the batteries is calculated using a depreciation time of 8 years, in combination with the equation by Hoke et al. (2011), the economic effects of an increased DOD are investigated in simulation 3, see subsection 6.3.5. How this equation affects the cycle life is presented in Figure 3.

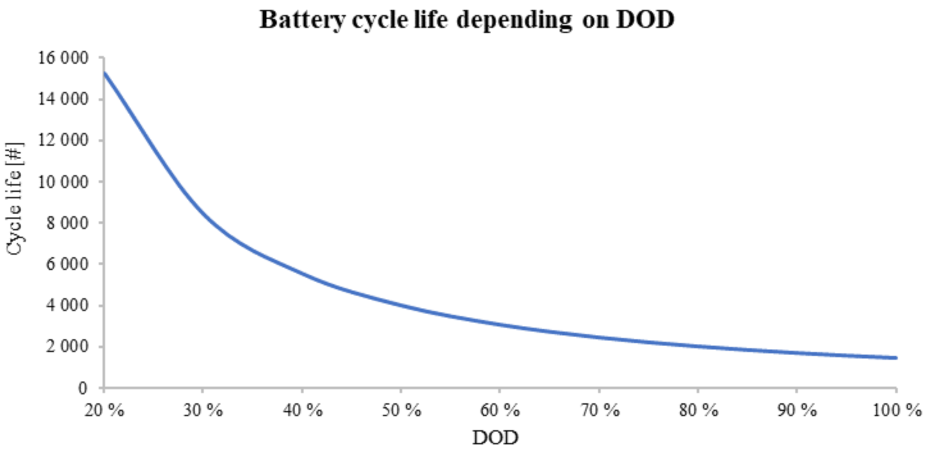


Figure 3 - Battery cycle life (Pelletier, Jabali, Laporte & Veneroni 2017)

The size of the batteries available on the market today differs between bus OEM. The battery capacity is specified based on the operating conditions; therefore, it can be difficult to tell how high capacity each bus OEM offers. For example, MAN Lion's City E offers a solo overnight charged bus with a battery pack of 480 kWh, and an articulated overnight charged bus with 640 kWh (MAN 2018). Some other available sizes for batteries was presented in Table 1. Different charging strategies demands different battery sizes to manage the driving distance between charging, and these different charging strategies will be introduced in the following section.

2.3 Charging strategies

There are several different strategies that can be utilised when charging an electric bus and they can be categorized into three major categories – static, stationary and dynamic (Karlsson 2016). Static charging takes places while the bus remains inactive for a longer period of time, most likely in the bus depot. Stationary charging means that the bus is charged while inactive for a short moment, either by inductive or conductive chargers (Karlsson 2016). Dynamic charging takes place when the vehicle is moving, an example of this is the trolley bus. This report will only analyse two different charging strategies, namely static (overnight charging) and stationary charging (opportunity charging). The reason for this is that these two strategies appears more frequent in contemporary commercial launches (Baguette 2018). According to Baguette (2018), of 1 146 buses ordered in Europe 2017, some 40 % were for plug only charging, i.e. overnight charging, while some 60 % were for pantograph charging, i.e. opportunity charging.

2.3.1 Opportunity Charging

As mentioned, roughly 60 % of the electric buses ordered in Europe will be charged with either roof-mounted or gantry-mounted pantographs, making it the most desirable solution of choice for many operators (Baguette 2018). Roof-mounted pantograph means that the pantograph is mounted on the roof of the bus, while gantry-mounted pantograph, has the pantograph mounted on the gantry, see Figure 4. Since opportunity charged buses can be recharged at end-stops or along the route, they can utilize smaller batteries than overnight charged buses, thereby reducing the weight contribution of the batteries and making more room for passengers. The battery capacity typically ranges between 50-150 kWh depending on the operating conditions, and the effect of the high-power charging pantographs usually ranges from 200-450 kW (Transport & Environment 2018). However, ABB, Heliox and Siemens offers opportunity chargers from 150-600 kW (ABB 2018; Heliox 2018; Siemens 2018).

Figure 4 – Left: Roof-mounted pantograph (VDL 2018b), Right: Gantry-mounted pantograph (Scania 2018)

The small batteries onboard of the opportunity charged bus contributes to relatively low vehicle capital costs in relation to the overnight charged bus. However, the requirements of the charging infrastructure can be somewhat unconditional (Pihlatie et al. 2014). While the installation of the charging poles does not necessarily need any major modification to the current landscape surrounding the bus route, the required number of chargers and the subsequent distribution of the charging spots can act as a barrier to the implementation of opportunity charged buses (Mahmoud et al 2016). Based on the operating conditions, extensive planning must be made in order to decide the right location and effect of the chargers. Poorly placed chargers results in unnecessary travelling time, which consequently leads to a more adverse financial outcome. Additionally, high-effect chargers can have quite a big impact on the utility grid, an under some circumstances the grid can serve as a roadblock for the implementation, especially in larger metropolitan areas or areas with an outdated utility grid (Mahmoud et al 2016).

An example of a bus network using opportunity charged buses is Schiphol airport in Amsterdam. Here, a fleet of 100 electric buses serves on 6 routes around the airport 24 hours a day (Electrive 2018a). The buses have a battery capacity of 169 kWh and can be charged with up to 420 kW, with 23 fast chargers with an effect of 450 kW. The system uses roof-mounted pantograph and allows a charge time of 2 to 4 minutes. The charging system is complemented with 86 depot chargers with an effect of 30 kW, and according to VDL (2018a), these 100 buses will travel 30 000 km per day.

As opportunity charging requires that buses stop for charging, additional time can be added when comparing with an overnight charged bus. However, extra time will only be needed if the time for coupling to the charger, charging, and decoupling is longer than the dwell time. To calculate the added time at each end station, Olsson, Grauers and Pettersson (2016) used the equation presented in (2), that includes the charging time $(T_{recharge})$, coupling time for the pantograph charger ($T_{coupling}$), and the dwell time at each end station (T_{dwell}).

$$T_{added\ stop\ time\ at\ end\ stations} = T_{recharge} + 2T_{coupling} - T_{dwell} \tag{2}$$

2.3.2 Overnight Charging

Overnight charged buses typically have a battery capacity of over 200 kWh and they are recharged at the depot using slow chargers with an effect typically ranging between 40-120 kW (Transport & Environment 2018). The charger must have enough power to both be able to charge the battery during night, and if needed, charge the battery during the day depending on the timetable (Olsson, Grauers & Pettersson 2016). Depot charged electric buses can under favourable conditions be designed to have a battery range of up to 300km during one charge, the stored energy can in some cases be enough to complete a whole day of transport work without charging an extra time (Olsson, Grauers & Pettersson 2016). But according to Transport & Environment (2018), no products in the market is reliably manage over 250 km yet. This can lead to that additional buses are needed when buses must charge during the day, and also to additional time, see (3). This additional time is the time for driving to and from the depot, start charging the used bus, and prepare the new bus (Olsson, Grauers & Pettersson 2016).

$$T_{switch\ bus} = 2T_{driving\ to\ depot} + T_{start\ charging} - T_{prepare\ new\ bus} \tag{3}$$

Overnight charged buses are usually charged few times a day, and no charging takes place along the bus route, meaning that the operating characteristics are somewhat similar to that of combustion engine buses (Olsson, Grauers & Pettersson 2016). Additionally, current infrastructure can be used and there is no need for additional investments in chargers along the route. Making this a flexible strategy in terms of adopting electric buses in traditional inner-city bus systems (Olsson, Grauers & Pettersson 2016).

As mentioned earlier, due to the limitations in range, overnight charged buses may not be suitable for all types of operating routes. However, depending on the operating conditions and the context of the procurement, overnight charged buses can be the enabler of electric buses (Transport & Environment 2018). An example of this is cities where historical and cultural heritage may prevent the implementation of opportunity charged buses, or where the utility grid cannot handle the effect of fast chargers (Transport & Environment 2018).

Shenzhen, the city that has the world's first 100 % electrified bus fleet (World Resource Institute 2018) is using overnight charging, as the vast majority of Shenzhen's fleet of 16 000 buses is provided by BYD (Bloomberg LP 2018). In Shenzhen, the overnight charging is complemented with charging between driver shifts, and if needed, there are charging facilities at the end-stations for certain routes (Castellanos & Li 2017). A European example of a city that is going to use overnight charging is the German town of Hamburg where the local public transport provider, Hamburg Hochbahn, has ordered 30 fully electric buses. The buses will have a range of about 150 km, and they are powered with 240 kWh batteries which will be charged in the depot using 150 kW chargers (Electrive 2018b).

2.4 Energy consumption and operating conditions

According to ZeEUS (2017b), it is very important that the operators get objective information about the energy consumption, as it is an important key factor for TCO, hence this chapter is included in this report.

As mentioned in 2.1, SORT is an initiative started by UITP Bus Committee. The main aim with this project was to design reproducible test cycles for on-road test pf buses, to make it possible to measure fuel consumption (Gis, Kruczyński, Taubert & Wierzejski 2017). There are three different driving cycles in SORT tests, i.e. SORT 1 that corresponds to heavy urban driving, SORT 2 that corresponds to ease urban driving and SORT 3 that corresponds to easy suburban driving. Most of the energy consumption found from the manufacturers was specified as the consumption using the SORT test, e.g. Solaris Urbino 12 electric with a consumption of 0,9 kWh/km or Yutong NEW E12LF and BYD 12 m Overseas with a range under SORT of 300 km with a respectively 320 km, both last-mentioned buses with 324 kWh battery capacity (ZeEUS 2017a).

All SORT cycles are performed without any auxiliary load (Goethem, Koorneef & Spronksman 2013), i.e. air condition, heating, radio, lighting etc. are turned off. The energy consumption by auxiliary devices for electric buses will have a higher percentage of the total energy consumption compared with buses with internal combustion engines (Lajunen 2014). Higher real-world energy consumption is also supported by He et al. (2018), and according to Zhou et el. (2016), maximum air condition and full passenger load leads to an increase in energy consumption of 21-27 %, where air condition contributes most to the increased energy consumption. Moreover, Lajunen (2018) found that the energy consumption will increase by 30-50 % while going from an auxiliary load at 6 kW to 14 kW. Where 6 kW auxiliary load corresponds to operation in mild weather conditions, while 14 kW auxiliary load corresponds to hot or ambient cold conditions. According to Lajunen (2018), increased auxiliary power can make the lifecycle costs increases as much as 10% for end station charging buses and up to 30% for opportunity charging buses. Furthermore, the overnight charged buses in the study by Lajunen (2018) had an 10 % higher energy consumption on average than opportunity charged buses.

A summary of different energy consumptions found in the literature review is presented in Table 2.

Table 2 - Energy consumption from the literature review

Source	Energy consumption [kWh/km]	Auxilary power [kW]	Notes
Bi et al. (2016)	1,46	Unknown	BYD, average of several road tests
Bloomberg NEF (2018)	1,20 - 1,30	Unknown	
Lajunen (2018)	0,87 - 1,20	6	Opportunity charging
Lajunen (2018)	0,95 - 1,28	6	Overnight charging
Pihlatie et al. (2014)	1,05 - 1,26	Different scenarios	Optimistic and pessimistic scenarios
Transport & Environment (2018)	1,30	Unknown	Conservative scenario

What was found in the literature study, and presented in Table 2 was that most articles used an energy consumption between 0,87 kWh/km and 1,46 kWh/km. However, it should also be mentioned the estimated energy consumption varies significantly between studies, e.g. Zhou et al. (2016) uses an energy consumption of 1,75 to 2,11 kWh/km for a 12 m electric bus and He et al. (2018) an energy consumption of 1,7 to 4,1 kWh/km for a 12 m electric bus. The variation in the estimated energy consumption in these studies depends on the passenger load, average driving speed and AC.

2.5 Total Cost of Ownership

As the focus in this master's thesis was on the TCO for the two most common charging strategies for electric buses, this section will focus on literature associated with TCO, and in particular TCO related to electric buses. The first part will include a general review of literature associated with TCO, while 2.5.1 and 2.5.2 will break the TCO down into investment costs and operating costs.

Instead of just looking at the capital expenditure associated with the investment, or at the operating costs during the usage, the TCO approach allows the customer to compare all the costs that are associated with the investment and the usage of the product (Letmathe & Suares 2017). Electric buses have a high cost of investment compared to a combustion bus, but instead a lower running costs (Olsson, Grauers & Pettersson 2016). This means that looking at the investment cost alone can give a misleading impression of the investment. One example of different costs that can be included in the TCO for urban buses with alternative powertrains is presented in Figure 5.

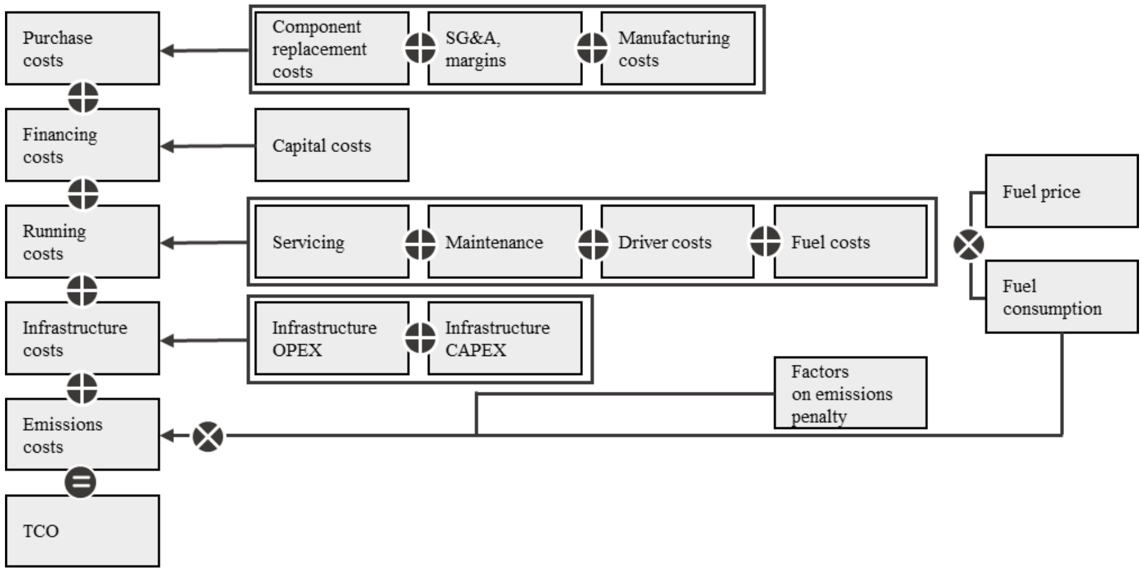


Figure 5 - Total Cost of Ownership (FCH JU 2012)

It was mentioned in the previous paragraph that the TCO approach take both capital expenditures and operating costs in considerations. This approach is also used by Lajunen and Lipman (2016), and Lajunen (2018), where both articles included a calculation of lifecycle costs (C_{LC}) with the aim to compare different powertrain alternatives, but also for different charging methods for city buses. The cost calculation in these articles consisted of three different cost categories, i.e. capital costs (C_{CAP}), operating costs (C_{OP}) and technology replacement costs (C_{REP}), see (4). The technology replacement costs here refer to the costs for replacing the batteries (Lajunen 2018). However, Lajunen and Lipman (2016), and Lajunen (2018) did not call this for TCO, instead they call it lifecycle cost.

$$C_{LC} = C_{CAP} + C_{OP} + C_{REP} \tag{4}$$

TCO was also used by Topal and Nakir (2018), where they used it to compare buses driven by diesel, natural gas, CNG, or electricity in Istanbul conditions. They used the calculation presented in (5) for this comparison and it consisted of fixed costs (TCO_S), and variable costs (TCO_D).

$$TCO = TCO_S + TCO_D \tag{5}$$

Except just examine the cost side, Topal and Nakir (2018) took the revenue side in consideration by the usage of the tender unit price for electric buses from ESHOT, a Turkish General Directorate that operates buses (ESHOT n.d.). The result was then compared with three different methods, i.e. NPV, Internal Rate of Return (IRR) and Payback Period (PB).

Pihlatie et al. (2014) called their approach to do an TCO calculation for the Equivalent Annual Cost (EAC), i.e. the cost per year for owning and operating a fleet of electric buses. The calculation is presented in (6), and consists of the vehicle costs ($EAC_{Vehicle}$), charger costs (EAC_{Charge}), energy costs ($Energy$), service and maintenance costs ($S\&M$) and urea costs ($Urea$). The EAC calculation take the Net Present Value (NPV) into consideration by the usage of annuity factors.

$$EAC = EAC_{Vehicle} + EAC_{Charge} + Energy + S\&M + Urea \tag{6}$$

Table 3, presents depreciation time for buses, chargers and batteries used in these articles and the discount rate, found in the literature review.

Table 3 - Depreciation time and discount rates found in the literature review

Source	Depreciation bus [yrs]	Depreciation chargers [yrs]	Depreciation batteries [yrs]	Discount/Interest [%]
Bi et al. (2016)	12	24	3000 cycles	3,6
Lajunen & Litman (2016)	12	20		4
Lajunen (2018)	12	20		3
Olsson et al. (2016)	10	20	10	5
Pihlatie et al. (2014)	12	10		5
Rogge et al. (2018)	12	12		
Rothgang et al. (2015)	12	20	5	4
Topal & Nakir (2018)			5	8, 12, 14 and 16
Transport & Environment (2018)	10		8	4

To evaluate the difference in TCO for different routes, powertrains and charging strategies, all of the articles presented in Table 3 used the performance metric cost per operating kilometer, €/km. Philatie et al. (2014) even called the metric €/km for TCO. However, according to Lajunen (2018), the cost per distance may not present the life cycle cost of city buses well, and therefore Lajunen (2018) added the cost per operating hour, €/h, as a complementary performance metric.

According to Lebeau et al. (2013), the TCO approach can be applied in two different ways, one way is the consumer-oriented approach, while the other ways is the society-oriented approach. The main differences between these approaches are which types of costs to include in the calculations. For the consumer-oriented approach capital expenditures and operating costs are included, and for the society-oriented approach this will also include environmental costs, e.g. carbon oxide costs. However, as this master's thesis was delimited to the consumer-oriented approach, the following two sections will focus on the consumer-oriented approach.

2.5.1 Investment costs

As mentioned in 2.5, one part of the TCO is the investment cost, also called purchase cost, capital cost, capial expenditures, etc. depending on author. In the EAEB project, the investment costs were divided into vehicles, batteries and charging infrastructure (EAEB 2018a). These investment costs were then annualized with an interest rate and depreciation time to make it possible to add these costs to the total annual costs. This approach was also used by Olsson, Grauers and Pettersson (2016), where their investment cost also included vehicles, batteries and charging infrastructure. These investment costs were then annualized to the annuity (A), by the usage of the NPV, interest rate (p), and the depreciation time (n), with the equation presented in (7).

$$A = \frac{NPV \cdot p}{1 - (1+p)^{-n}} \tag{7}$$

Lajunen and Lipman (2016), and Lajunen (2018) included the number of buses (N_{bus}), purchase cost of the buses (C_{bus}), the initial costs of the charging infrastructure (C_{chg}), and the salvage value (C_{sv}), see (8).

$$C_{CAP} = N_{bus}C_{bus} + C_{chg} - C_{sv} \tag{8}$$

The salvage value in (8) includes both buses and charging infrastructure, however the salvage value for electric buses was assumed to be zero at the end of their service life, i.e. the depreciation time presented in Table 3. The assumption that the salvage value for electric buses was zero at the end of their service life was also made by Pihlatie et al. (2014), that further assumed the salvage value for batteries to be zero at the end of their service life.

Topal and Nakir (2018) included the vehicle purchase cost for one vehicle (M_0), and the total infrastructure installation cost divided by the number of buses (250 in their case), presented in (9), to the fixed costs in their TCO calculation.

$$TCO_s = M_0 + \frac{P}{250} \tag{9}$$

Cost parameters for investment costs and associated values found in the literature study is presented in Table 4.

Table 4 - Investment costs found in the literature review

Source	Bus 12 m without battery [€ per bus]	High-energy battery [€ per kWh]	High-power battery [€ per kWh]	Fast charger [€ per kW]	Overnight charger [€ per kW]
Bi et al. (2016)	450 450	450	450		
Lajunen & Litman (2016)	450 000	500	750		
Lajunen (2018)	350 000	500	800	250 000**	20 000**
Olsson et al. (2016)	400 000	540	1 130	1 000	
Pihlatie et al. (2014)	300 000 - 320 000	600	1 200	250	50
Rogge et al. (2018)	250 000 - 350 000	600	700		
Rothgang et al. (2015)	300 000	800*	800*		
Topal & Nakir (2018)	359 000				
Transport & Environment (2018)	247 863	335	369		

*) Type of battery is not specified, **) Cost per charger [€]

When it comes to the investment cost for a 12 m electric bus without battery, the purchase price was between approximately € 250 000 and € 450 000 per bus. To this, an additional investment of between € 335 to € 1 130 per kWh was added for the batteries, depending on which article the values was taken from and also the type of battery. Not all authors presented the cost they used as investment cost for the charging infrastructure. However, Olsson, Grauers and Pettersson (2016) calculated with € 1 per kW, and Lajunen (2018) with € 250 000 for a charger with an affect higher than 200 kW. Notice that all values from Bi, Kleine and Keoleian (2016) is converted from $ to € by using the average exchange rate for 2016 from Credit Suisse (2017).

2.5.2 Operating costs

When it comes to operating costs, the EAEB project included insurance and maintenance, energy and labor costs for drivers to the calculations (EAEB 2018a). This is also in line with Lajunen and Lipman (2016), and Lajunen (2018), however they assumed that labor costs for drivers are equal for all different bus operations and Lajunen also included emissions costs. The calculation used for annualised operating costs by Lajunen and Lipman (2016), and Lajunen (2018) is presented in (10).

$$C_{OP} = \sum_{j=0}^{T} (N_{bus} D_j (C_{nrj\_j} + C_{m\_j} + C_{co2\_j}) + C_{chg} m_{chg}) \cdot (1 + d_{rate})^{-j} \tag{10}$$

In this calculation, the authors, includes the yearly driven distance (D_j), energy cost (C_{nrj_j}), maintenance cost (C_{m_j}), emission costs (C_{co2_j}), charger maintenance as a percentage of investment cost (m_{chg}), and the discount rate (d_{rate}). Furthermore, as mentioned in 2.5, Lajunen and Lipman (2016), and Lajunen (2018) did not included the battery costs in their investment costs, instead the authors calculated the annualized replacement cost with (11).

$$C_{REP} = \sum_{j=0}^{T} (N_{bus} C_{tech\_j}) \cdot (1 + d_{rate})^{-j} \tag{11}$$

Where the technology replacement costs was calculated with (12), which includes the battery cost per kWh (C_{batt}), the battery capacity (E_{batt}), and $F_R(D_{cum\_j}, L_{BATT})$ that is the replacement function for that indicates if the battery will be replaced or not (Lajunen and Lipman 2016, Lajunen 2018). D_{cum_j} is the cumulative driven distance, while L_{BATT} is the life time of the battery.

$$C_{tech\_j} = C_{batt} E_{batt} F_R(D_{cum\_j}, L_{BATT}) \tag{12}$$

Topal and Nakir (2018) calculated the operating costs with (13), that includes the maintenance cost per km (m_{bkm}), the average fuel cost per km ($Bf_{d,ng,e}$) and the financial value of the greenhouse emissions (G_{hg}).

$$TCO_d = (m_{bkm} + Bf_{d,ng,e} + G_{hg}) \cdot (l_{km} \cdot t) \tag{13}$$

Cost parameters for operating costs and associated values found in the literature study is presented in Table 5. Note that energy costs are excluded from this table, instead these are presented in Table 6.

Table 5 - Operating costs found in the literature review

Source	Driver cost [€ per hour]	Maintenance vehicles [€ per km]	Maintenance chargers [% of investment per year]
Bi et al. (2016)		4741****	~ 5
Lajunen & Litman (2016)			
Lajunen (2018)		0,2	3
Olsson et al. (2016)	35	0,183	2
Pihlatie et al. (2014)		8000****	3 000 and 5 000***
Rogge et al. (2018)	25**		
Topal & Nakir (2018)		0,04*	
Transport & Environment (2018)		0,183	2

*) All M&O costs, **) Time-dependent cost, ***) Depot and fast [€ per year], ****) [€ per bus per year]

The labor cost was excluded from most of the articles, see some of them in Table 5. Olsson, Grauers and Pettersson (2016) included labor costs for drivers and argues that it can be decisive between different alternatives, e.g. there is an additional cost for drivers for opportunity charging, as they have to stop for charge at the end station. The calculation of this added time for charging at the end station was presented in equation (2). According to the same authors there is also a possibility that an additional bus need to be added to manage the same time table for this added charging time. An additional cost of drivers, and additional costs for buses can also be true for overnight charging, as the bus might not have enough energy to drive for an entire day without charging (Olsson, Grauers & Pettersson 2016). The calculation for the additional time to switch bus was presented in equation (3) in 2.3.2.

In the article by Olsson, Grauers and Pettersson (2016), the energy costs excluding the consumption cost, i.e. the annual fee, power fee and variable energy fee, was divided into two different cost categories, depending on if the installations were lower or higher than 1MW. The most other articles in this review did not take this in considerations, instead most of them used one cost, i.e. the energy consumption cost. A comparison of which energy costs that was included in some of the reviewed articles can be found in Table 6, where also their associated values can be found.

Table 6 - Energy costs found in the literature review

Source	Energy annual fee [€ per year]	Power fee [€ per kW per month]	Variable energy fee [€ per kWh]	Consumption cost** [€ per kWh]	HVO for heating [€ per liter]
Bi et al. (2016)				0,102	
Lajunen & Litman (2016)				0,100	
Lajunen (2018)		10		0,100	
Olsson et al. (2016) < 1 MW	520	4,12	0,0068	0,075	0,995
Olsson et al. (2016) > 1 MW	930	3,42	0,0031	0,075	0,995
Pihlatie et al. (2014)				1,000	
Rogge et al. (2018)				0,250	
Topal & Nakir (2018)				0,110*	
Transport & Environment (2018)				0,112	

*) For the first year, **) Refered to as electricity cost in some of the articles

The energy consumption cost was € 0,075 per in the study by Olsson, Grauers and Pettersson (2016), where additional costs were added for the annual fee, power fee and variable fee. For most articles were the consumption cost was assumed to be the total energy cost per kWh, the cost was between € 0,10 and € 0,25 per kWh, except Pihlatie et al. (2014) where the electricity cost was set to € 1 per kWh for their baseline case.

2.5.3 Findings from previous studies

This section will present some of findings from previous studies regarding the TCO for electric buses, and also some result for diesel buses. However, the focus will be on electric buses as this master's thesis did not aimed to do a comparison between electric buses and diesel buses, but between opportunity charging and overnight charging.

In the article by Lajunen and Lipman (2016), six different routes were investigated, and it was found that opportunity charging was a more cost-efficient solution for electric buses than overnight charging. That opportunity charging has a lower life cycle cost than overnight charging was also the result from Lajunen (2018) were four different routes were investigated. The life cycle cost is heavily impacted by the capital cost, and on average opportunity charged buses are 7 % more expensive than diesel buses and the same number for overnight charged buses is 26 %. However, the same author states that buses that charge at the end station (mentioned as opportunity charging in this master's thesis) can have a slightly lower life cycle cost than diesel buses. When it comes to the TCO, the cost per km for opportunity charged buses was between € 0,6 and € 1,0, corresponding to € 14 and € 18 per hour, and for overnight charging the cost per km was between € 0,8 and € 1,4, corresponding to € 16 and € 28 per hour (Lajunen 2018). This was compared with a diesel bus where the cost per km was between € 0,7 and € 1,1. In both of the previous mentioned articles, the driver cost was excluded from the analysis. Furthermore, the sensitivity analysis from Lajunen (2018) showed that a change in vehicle cost, followed by a change in maintenance cost will have the greatest impact on TCO for opportunity charge, while vehicle cost followed by the battery cost will have the greatest impact for overnight charge. A sensitivity analysis was made also in the study by Bi, Kleine and Keoleian (2016) that showed that the battery cost will have the greatest impact on the TCO for overnight charging.

The lowest TCO is achieved with opportunity charging and multimodal components according to Pihlatie et al. (2014). According to the same authors, the TCO can be lower than or conventional diesel buses and low TCO is achieved with a high utilization. However, the cost per km in this article was found to be between € 0,8 and € 0,9 for opportunity charging, approximately € 1,1 for overnight charging and slightly lower than € 0,8 for diesel buses.

Bloomberg NEF (2018) performed three different analysis of the TCO, one corresponding to small cities with an annual driving distance per bus of 30 000 km, followed by medium cities with 60 000 km and large cities with 80 000 km. The result from this study, converting $ to € with the average exchange rate for 2018 from Credit Suisse (2019), was that for small cities the cost per km for opportunity charging was € 1,73, compared with € 1,43 for overnight charging, € 1,35 for diesel and € 1,55 for CNG. For medium sized cities the cost per km for opportunity charging was € 0,83, compared with € 0,84 for overnight charging, € 0,89 for diesel and € 1,00 for CNG. Lastly, for large cities the cost per km for opportunity charging was € 0,68, compared with € 0,78 for overnight charging, € 0,78 for diesel and € 0,87 for CNG.

In the study by Transport & Environment (2018), also the external costs on health and climate was included in the TCO. According to this study, the comparison of electric buses and diesel buses is strongly dependent on if external costs are included in the analysis or not. Without external costs, the cost per km was approximately € 1 for both charging strategies and € 0,94 for diesel. However, when external costs were included, the cost per km was € 1,04 for opportunity charging, € 1,05 for overnight charging and € 1,12 for diesel. Another finding in the study by Transport & Environment (2018) was that the daily driving distance is important, and that the battery price can account up to half of the vehicle's capital cost, and therefore it is important to optimize the size of the batteries.

One study that included the driver cost was the study by Olsson, Grauers and Pettersson (2016). According to the authors, the operator cost stands out as a significant cost, and hence it is important with a high utilization of vehicles and drivers. The cost per km found in the study was € 3.23 for opportunity charging, € 3.56 for overnight charging and € 3.17 for HVO buses. Furthermore, Olsson, Grauers and Pettersson (2016) stated that costs might vary greatly between cities and routes. One of their examples of this is that cities with a greater bus system can get better price from large scale procurements.

3 Methodology

This chapter aims to introduce the methodology used in this thesis, starting with the research process, research strategy and design, research methodology, simulations methodology, quality criteria and lastly ethical considerations. However, this chapter will not introduce the calculations used, as they will be presented in chapter 4.

3.1 Research process

The research process for this thesis was divided into four different parts, as presented in Figure 6. Each with the aim to either give answers to the research questions and/or generate output that was used in the next parts. Part 1 was performed first, then part 2, and so forth, however the shape of Figure 6 illustrates that some iterations was done, especially between part 2, 3 and 4. As new findings were analyzed, the Excel tool was enhanced, routes were added, parameters was changed, and more simulations was found of interest.

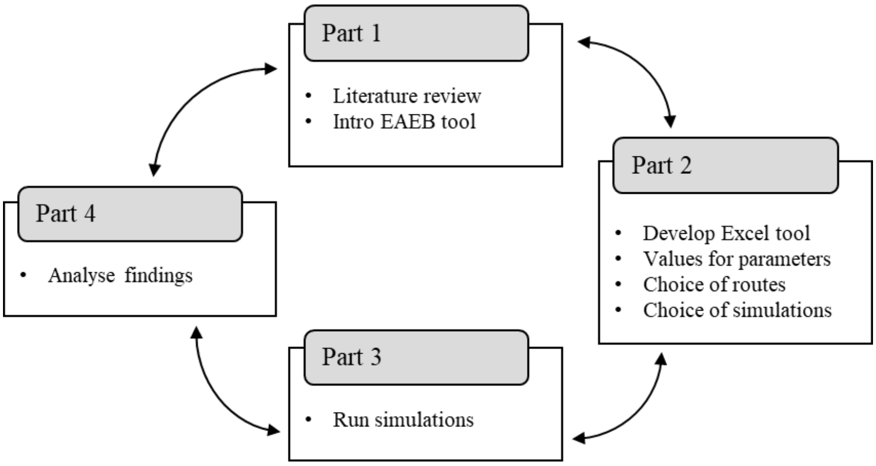


Figure 6 - The used research process

The first part consisted of a literature review, where the literature found most useful were presented in chapter 2. The EAEB tool combined with the literature review provided the information to decide what parameters that could be included in the TCO calculation. The main goal with the first part of the research was to get more insights in the investigated topic and to answer the first research question:

RQ 1 – What parameters to include in the TCO calculation for an electric bus system?

The second part of the research involved the development of an Excel tool, selection of values for parameters, selection of routes, and also the planning and construction of the simulations. The selected routes are presented in section 5.1, along with a summary of the route characteristics.

In the third part of the research, five simulations and one sensitivity analysis were performed. Here, the output from part 2 was used as input. As mentioned earlier, some iterations were done, and before part 2 was finalized, one more route was added and some adjustments in simulations, calculations and cost was performed. The main goal with this part was to produce the result that should be analyzed in the fourth part of the research.

The fourth part of the research was the analysis. Here, the outcome from part 3, i.e. the findings from this research were analyzed. First, each charging strategy was analyzed separately one by one for each route with the aim to answer the second research question:

RQ2 – What parameters seems to have greatest impact on the TCO for each charging strategy?

This was followed by an analysis where the parameters were analyzed separately for each charging strategy with respect to operating conditions, with the aim to answer the third research question:

RQ3 – What operating conditions seems to be most favourable for each charging strategy?

Lastly in part 4 of the research, the findings were analysed with respect to the difference between opportunity charging and overnight charging, with the aim to answer the fourth research question:

RQ4 – How does the TCO differ between the two charging strategies?

3.2 Research strategy and design

A research strategy can be either a quantitative or a qualitative strategy (Bryman & Bell 2015). As the purpose with this master thesis, as presented in 1.2, was to achieve a greater understanding of opportunity charging and overnight charging when it comes to the TCO, a quantitative research strategy was chosen. With a quantitative research strategy, it was possible to use the needed data and to do the calculations needed to calculate the TCO for the two investigated charging strategies.

The research design in this thesis was mainly a multiple-case study design where each of the routes that will be presented in chapter 5 can be viewed as a case study. A multiple-case study was chosen as it makes it possible reflect on what part of the findings that is unique for the different cases and what is common for them (Bryman & Bell 2015). Each case was represented by a route, and four routes were chosen, which are presented in chapter 5. With this research design, the aim was to conduct a study where it was possible to see how different parameters affected the TCO, and thereby achieve the purpose with this master's thesis.

3.3 Research methodology

A literature review is an important part when it comes to research, as it is important to see what is already known about the topic and what methods that has been applied earlier (Bryman & Bell 2015). This was also the reason why this thesis was initiated with a literature study, so the authors of this thesis could see what has been done and gather ideas on how to perform this thesis. The literature review was also used for input to the Excel tool that will be presented in 3.4.2. Moreover, findings from the literature review was also used to ensure that the aim and research questions was connected to existing literature. Which according to Bryman and Bell (2015) is important to demonstrating credibility of the research questions. Several sources were used, including both academic work and more commercial sources regarding buses, chargers and batteries. A great amount of the literature was gathered through Chalmers Library's search engine using keyword related to TCO and electric buses. Moreover, literature founded from the reference list of articles that was founded interesting was used. In addition to this, some of the literature was gathered through specialists that recommended some of the articles.

Since this master's thesis was carried out in collaboration with Scania CV AB, the feasibility of certain parts of the gathered literature was discussed and confirmed. Thus, in addition to the literature review, interviews were performed at Scania CV AB to confirm the findings from the literature review and to gather additional information. However, as the data from these interviews was not used in this master's thesis of confidentiality, nor the interview questions or values discussed during the interviews will be presented.

As mentioned in 3.1, the tool developed during the EAEB project, in this thesis called the EAEB tool was used to generate input to the TCO calculation. Before this starting to use this tool, the authors of this thesis visited RISE Viktoria AB in Gothenburg, and learned how the tool worked, and eventually were given access to its functions. The calculation model used in the EAEB tool contributed with important insights into what parameters that should be included, as the model, together with the literature review served as a basis for the Excel model developed in this thesis. It should also be mentioned that this tool was used during the simulations to produce the input, e.g. driving time, number of buses and number of chargers to the TCO analysis. The EAEB tool and the usage of it is described more in-depth in 3.4.1.

In addition to the literature review, supporting interviews, and the EAEB tool, an Excel tool was developed and used both to extract the simulation matrixes, i.e. charge time, charge effect, and battery sizes, but also to perform the TCO analysis. A more thorough description of the Excel tool can be found in 3.4.2, while the calculations used in the Excel tool is presented in chapter 4.

3.4 Simulations methodology

To be able to answer research question two to four, several simulations was performed as mentioned in 3.1. Even though the characteristics of the simulations differed, the same methodology was used. The simulations methodology is visualized in Figure 7.

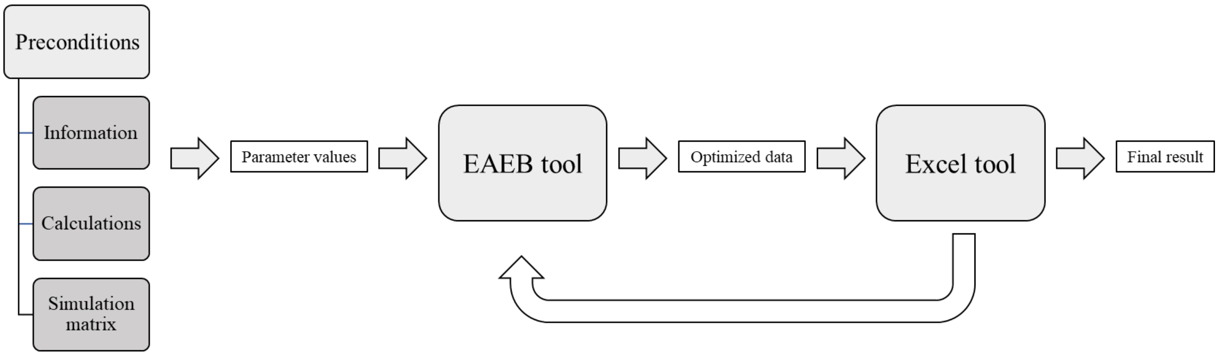


Figure 7 - Simulations methodology used in this master's thesis

The first part of the simulations methodology was to establish the preconditions for the simulation. This involved several steps and depending on the type of simulations, the extent of these step varied. The goal with part one was to create a simulation matrix containing information about what parameters that should be adjusted, the value of these parameters, how many runs that should be simulated and what parameter value that should be assigned to each run. An example of this is Table 15 that illustrates the simulation matrix used in simulation 3. The first step in the creation of the simulation matrixes was to gather information about what parameters that should be included in the simulation, and the data required to calculate the parameter values. The second step was to calculate the value of each parameter. This step was only necessary if the parameter values could not be extracted from the information gathered in step one. An example of this occurred in simulation 3, where the cycle life had to be converted into depreciation time, see subsection 5.2.4. The output from step one and two was then summarized in step three where a simulation matrix was created.

Two initial simulations were created based on the information collected from the literature review, interviews and preliminary simulations in the EAEB tool. The simulation matrix resulted in eight parameter values that should be tested, and consequently eight simulation runs in the EAEB tool had to be conducted on each of the four routes. The reason why eight datasets were used is because of the chosen charge time in simulation 1. The charge time goes from 10 to 3 minutes with an interval of 1 minute, resulting in eight parameter values and thus requiring eight simulation runs. The same number of runs was used in simulation 2 to achieve a uniform format. The process of creating and planning the simulations was iterative. Once the initial simulations were completed, new questions and information emerged, and therefore new simulations had to be constructed. Consequently, the Excel tool had to be further developed and new parameters and functions had to be added. The number of datasets that was used in each simulation varies due to the characteristics of each simulation, see section 5.2. Nevertheless, the same simulation methodology presented in Figure 7 was used.

As mentioned earlier, the EAEB tool constituted the input to the TCO calculations, and before the simulations that was used for the result in this thesis could be executed in the EAEB tool, a pilot was done. Here, the EAEB tool was pre-calibrated using the parameter values attained in part 1 of the research process. When the required values were set, the first simulation could be carried out by implementing the parameter values from the simulation matrix. Once the simulation was done, the result was examined and validated before it was used as an input to the Excel tool. The output of the EAEB tool consists of a list cost data, this output served as the input for the Excel tool. The Excel tool allowed for further manipulation of the output data from the EAEB tool, and it enabled the creation of the final result that is presented in chapter 6. Additionally, the tool contained various features that facilitated the visualization and analysis of the result.

Once the result from each simulation was visualized, the analysis of the result began, and notes of the findings were taken before the next simulation was executed. The purpose with the white arrow in Figure 7 is to demonstrate that the simulation methodology described in this chapter is an iterative process. The arrow illustrates that once a simulation run had been finished in the EAEB tool and the output implemented in the excel tool, the process had to be repeated for the other runs and on each of the four routes. Moreover, the result from the Excel tool sometimes indicated that some parameters had to be calibrated and thus the process had to be repeated once again. The white arrow in Figure 7 also indicates that the simulation matrixes extracted by the Excel tool was used in the EAEB tool.

3.4.1 EAEB tool

The EAEB tool was developed in the project "Energy transfer solutions for electrified bus systems" (EAEB 2018a). Some reasons why this tool was developed were to make it possible to compare different ways to design an electric bus system, and to calculate the costs of these systems in an easy way (EAEB 2018a). The EAEB tool is divided into three different parts, where the first two parts is used to configure the routes, chargers and bus schedule, while the last part demonstrates the costs associated with the chosen bus system. For an illustration of the graphical interface of the EAEB tool, see Appendix E – EAEB tool.

The first part of the tool is used to configure the preconditions for the bus system, including selection of routes and the technical conditions. Here, the user is given the option to selected where the chargers and depot should be located, and what the charge effect should be at each charge point respectively. When the route is selected, route information appears, including number of trips, length and trip duration. The EAEB tool contained a database over different routes located in Sweden. This database was used in this masters's thesis to select what routes that should be analyzed, and the decision was made based on the subroute data with the purpose to include a diverse set of routes with regards to the route characteristics.

When the preconditions are set in the first part of the tool, the next part is where the user decides what kind of buses that should be used and what time constraints they should operate under, including charge time and dwell time. Next, the user is given the option to either manually or automatically assign the trips to the buses. The tool can automatically calculate the required number of buses and assign the trips to optimize based on minimizing the total annual cost. Subsequently, the bus schedule appears, and one can follow the daily schedule of each bus. In this master's thesis, this optimization was used to get the number of buses needed, driving time, number of chargers and driving distance.

Part three in the tool contains the result, divided into investment expenditures and total annual cost. Here the user can configure the values of the cost parameters, and compare the total annual cost between different configurations, e.g. different routes, charging strategies or other changes. The investment cost in the EAEB tool is divided into three categories, i.e. vehicles, batteries and charging infrastructure. While the total annual cost is divided into six categories i.e. depreciation vehicles, depreciation batteries, depreciation charging infrastructure, insurance and maintenance, energy, and lastly drivers. However, these annual costs were not used directly in this master's thesis, instead an Excel tool was developed that used the previous mentioned optimized numbers, i.e. the number of buses needed, driving time, number of chargers and driving distance. Even if the EAEB tool was not used for the calculations of TCO, the authors of this master's thesis want to state that the EAEB tool was both useful to generate the input for the previous mentioned data, but also as an inspiration when the Excel tool was developed. Furthermore, the EAEB tool was used to do sanity checks of the Excel tool during the development to ensure the validity of the calculations.

3.4.2 Excel tool

The EAEB tool contributed with a model of how an electric bus system could be analyzed and it facilitated a way to simulate bus operations and export the data for other purposes. But due to the restrictions of this tool, one being the limited input for the vehicles, a separate Excel tool was developed. This allowed for a greater discretion in the manipulation of the input data and calculations, and more options to visualize and analyze the result. This also allowed some additional simulations and sensitivity analysis to be perform directly in the Excel tool. But, as mentioned earlier the optimized outputs from the EAEB tool was still utilized and served as an input for the excel tool, and thus constituting the base for the Excel tool.

Except for the TCO analysis, the Excel tool contains additional functions, e.g. for simulating battery degradation, and dimensioning of batteries and chargers. These functions made it possible to use the Excel tool when the simulation matrixes were extracted, e.g. the needed charging effect to charge the battery to the specified SOC in a specified time. Moreover, this tool calculated the battery size needed for each route and each strategy for the specified SOC. With the combination of the EAEB tool and the Excel tool, it was possible to create the simulation matrixes, run the simulations, calculate the TCO and visualize the findings.

This Excel tool was developed by using the calculations that are presented in chapter 4, where most of the calculations when gathered from the EAEB tool and the literature review. These two different methods of gathering useful calculations for the TCO calculation was used in combination to validate the Excel tool.

3.5 Quality criteria

When considering the quality of a study, the three most prominent criteria for evaluation a study within business and management are reliability, replication, and validity (Bryman & Bell 2015). Reliability here considering if the results from a study are repeatable, while replication considering if it is possible to replicate the study, and validity that considering the integrity of the conclusions that are generated from a study. During the whole master's thesis, these quality criteria was kept in mind to enhance the quality of the study.

The reliability of a study is particularly an issue in quantitative research according to Bryman and Bell (2015), and hence of importance in this master's thesis as the base for the analysis is quantitative. Reliability here considering the consistency of the measures, i.e. if the results from this master's thesis are repeatable. According to Pruzan (2016), consistency is necessary for internal validity, however consistency is not sufficient for reliability, as improper calibrating can lead to inaccurate measures and invalid conclusions. To enhance the reliability of this master's thesis, a literature study was performed to found parameters and costs used in previously studies and how these differed from each other. Furthermore, insights were gained from the EAEB project, where many professionals were involved, and costs and assumptions were also discussed with specialists at Scania CV AB.

According to Pruzan (2016), replication is important and unless other researcher cannot repeat the study and get the same result, the result will not be accepted by the scientific community. To be able to make it possible to replicate this master's thesis, the methodology was described in a way, so other researchers should be able to do the same study if wanted. Moreover, all equations, costs and assumptions that was used is presented in chapter 4, followed by chapter 5, where also the investigated routes are presented. However, to be able to replicate the bus schedule optimization it is necessary to have access to the tool from the EAEB that is not available for commercial use. Still, some of the input, e.g. time schedule and route data for different bus routes in Sweden is public available in GFTS-format (Trafiklab n.d.).

When it comes to the validity of a research, this can be divided into measurement validity, internal validity, external validity and ecological validity (Bryman & Bell 2015). In this master's thesis the main focus was on the measurement validity, internal validity and external validity. Measurement validity refers to whether or not a measurement really does reflect to the concept it is supposed to measure (Bryman & Bell 2015). Here, the main purpose was to achieve a greater understanding of opportunity charging and overnight charging when it comes to the TCO, hence the main measurement was TCO. However, TCO can be defined in different ways, e.g. cost per hour or cost per km, and the TCO can also include different costs from one case to another. Internal validity refers mainly to the issue of causality, when two or more variables is involved (Bryman & Bell 2015). In this master's thesis, many different parameters were involved as the system for electric buses is a complex system to analyze. To enhance the internal validity, the TCO was divided into different cost categories and an investigation was performed to see how these changed for different operating conditions and what operating conditions that affected what costs and in what way. According to Bryman and Bell (2015), external validity refers to whether the results of a study can be generalized to other research context. And according to Pruzan (2016), external validity is whether a relationship behind the independent and dependent variables holds, independent of the context. Here, the TCO analysis was performed for four different routes to enhance the external validity.

A further discussion of the methodology used in this master's thesis and how it affected the quality of the master's thesis will be discussed in section 7.2, while ethical considerations will be presented in the next section.

3.6 Ethical considerations

There are four main ethical principles to follow when a study is performed according to Bryman and Bell (2015), i.e. harm to participants, lack of informed consent, invasion of privacy and deception. And according to Pruzan (2016), unethical research is when there is harm to sentient beings and to the environment, lack of informed consent and invasion of privacy, or deception and coercion.

The participants in this study were mainly industry professionals and researchers in the field of electric buses, that were asked questions during the study to enhance the knowledge needed for the authors to complete this master's thesis, and to validate parameters and results. As the information gathered from these meetings was not used in this report, and all participants remain anonymous for ethical reasons. Moreover, all of these participants were informed in advance about the master's thesis, and that it was conducted in collaboration with Scania CV AB to mitigate lack of informed consent.

As this master's thesis was performed in a collaboration with Scania CV AB it was of great importance to not disclose any secret information. Hence, input values for the TCO analysis was taken from the literature and other previous projects.

Except previous mentioned ethical considerations, affiliation and conflicts of interest was also considered during this study. According to Bryman and Bell (2015), it is recognized in all areas of scientific study that affiliation have the power to influence research issues and how the findings from a study is presented. As this study was performed in cooperation with Scania CV AB, it is possible that this could have influenced the study. However, the intention from both the authors of this master's thesis and Scania CV AB was do a fair comparison, and to achieve a greater understanding of opportunity charging and overnight charging, when it comes to the TCO.

4 Calculations, parameters and costs

This chapter will introduce the calculations that was used to calculate the TCO in this thesis. Moreover, the aim with this chapter is to answer the first research question:

RQ 1 – What parameters to include in the TCO calculation for an electric bus system?

The first section, 4.1, will cover the economical calculations, 4.2 will present the used energy model, while assumptions and costs for the simulations will be presented in 4.3.

4.1 Total Cost of Ownership Calculations

To calculate the total annual cost, equation (14) was used. This calculation takes the annualized investment costs (Annual cost of depreciation), described in 4.1.1 into consideration, but also the annual operating costs described in 4.1.2.

$$TCO_{annual} = C_{annual\ depreciation} + C_{annual\ operation} \tag{14}$$

Furthermore, in line with most of the literature the total annual costs were divided by the annual number of operating km as presented in (15). Where TCO_{km} is the total cost per km, the equation also includes the annual operating distance ($D_{service\ annual}$), i.e. the total distance the buses are in service, and the total annual cost. The reason why this distance was used and not the total distance was because it is a fair number to use, as the total driving distance will give a lower total cost per km for alternatives that drives more km due to e.g. a longer distance to the depot.

$$TCO_{km} = \frac{TCO_{annual}}{D_{service\ annual}} \tag{15}$$

According to Lajunen (2018), the cost per distance may not present the life cycle cost of city buses well. Hence, to complement the total cost per km, the total cost per hour which is presented in equation (16) was used.

$$TCO_{h} = \frac{TCO_{annual}}{T_{service\ annual}} \tag{16}$$

4.1.1 Annual costs of depreciation

The annual costs of depreciation consisted of three different depreciation costs that are presented in (17), i.e. the depreciation cost for buses ($C_{dep\ vehicles}$), the depreciation cost for batteries ($C_{dep\ batteries}$), and the depreciation cost for charging infrastructure ($C_{dep\ infrastructure}$).

$$C_{annual\ depreciation} = C_{dep\ vechicles} + C_{dep\ batteries} + C_{dep\ infrastructure} \tag{17}$$

According to Berk and DeMarzo (2014), the annuity of a loan can be calculated with (18), where C is the annual payment, P the principal, r is the interest rate, and N is the number of equal periodic payments. This is also the same equation as equation (7) that was used by Olsson, Grauers and Pettersson (2016).

$$C = \frac{P}{\frac{1}{r} - \left(\frac{1}{(1+r)^{N}}\right)} \tag{18}$$

Equation (18) was also used in this thesis to calculate the annual costs of depreciation for vehicles, batteries and charging infrastructure. In this thesis, C was the annual cost of depreciation, P was the present value of the investment, r the interest rate and N the depreciation time. Annual depreciation cost for the buses was calculated with (19), that includes the present value of the bus investment ($PV_{vehicle\ investment}$), that is the purchase cost of the buses, interest rate (r), and the depreciation time for the buses ($N_{vehicles}$).

$$C_{dep\ vehicles} = \frac{PV_{vechicle\ investment}}{\frac{1}{r} - \left(\frac{1}{(1+r)^{N_{vechicles}}}\right)} \tag{19}$$

The present value for the buses was calculated with (20), where C_{bus} is the purchase price for one bus and N_{buses} is the number of buses needed for the investigated route. Important to note here is that the number of buses was an outcome from the tool developed in the EAEB project.

$$PV_{vechicle\ investment} = C_{bus} \cdot N_{buses} \tag{20}$$

The second depreciation cost in this thesis was the depreciation cost associated with batteries, and this cost was calculated in the same way as for the buses. However, there was a different present value and another depreciation time, so the used equation is presented in (21), that included the battery purchase price ($PV_{battery\ investment}$), interest rate (r), and the depreciation time for the batteries ($N_{batteries}$).

$$C_{dep\ batteries} = \frac{PV_{battery\ investment}}{\frac{1}{r} - \left(\frac{1}{(1+r)^{N_{batteries}}}\right)} \tag{21}$$

The present value of the battery investment was calculated with (22), that includes battery purchase price per kWh $\left(C_{battery\ per\ kWh}\right)$, and the total dimension for all batteries needed in the bus fleet ($E_{total\ batteries\ kWh}$). The equation for the last-mentioned parameter is derived and presented in 4.2.

$$PV_{battery\ investment} = C_{battery\ per\ kWh} \cdot E_{total\ batteries\ kWh} \tag{22}$$

To complete the calculations of the depreciation costs, the depreciation cost for the charging infrastructure was calculated with (23), that included the charging infrastructure purchase and installation price $\left(PV_{infrastructure\ investment}\right)$, interest rate ($r$), and the charging infrastructure depreciation time ($N_{infrastructure}$).

$$C_{dep\ infrastructure} = \frac{PV_{infrastructure\ investment}}{\frac{1}{r} - \left(\frac{1}{(1+r)^{N_{infrastructure}}}\right)} \tag{23}$$

The present value of the infrastructure investment was divided into three different parts, i.e. the investment cost for chargers ($C_{chargers}$), investment cost for grid connections $\left(C_{grid\ connections}\right)$, and the cost for cable installations ($C_{cable\ installation}$), as presented in equation (24).

$$PV_{infrastructure\ investment} = C_{chargers} + C_{grid\ connections} + C_{cable\ installation} \tag{24}$$

To get the investment cost for chargers, equation (25) was used. This calculation included purchase price for charger per kW $(C_{charger\ per\ kW})$, and the total charge effect needed for the investigated route $(P_{total\ kW})$. The total charge effect needed will be derived in 4.2.

$$C_{chargers} = C_{charger\ per\ kW} \cdot P_{total\ kW} \tag{25}$$

In addition to the investment cost for the chargers, also the costs associated with grid connections was considered. In this thesis, two different costs were considered and those are presented in (26). The total cost for transformers consisted of the price for one transformer $(C_{transformer})$ and the number of needed transformers $(N_{transformers})$, while the total cost for substations consisted of the price for one substation $(C_{substations})$ and the number of needed substations $(N_{substations})$.

$$C_{grid\ connections} = C_{transformer} \cdot N_{transformers} + C_{substation} \cdot N_{substations} \tag{26}$$

The last part of investment cost for the charging infrastructure was the cost of cable installation, presented in (27). This cost included the cable installation cost per m in urban dense areas $(C_{urban\ d})$, length of cable in urban dense areas $(L_{urban\ d})$, cable installation cost per m in urban sparse areas $(C_{urban\ s})$, length of cable in urban sparse areas $(L_{urban\ s})$, cable installation cost per m in rural areas (C_{rural}), and length of cable in rural areas (L_{rural}).

$$C_{cable\ installation} = C_{urban\ d} \cdot L_{urban\ d} + C_{urban\ s} \cdot L_{urban\ s} + C_{rural} \cdot L_{rural} \tag{27}$$

4.1.2 Annual operating costs

The equation for total annual operating cost used in this thesis, $(C_{annual\ operation})$, is presented in (28). The total annual operating cost included the annual cost for maintenance and insurance for buses $(C_{annual\ M\&I\ vehicles})$, annual maintenance cost for the charging infrastructure $(C_{annual\ maintenance\ infrastructure})$, annual driver cost $(C_{annual\ drivers})$, annual energy cost $(C_{annual\ energy})$, and the annual cost for HVO heating $(C_{annual\ HVO})$.

$$\begin{aligned} C_{annual\ operation} = C_{annual\ M\&I\ vechicles} + C_{annual\ maintenance\ infrastructure} + \\ + C_{annual\ drivers} + C_{annual\ energy} \end{aligned} \tag{28}$$

For annual maintenance and insurance costs related to buses, three different types of costs were included according to (28). These were annual costs for vehicle insurance $(C_{annual\ insurance})$, the annual costs for maintenance of vehicles $(C_{annual\ maintenance\ vechicles})$, and the annual cost of tires $(C_{annual\ tires})$.

$$C_{annual\ M\&I\ vehicles} = C_{annual\ insurance} + C_{annual\ maintenanc\ vehicles} + C_{annual\ tires} \tag{29}$$

To calculate the annual cost for vehicle insurance equation (29) was used, which included the annual insurance cost for one bus $(C_{insurance\ per\ bus\ per\ yr})$, and the number of buses (N_{buses}).

$$C_{annual\ insurance} = C_{insurance\ per\ bus\ per\ yr} \cdot N_{buses} \tag{30}$$

The annual costs for maintenance of buses was based on (31), that included the total daily travel distance ($D_{total\ daily\ km}$), number of travel days per year ($N_{days\ per\ yr}$), and maintenance cost per km ($C_{maintenance\ per\ km}$). Here, the total daily distance includes both the distance when the buses are in service and travel to and from the depot, since all driving affects the need for maintenance.

$$C_{annual\ maintentance\ vehicles} = D_{total\ daily\ km} \cdot N_{days\ per\ yr} \cdot C_{maintenance\ per\ km} \tag{31}$$

In addition to the two earlier costs included in the annual maintenance and insurance costs related to the buses, also the cost for tires was added, according to (32). Here the same total daily distance and number of travel day per year is used as in (31). Moreover, the cost per tire (C_{tire}), tire lifespan ($D_{life\ time\ km}$), and the number of tires per bus ($N_{tires\ per\ bus}$), are included to calculate the annual tire cost for the whole fleet.

$$C_{annual\ tires} = \frac{C_{tire} \cdot D_{total\ daily\ km} \cdot N_{days\ per\ yr}}{D_{life\ time\ km}} \cdot N_{tires\ per\ bus} \tag{32}$$

Furthermore, the maintenance cost for charging infrastructure was included. Most of the articles, e.g. Bi, Kleine and Keoleian (2016), Lajunen (2018), and Olsson, Grauers and Pettersson (2016), in the literature review chose to calculate this maintenance cost as an annual percentage of the initial investment cost, see Table 5. In this master's thesis, the same method was used and the equation is presented in (33).This equation includes the initial cost for the infrastructure investment, presented in (24), but also the annual percentage of maintenance costs ($r_{maintenance\ infrastructure}$).

$$C_{annual\ maintenance\ infrastructure} = PV_{investment\ infrastructure} \cdot r_{maintenance\ infrastructure} \tag{33}$$

Most of the articles found in the literature review did not take the labor cost for drivers into consideration, with the assumption that this will be consistent between different powertrains and charging strategies. However, Olsson, Grauers and Pettersson (2016) argued that this can affect the decision. With this argument as background, and as the tool developed in the EAEB project was used for some of the input to the calculations, where it is possible to get the annual number of driver time, the labor cost for drivers was taken into consideration by using (34). This included the annual driver time ($T_{annual\ driving\ hrs}$), driver utilization ($r_{driver\ utilisation}$), and the hourly cost for a driver ($C_{driver\ per\ hr}$).

$$C_{annual\ drivers} = \frac{T_{annual\ driving\ hrs}}{r_{driver\ utilisation}} \cdot C_{driver\ per\ hr} \tag{34}$$

When it comes to energy costs, four different equation was used as presented in (35), i.e. for the annual fee, power fee, variable fee and consumption fee to get the total annual energy cost. These are the same costs that was included in the EAEB project, aside a subscription fee that was assumed to be negligible in this thesis. Moreover, these energy costs were divided into two different cost categories depending on if the sum of the charging infrastructure was under or over 1 MW.

$$C_{annual\ energy} = C_{annual\ energy\ fee} + C_{power\ fee} + C_{annual\ variable\ energy\ fee} + \\ + C_{annual\ energy\ consumption} + C_{annual\ HVO} \tag{35}$$

The annual fee was calculated with (36), that included the annual cost for each connection to the grid ($C_{annual\ energy\ fee\ per\ connection}$), and the total number of grid connections ($N_{grid\ connections}$).

$$C_{annual\ energy\ fee} = C_{annual\ energy\ fee\ per\ connection} \cdot N_{grid\ connections} \tag{36}$$

For energy related costs, also the power fee was taken into consideration. This fee was calculated with (37), where the usage rate of the chargers ($r_{usage\ chargers}$), was included to make it possible to calculate the averaged used charging effect per hour.

$$C_{power\ fee} = P_{total\ kW} \cdot r_{usage\ chargers} \tag{37}$$

The variable energy fee presented in (38) and the energy consumption fee presented in (39) was calculated in a similar way, as both of these are related to the energy consumption. These two calculations included the average consumption per km ($AVG_{\Delta E\ km}$), the charger efficiency ($\eta_{charger}$), daily distance, number of travel days per year and the cost per kWh. However, the last-mentioned cost differs between the variable fee and the consumption fee. For the variable fee, the variable cost per kWh ($C_{variable\ fee\ per\ kWh}$), was used, and for the consumption fee, the consumption fee per kWh ($C_{consumption\ fee\ per\ kWh}$), was used.

$$C_{annual\ variable\ energy\ fee} = \frac{AVG_{\Delta E\ km}}{\eta_{charger}} \cdot D_{daily\ km} \cdot N_{days\ per\ yr} \cdot C_{variable\ fee\ per\ kWh} \tag{38}$$

$$C_{annual\ energy\ consumption} = \frac{AVG_{\Delta E\ km}}{\eta_{charger}} \cdot D_{daily\ km} \cdot N_{days\ per\ yr} \cdot C_{consumption\ fee\ per\ kWh} \tag{39}$$

All buses in this master’s thesis was assumed to have HVO heating, and therefore the annual cost for this was calculated with (40), that included the HVO cost per liter ($C_{HVO\ per\ l}$), and the HVO consumption in liter per km ($L_{HVO\ per\ km}$).

$$C_{annual\ HVO} = C_{HVO\ per\ l} \cdot L_{HVO\ per\ km} \cdot D_{daily\ km} \cdot N_{days\ per\ yr} \tag{40}$$

4.2 Energy model

In this master’s thesis, the energy model developed during the EAEB project was used. The same model was used twice for each route, as both subroutes did not have the same energy consumption. In this model, the EAEB project included the energy consumption constant (Cs_{dim}), driving distance (Δs), auxiliary power ($Paux_{dim}$), driving time (Δt), bus operating weight (M_{dim}), local gravitational field (g), elevation gain (Δh_{gain}), electric efficiency (η), and elevation loss (Δh_{loss}). The energy consumption in this master’s thesis for subroute 1 ($sr1$) and subroute 2 ($sr2$), the energy consumption for each of these subroutes was calculated with (41) and (42).

$$\Delta E_{sr1} = Cs_{dim} \cdot \Delta s_{sr1} + Paux_{dim} \cdot \Delta t_{sr1} + \frac{M_{dim} \cdot g \cdot \Delta h_{gain\ sr1}}{\eta} + M_{dim} \cdot g \cdot \Delta h_{loss\ sr1} \cdot \eta \tag{41}$$

$$\Delta E_{sr2} = Cs_{dim} \cdot \Delta s_{sr2} + Paux_{dim} \cdot \Delta t_{sr2} + \frac{M_{dim} \cdot g \cdot \Delta h_{gain\ sr2}}{\eta} + M_{dim} \cdot g \cdot \Delta h_{loss\ sr2} \cdot \eta \tag{42}$$

To calculate the average consumption per km, equation (43) was used, which consist of the energy consumption for the first subroute (41), and for the second subroute (42). To get the average cost per km, this calculation also included the distance for each subroute (Δs_{sr1} , Δs_{sr2}).

$$AVG_{\Delta E\ km} = \frac{\Delta E_{sr1}}{2 \cdot \Delta s_{sr1}} + \frac{\Delta E_{sr2}}{2 \cdot \Delta s_{sr2}} \tag{43}$$

The battery dimensioning was done in several ways, depending on charging strategy, but also if the dimensioning should be theoretical, i.e. the exactly calculated or if the dimensioning should be a battery dimension that exists on the market today. For those simulations where nothing else is stated, the used dimensions are the theoretical dimensions. For opportunity charging, the battery dimension per bus ($E_{opp\ per\ bus\ kWh}$), was calculated with (44), including the safety factor (F_{safety}), the maximum energy consumption, i.e. the energy consumption from the subroute with highest energy consumption, $MAX(\Delta E_{sr1}, \Delta E_{sr2})$, and SOC window. The safety factor here means how many trips you can drive without charging and still be in the allowed SOC window. So, if the safety factor is 1, drivers cannot miss a charge and still be in the allowed SOC window, but if the safety factor is 2, drivers can miss one charging point.

$$E_{opp\ per\ bus\ kWh} = F_{safety} \cdot \frac{MAX(\Delta E_{sr1}, \Delta E_{sr2})}{SOC_{window}} \tag{44}$$

To get the battery dimension for the whole opportunity charged fleet ($E_{total\ opp\ batteries\ kWh}$), to be able to calculate the total investment costs for batteries, equation (45) was used.

$$E_{total\ opp\ batteries\ kWh} = E_{opp\ per\ bus\ kWh} \cdot N_{buses} \tag{45}$$

For overnight charging, there were also several different alternatives on how to calculate the battery dimension. On the same way as for opportunity charge, the battery dimension was either the theoretical dimension or the nearest dimension existing on the market today. Also, for overnight charging, if nothing else is stated, the used dimensions are the theoretical dimension. However, in in the case with overnight charging, the battery dimension need to be large enough to handle all the trips the bus is supposed to drive before charging, from the start of the day to the end of the day. The battery dimension per bus ($E_{on\ per\ bus\ kWh}$), was calculated with (46), that includes the total driving distance for one bus during one day ($D_{max\ per\ bus\ per\ day}$).

$$E_{on\ per\ bus\ kWh} = D_{max\ per\ bus\ per\ day} \cdot \frac{\Delta E_{sr1} + \Delta E_{sr2}}{2 \cdot SOC_{window}} \tag{46}$$

The total battery dimension for the whole fleet with overnight charged buses, independent on if there was a complementary charging or not, was then calculated with (47), and used for the battery investment cost.

$$E_{total\ on\ batteries\ kWh} = E_{on\ per\ bus\ kWh} \cdot N_{buses} \tag{47}$$

The energy model, which equations was presented in (41) and (42) was also used to do the dimensioning of chargers. In the same way as for the batteries, also this dimensioning was done either by the theoretical value, i.e. the necessary charger effect to fill up the battery with the same amount as the energy consumption was for the subroute before the charging point, or by using charger effects that exists on the market today. If nothing else is stated, the charger was dimensioned by the theoretical needed charge effect. The equation used for the calculation of charge effect at position one, i.e. the start position for the first subroute is presented in (48), and consists of the consumed energy on subroute 2, the charger efficiency ($\eta_{charger}$), and the charge time at position 1 ($T_{charge\ pos\ 1}$).

$$P_{opp\ chargers\ pos\ 1} = \frac{\Delta E_{sr2}}{\eta_{charger} \cdot T_{charge\ pos\ 1}} \tag{48}$$

The same procedure is used for the charge effect at position 2 ($P_{opp\ chargers\ pos\ 2}$) and is presented in (49). What differs here is that the energy consumption now is from subroute 1, and the charge time is for position 2 ($T_{charge\ pos\ 2}$).

$$P_{opp\ chargers\ pos\ 2} = \frac{\Delta E_{sr1}}{\eta_{charger} \cdot T_{charge\ pos\ 2}} \tag{49}$$

In addition to the charger effect, also the number of chargers was taken into consideration, and here the tool from the EAEB project was used to see when there was a need for a second charger at one, or both of the end stations. Furthermore, also with the opportunity charged system it was assumed that depot charging was used, but only during the night. The total charger effect for the opportunity chargers, that was used to calculate the investment cost for chargers is presented in (50).

$$P_{total\ kW} = P_{opp\ chargers\ pos\ 1} \cdot N_{opp\ chargers\ pos\ 1} + P_{opp\ chargers\ pos\ 2} \cdot \\ \cdot N_{opp\ chargers\ pos\ 2} + P_{depot\ per\ bus} \cdot N_{buses} \tag{50}$$

Equation (50) was also used to calculate the total charger effect for the case with only overnight charged buses, however, in that case the effect at both charge point is zero. The depot chargers were dimensioned according to (51), for both overnight charging and opportunity charging. This calculation includes the energy consumed since the last charge ($\Delta E_{since\ last\ charge}$), the charger efficiency ($\eta_{charger}$), and charging time in the depot ($T_{charge\ depot}$).

$$P_{depot\ per\ bus} = \frac{\Delta E_{since\ last\ charge}}{\eta_{charger} \cdot T_{charge\ depot}} \tag{51}$$

4.3 Costs and assumptions

This section will present the values used for costs and assumptions in this master's thesis. Important to notice is that in some of the simulations, these values were changes between the runs. And there was also sensitivity analysis made, where different costs were changed. However, if nothing else is stated, the values presented in this section was used. As mentioned before, some costs were converted using the average rate for between \$ and € for year 2016 and 2018. Moreover, costs found from the EAEB project was converted from SEK to € by using the average exchange rate between 2019-01-01 and 2019-08-31 by Sveriges Riksbank (2018). To strengthen the validity of the used costs and assumption, these were also discussed with specialists at Scania. The input data used for investment costs are presented in Table 7.

Table 7 - Input data for investment costs

	Abbreviation	Value	Note
Bus 12 m without battery	C_{bus}	€ 350 000 / bus	Lajunen (2018)
High-power battery	$C_{battery\ per\ kWh\ power}$	€ 950 / kWh	Average*
High-energy battery	$C_{battery\ per\ kWh\ energy}$	€ 540 / kWh	Olsson et al. (2016)
Opportunity charger	$C_{charger\ per\ kW\ opportunity}$	€ 900 / kW	Average**
Overnight charger	$C_{charger\ per\ kW\ depot}$	€ 450 / kW	50 % of Opportunity
Grid connection transformer	$C_{transformer}$	€ 97 705 / transfomer	EAEB (2018b)
Grid connection substation	$C_{substation}$	€ 195 411 / substation	EAEB (2018b)
Cable installation urban dense	$C_{urban\ d}$	€ 205 / m	EAEB (2018b)
Cable installation urban sparse	$C_{urban\ s}$	€ 107 / m	EAEB (2018b)
Cable installation rural	C_{rural}	€ 59 / m	EAEB (2018b)
Depreciation time bus	$N_{vechicles}$	10 yrs	Olsson et al. (2016)
Depreciation time chargers	$N_{infrastructure}$	15 yrs	Assumption
Depreciation time batteries	$N_{battery\ investment}$	8 yrs	Transport & Environment (2018)
Interest rate	r	4 %	Transport & Environment (2018)

*) Approximation of the average found in the literature review, **) Average of Lajunen (2018) and Olsson et al. (2016)

In addition to the input for investment costs presented in Table 9, the data input presented in Table 10 were used for operating costs.

Table 8 - Input data for operating costs

	Abbreviation	Value	Note
Driver cost	$C_{driver\ per\ hr}$	€ 35 / h	Olsson et al. (2016)
Maintenance vehicles	$C_{maintenance\ per\ km}$	€ 0,2 / km	Lajunen (2018)
Insurance vehicles	$C_{insurance\ per\ bus\ per\ yr}$	€ 3 908 / yr	EAEB (2018b)
Tires	C_{tire}	€ 391 / tire	EAEB (2018b)
Maintenance chargers	$r_{maintenance\ infrastructure}$	2,5 % of initial investment per yr	Average*
Annual energy fee	$C_{annual\ energy\ fee}$	€ 520 or € 930**	Olsson et al. (2016)
Power fee	$C_{power\ fee}$	€ 48 / kW or € 40 / kW**	EAEB (2018b)
Variable energy fee	$C_{variable\ fee\ per\ kWh}$	€ 0,0068 / kWh or € 0,0031 / kWh**	Olsson et al. (2016)
Consumption cost	$C_{consumption\ per\ kWh}$	€ 0,0733 / kWh	EAEB (2018b)
Usage rate of chargers	$r_{usage\ charger}$	60 % or 40 %***	Assumption
Charger efficiency	$\eta_{charger}$	90 % or 95 %***	Assumption
HVO for heating	$C_{HVO\ per\ l}$	€ 0,97 / l	Olsson et al. (2016)

*) Average of Olsson et al. (2016) and Lajunen (2018), **) Installation under or over 1 MW, ***) Opportunity or Overnight

Data presented in Table 9 was used as input to the energy model. The vehicle weight for opportunity charging was taken from the literature and an assumption that 2 000 kg will be added to the overnight charged bus. This value is based on the assumption that 260 kWh will be needed and the battery specific energy from Bi, Kleine and Keoleian (2016). The consumption constant was set so that opportunity charged buses all four routes got a consumption that was in line with consumptions presented in the theoretical framework. A sanity check was also done several times at different values for the auxiliary power to ensure the validity of the energy model. Overnight charged buses has on average a consumption that is 10 % higher than an opportunity charged bus (Lajunen 2018), hence the consumption constant for overnight charges buses was set according to that.

Table 9 - Energy model input

	Abbreviation	Oppurtunity	Overnight	Notes
Vehicle weight*	M_{dim}	16 000 kg	18 000 kg	Literature + calculation
Consumption constant	Cs_{dim}	0,50 kWh/km	0,60 kWh/km	Iterated values
Auxilary power	P_{aux}	6 kW	6 kW	Lajunen (2018)
Efficiency**	η	72%	72%	EAEB (2018b)
HVO consumption	$L_{HVO\ per\ km}$	0,03 l/km	0,03 l/km	EAEB (2018b)

*) Total, including batteries and passengers, **) From battery to wheels

Other assumptions made in this master's thesis was that buses, including batteries and also charging infrastructure was assumed to be route specific, hence the whole cost for these are considered in the TCO for each route. Moreover, the same input was used for all routes, i.e. all routes was assumed to be located in the same geographical area.

Furthermore, no discounting was done of the annual costs in this master's thesis. Instead the investment cost was annualized to an annual cost of depreciation, corresponding the yearly payment of a loan with a 4 % interest. The contract life was assumed to 10 years, i.e. the same as the depreciation time for the buses that was assumed to have zero residual value after this period. The residual value was assumed to be zero at the end of the depreciation time also for batteries and charging infrastructure. For the batteries, an assumption was done that a battery change was needed when the depreciation time was passed, which implies a battery replacement after 8 years.

It was also assumed that all the investigated routes could be operated with a 12 m electric bus, and that the battery size for all routes did not affected the possibility to manage the passenger capacity needed. Another assumption associated with the buses was that batteries for opportunity charging was assumed to manage the charging power needed to charge the battery to 80 % SOC in 3 min, and still have a life time of 8 years. Furthermore, the sizes of batteries and chargers was assumed to be able to be purchased in the theoretical needed sizes calculated with the equations presented earlier in this chapter.

5 Presentation of routes and simulations

The following chapter will start with a presentation of the routes that was included in this master's thesis, followed by a description of the different simulations that was performed.

5.1 Routes

Four different routes were chosen to be included in the simulations, and these four routes were chosen as they differ when it comes to the number of stops, trip length, trip duration, trip frequency, elevation gain and the total number of trips per day. Currently, none of these four routes are electrified, but Route 1 and Route 2 were included in the study by Karlsson (2016). However, the main focus in that study was on the grid connection, and many of the costs presented in chapter 4 was excluded. Maps of the four routes are presented in Figure 8, while information about each route is presented in the next four sections. In Figure 8, Route 1 is marked in green, Route 2 in blue, Route 3 in red, and Route 4 in yellow.

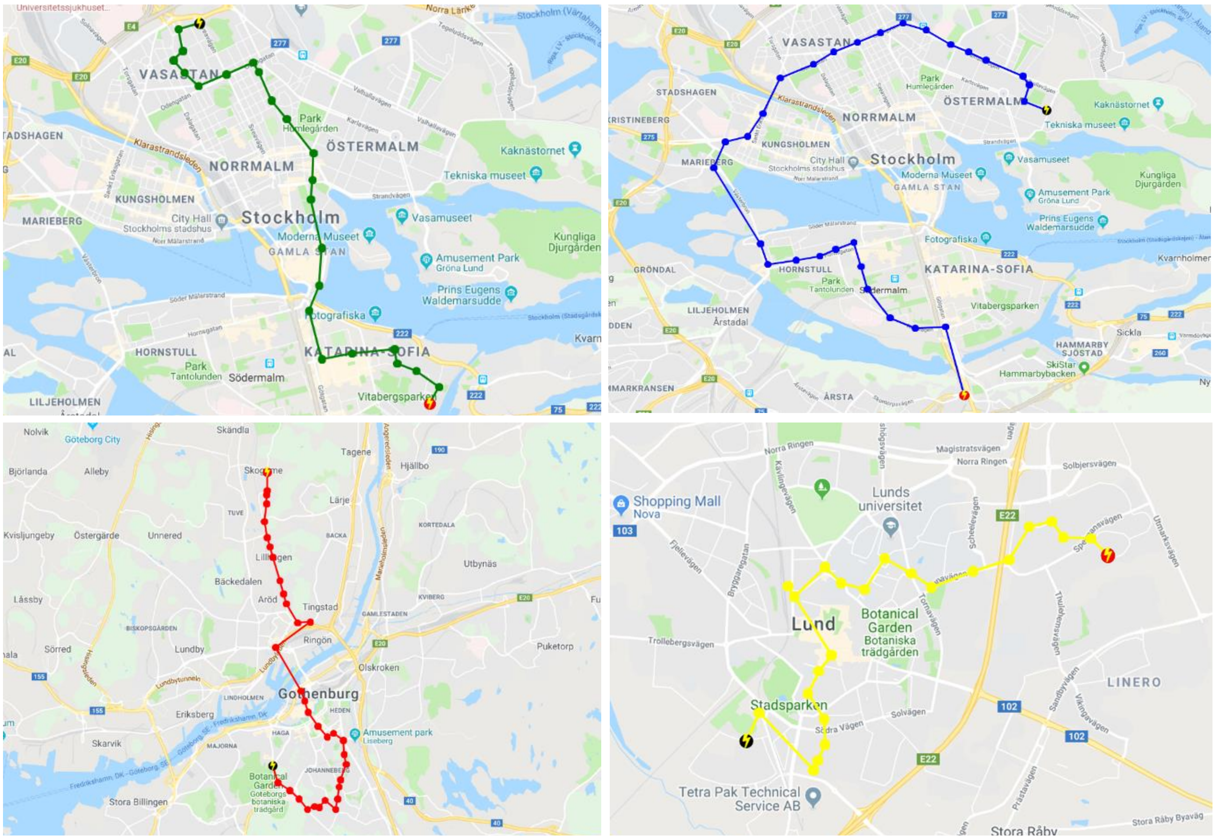


Figure 8 – Upper left: Route 1, Upper right: Route 2, Lower left: Route 3, Lower right: Route 4

5.1.1 Route 1

Route 1 is located in Stockholm city, administered by the agency Storstockholms Lokaltrafik and its official name is SL 2. The route has a length between 7257 to 7322 m and begins at and has its end-stop at Sveaplan. The route has a total of 23 to 24 stops depending on the direction of travel, and the trip time varies between 27 and 49 minutes, see Table 10. The depot is located south of Barnängen, in Fredriksdal. Route 1 is the shortest route, with an intermediate trip duration, high trip frequency and a high total number of daily trips, compared to the other routes in this thesis.

Table 10 - Subroute data for Route 1

Subroute details	Barnängen - Sveaplan	Sveaplan - Barnängen
Agency	SL	SL
Route name	2	2
No.stops	24	23
Length	7 322 m	7 257 m
Duration min	0:27:00	0:27:00
Duration max	0:48:00	0:49:00
Frequency	6-7 min	6-7 min
Cumulative elevation gain	69 m	63 m
Cumulative elevation loss	-63 m	-69 m
Tot.no trips/day	154	160

5.1.2 Route 2

The second route used in this thesis is SL 4 in Stockholm with end-stops in Gullmarsplan T-bana and Radiohuset. The route has a length of 11 643 to 11 753 m and 30 to 31 stops with a trip time between 35 and 59 minutes, for more details, see Table 11. The depot is located in Fredriksdal close to the end-top Barnängen. Compared to the other routes, Route 2 has an intermediate length, long trip duration, highest total number of daily trips and a high trip frequency.

Table 11- Subroute data for Route 2

Subroute details	Gullmarsplan T-bana - Radiohuset	Radiohuset - Gullmarsplan T-bana
Agency	SL	SL
Route name	4	4
No.stops	30	31
Length	11 753 m	11 643 m
Duration min	0:36:00	0:35:00
Duration max	0:56:00	0:59:00
Frequency	6-7 min	6-7 min
Cumulative elevation gain	42 m	64 m
Cumulative elevation loss	-64 m	-42 m
Tot.no trips/day	195	197

5.1.3 Route 3

The third route is located in Gothenburg, administered by Västtrafik and with end-stops at Linnéplatsen and Skogome. Route 3 is longest of the four routes, with a length of 14 410 to 14 489 m and a duration between 42 and 56 minutes, for more details see Table 12. Route 3 has an intermediate number of total trips per day, intermediate trip frequency and a long trip duration. The depot is located west of Lillhagen, close to the end-stop Skogome.

Table 12- Subroute data for Route 3

Subroute details	Göteborg Linnéplatsen - Skogome	Skogome - Göteborg Linnéplatsen
Agency	Västtrafik	Västtrafik
Route name	52	52
No.stops	35	34
Length	14 489 m	14 410
Duration min	0:42:00	0:42:00
Duration max	0:54:00	0:56:00
Frequency	10 min	10 min
Cumulative elevation gain	134 m	115 m
Cumulative elevation loss	-115 m	-134 m
Tot.no trips/day	99	99

5.1.4 Route 4

The fourth route is located in Lund and administrated by Skånetrafiken. The total number of trips is between 65 and 66, with a length of 7405 to 8215m and a duration between 29 and 39 min. This route was selected to demonstrate how the reduced charge time effects an operating schedule with a low number of daily trips and with a low trip frequency of 15 min, for more details, see Table 13. The route starts at Flygelvägen and ends at Klostergårdens Centrum. The depot is located at Maskinvägen, close to Klostergårdens Centrum.

Table 13 - Subroute data for Route 4

Subroute details	Flygelvägen - Klostergårdens Centrum	Klostergårdens Centrum - Flygelvägen
Agency	Skånetrafiken	Skånetrafiken
Route name	1	1
No.stops	24	31
Length	7 405 m	8 215 m
Duration min	0:29:00	0:30:00
Duration max	0:36:00	0:39:00
Frequency	15 min	15 min
Cumulative elevation gain	18 m	72 m
Cumulative elevation loss	- 61 m	- 29 m
Tot.no trips/day	65	66

5.1.5 Route summary

To facilitate the comparison of the routes, a summary of the route characteristics on each route is presented in Table 14. The routes are ranked relative to each other on four different dimensions, Trip length, Trip duration, Trip frequency and Trips per day. These dimensions characterize the operating conditions on the route. The values for the energy consumption can be found in 6.1, and the rest of the data can be found in the Subroute data table for each route. Three different levels are used, Low, Intermediate and High, and since some of the routes have similar characteristics, they share the same level.

Route 1 has a trip length of 14 400 m, Route 2 a trip length of 11 700 m and Route 1 and Route 4 has a trip length of 7 300 m and 8000 m. Since Route 1 has the highest trip length, it receives the level High, being the shortest, Route 1 and Route 4 are ranked low. With a trip length of 11 700 m, Route 2 has a moderate length relative to the other routes and is ranked Intermediate. The same logic follows for the rest of the characteristics. The total number of trips per day for route 1-4 was approximately 160, 200, 100, and 65. Since no distinct intermediate level could be distinguished, Route 1 was ranked Intermediate/high and Route 3 was ranked Low/intermediate.

Table 14 - Route characteristics

Characteristics	Route 1	Route 2	Route 3	Route 4
Trip length	Low	Intermediate	High	Low
Trip duration	Intermediate	High	High	Low
Trip frequency	High	High	Intermediate	Low
Trips per day	Intermediate/high	High	Low/intermediate	Low

5.2 Simulations

In this section, a thorough review of each simulation is presented. Five different simulations were conducted, each of which investigated how one or more factors influenced the TCO. Simulation 1 examines the implications of a reduced driver time, simulation 2 a reduced number of maximum trips per bus per day, while simulation 3 investigates how the usage rate affects the TCO. Simulation 4 analyses the trade-off between DOD and battery degradation, and finally, simulation 5 studies how an increased auxiliary load affects the energy consumption and hence the TCO.

5.2.1 Simulation 1 – Decrease charging time

Many articles from the literature review excluded the driver cost from the TCO analysis. However, Olsson, Grauers and Pettersson (2016) included the driver cost and found that the driver cost constituted the majority of the total annual cost. Hence, minimizing the driver time is of high priority if one wants to reduce the total annual cost. This can be done in several ways, e.g. by reducing the number of daily trips or the number of stops. However, there are ways one can reduce the driver time while maintaining the same operating schedule. The dwell time at the end stops is often used as a break for the drivers and should meet certain requirements according to collective agreements. However, if the charge time exceeds the required break time, unnecessary driver time is being spent waiting for departure. Therefore, by reducing the charge time one can reduce the inactive time of the drivers.

A reduced charge time has an immediate impact on the technical requirements of the bus system. Since the energy consumption remains unchanged and the charge time decreases, the same amount of energy must be charged in less time, meaning that the effect of the chargers must increase. Hence, there is an immediate trade-off between increased cost for chargers and the reduction in driver time. Moreover, a reduction of the time spent at the end-stops could potentially change the trip assignments of the buses. Ideally, by reducing the dwell-time new options regarding the trip assignments can emerge, and thereby resulting in a more optimal trip assignment with regards to the driver cost. If the inactive time of each bus can be minimized, the bus will have more free time for additional trips, thus lowering the required number of buses. Therefore, a reduced charge time could potentially reduce both driver cost, vehicle investments and battery investments.

Eight different runs were conducted, starting with a charge time of 10 minutes and decreasing by one minute for each run, resulting in 10 min for run 1 and 3 min for run 8. The charge times was based on the technical specifications of the buses in the ZeEUS project (ZeEUS 2017a). Furthermore, in reality, certain steps have to be conducted in order to commence the charging process, e.g. the bus have to be set in the right position relative to the chargers. Thereby, a 1 min dwell time was used to replicate the conditions of an actual charge process. The result from this simulation is presented in section 6.2.

5.2.2 Simulation 2 – Decrease maximum number of trips per bus

While the batteries for the opportunity charged buses can be dimensioned based on the energy consumed from point A to point B, the overnight charged batteries are designed to withstand a whole day of operation. Initially, the batteries were dimensioned based on the bus with the highest amount of driven km per day. But after initial simulations was conducted, it was found that the current dimensioning of the overnight batteries was not reflecting the required battery cost in a fair way. Since the batteries was optimized based on the bus with the highest driven km per day, and the driven km per day varies significantly between the buses, the batteries was over-dimensioned and thereby the battery cost was high.

Hence, in order to dimension the batteries to better reflect real operating conditions, one could level out the average usage rate of the buses and batteries, and thereby decreasing the maximum driven km per bus per day. This can be achieved by decreasing the maximum number of trips assigned to each bus. The simulation was conducted on all the four routes, and as the operating schedule differs, the maximum driven km per day varies between the routes. Using a similar simulation matrix where the highest number assigned trips per bus per day was based on an initial simulation run where the tool could assign the trips without any restrictions. When the baseline was calculated, a limit was applied where the number of trips assigned to each bus was restricted to a certain number, and thereafter reduced by one unit for each run. The maximum driven distance per bus could then be calculated and used as the dimensioning factor for the batteries.

5.2.3 Simulation 3 – Increased usage rate for Overnight Charge

It was found in the literature review that the usage rate is important for electric buses to lower the TCO (Olsson, Grauers & Petterson 2016; Pihlatie et al. 2014). That finding, together with the findings from simulation 2, that the battery cost affected overnight charging more than opportunity charging, as will be presented in chapter 6, made it interesting to investigate how the usage rate affects the TCO for overnight charge. The reason why this was only performed for overnight charge, and not opportunity charge, was that it was assumed to be more practically possible for overnight charge, as no charging infrastructure is needed on the other routes.

These simulations consisted of two parts, one where it was assumed that the battery capacity, i.e. battery size could be optimized for the whole fleet, and one where the buses was assumed to be used at other routes. In the first part, optimized battery size referred to the possibility to have different battery sizes for the buses in the fleet, depending on the total energy consumption per bus during the day. The TCO was investigated for five different usage rates, i.e. 60, 70, 80, 90 and 100 % of the battery capacity. The difference from the previous TCO calculation was that the annual cost of the battery depreciation was calculated for the new battery size.

In the second part, it was assumed that the buses could be used at other routes. Hence, the annual depreciation cost for vehicles, charging infrastructure and batteries, vehicle insurance cost and maintenance cost for chargers was calculated for 60, 70, 80, 90 and 100 % usage rate of the battery capacity.

5.2.4 Simulation 4 – Increased DOD for Overnight Charge

From previous simulations in this thesis, it was found that a major part of the investment cost in electric buses was the battery cost, especially for overnight charged buses as they had significantly higher battery capacity than opportunity charged buses. The cost used for high-energy batteries was € 540 / kWh, and if the battery capacity is assumed 640 kWh, as the for the articulated bus offered by MAN, the cost for the battery pack is € 345 600. Hypothetically, if the battery offered by MAN is dimensioned based on a DOD of 60 %, and the DOD is increase to 70 %, the battery capacity can be lowered to 545 kWh, resulting in a cost saving of € 51 300, when it comes to the initial investment cost. However, an increased DOD will eventually impact the life-time of the batteries, as demonstrated by Hoke et al. (2011). The economic consequences of this relationship can in turn be simulated using the battery degradation formula, see equation (1) , combined with the battery depreciation cost.

Table 15 - Simulation 3 matrix

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
DOD [%]	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %
Cycle life	3057	2720	2441	2206	2008	1838	1690	1562
Depreciation time [years]	9,3	8,2	7,4	6,7	6,1	5,6	5,1	4,7

To structure this simulation, eight different DOD values was used, and the depreciation time was calculated for each DOD value, see Table 15. The DOD values is based on initial simulations, after simulation 2 was conducted using a DOD of 60 %, it was found that the battery size was quite large and consequently a larger DOD would be more suitable in practical applications. Since the equation by Hoke et al. (2011) calculates the cycle life of the batteries, the cycle life must be converted into depreciation time to be able to fit the depreciation cost formula, see (21). Since the battery of an overnight charged bus is cycled once a day, one can convert the cycle life to depreciation time, ($N_{batteries}$), using (52).

$$N_{batteries} = \frac{CL}{N_{days\ per\ yr}} \tag{52}$$

Where CL is the cycle life, i.e. the number of times the battery can be fully discharged (using the specified DOD), and $N_{days\ per\ yr}$ is the number of operating days per year. By using the model by Hoke et al. (2011), combined with equation (52), with a DOD of e.g. 70 %, the cycle life will be 2 206 cycles which corresponds to a depreciation time of 7,4 years, see Table 15. This simulation was conducted on all four routes, and it is restricted to overnight charged buses since the batteries of opportunity charged buses is relatively small and hence the economic effect of a decreased battery capacity is assumed to be negligible. The result from this simulation can be found in subsection 6.3.5.

5.2.5 Simulation 5 – Auxiliary load

The energy model, see (41), consisted of four different elements, one being the auxiliary load which represent the energy consumed by e.g. air condition, heating, radio, lighting (Goethem, Koorneef & Spronksman 2013). The auxiliary load can vary depending on the operating conditions, and this in turn will influence the energy consumption, and hence, the dimensioning of batteries and chargers. A higher energy consumption implicate that more energy must be stored, i.e. a higher battery capacity is required. Additionally, a higher consumption means that more energy must be charged under the same period, thus a higher charger effect is required. Moreover, a higher energy consumption will lead to a higher energy cost. Therefore, investigating the implications of different auxiliary loads is of interest, as it has direct effects on the TCO of the bus system. In the study conducted by Lajunen (2018), the author concluded that an increased auxiliary power can make the lifecycle costs increases as much as 10 % for end station charging buses and up to 30 % for opportunity charging buses. Thus, the aim with this simulation was to get a greater understanding of how the auxiliary load affects the TCO.

This simulation was conducted for all four routes, and four different auxiliary loads were used, 0 kW which represents zero auxiliary load, 6 kW which represent mild weather, 10 kW intermediate weather conditions and 14 kW that corresponds to hot or ambient cold conditions (Lajunen 2018). The result from this simulation can be found in section 6.4.

5.2.6 Sensitivity analysis

To be able to see how a change in some of the cost categories will affect the total annual cost, a sensitivity analysis was performed. In this sensitivity analysis, six different costs were included, i.e. vehicle cost, battery cost, charger cost, insurance and maintenance cost, energy cost and driver cost. These costs were decreased with 10 %, in the same way as in the sensitivity analysis by Lajunen (2018), to see how many percentages the total annual cost was changed due to the 10 % decrease. The findings and analysis from this sensitivity analysis is presented in section 6.5.

6 Findings and analysis

The following chapter presents the findings and analysis from the simulations presented in the previous chapter. It begins with the findings and analysis of energy consumption, followed by findings and analysis of the TCO for all investigated routes and simulations, analysis of auxiliary load, comparative analysis of charging strategies, sensitivity analysis and lastly a summary of the whole chapter. This chapter aims to answer research question two to four:

RQ2 – What parameters have greatest impact on the TCO for each charging strategy?

RQ3 – What operating conditions seems to be most favourable for each charging strategy?

RQ4 – How does the TCO differ between the two charging strategies?

6.1 Findings and analysis of energy consumption

As mentioned in 2.4, energy consumption is an important part when performing an TCO analysis (ZeEUS 2017b). Here, Figure 9, presents the findings from using the equations in 4.2 and the parameters presented in Table 9, to calculate the average energy consumption, kWh/km, for all routes and charging strategies.

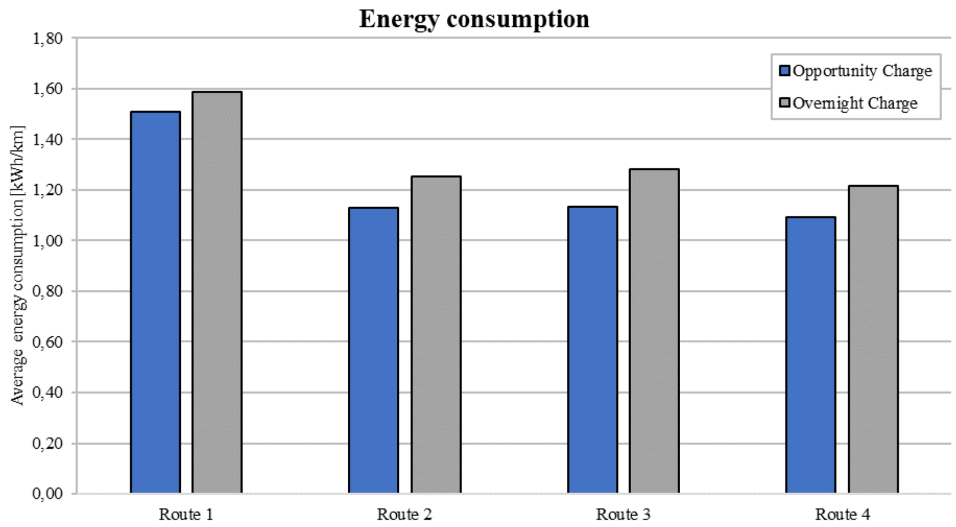


Figure 9 - Energy consumption for all investigated routes and charging strategies

From the calculations it was found that the energy consumption was between 1,09 kWh/km and 1,51 kWh/km for opportunity charge and between 1,22 kWh/km and 1,59 kWh/km for overnight charging. The route that differs most from the average of the investigated routes was Route 1. The major reason for this is that Route 1 has the highest ratio between the average trip time and the average trip distance, i.e. buses driving on Route 1 have a lower average driving speed than buses on the other routes, see Figure 10. This means that the auxiliary load has a higher impact on the energy consumption for Route 1, as the energy consumption from the auxiliary load depends on the time auxiliary devices are used, see equation (41) and (42). According to this, Route 3 should have a lower energy consumption than Route 2 and 4, however this is not the fact, and the reason for this is that the used energy model also accounts for the topography. When this was investigated further, it was found that the topography had the greatest impact on Route 3, due to the elevation gain and elevation loss that was presented in Table 12.

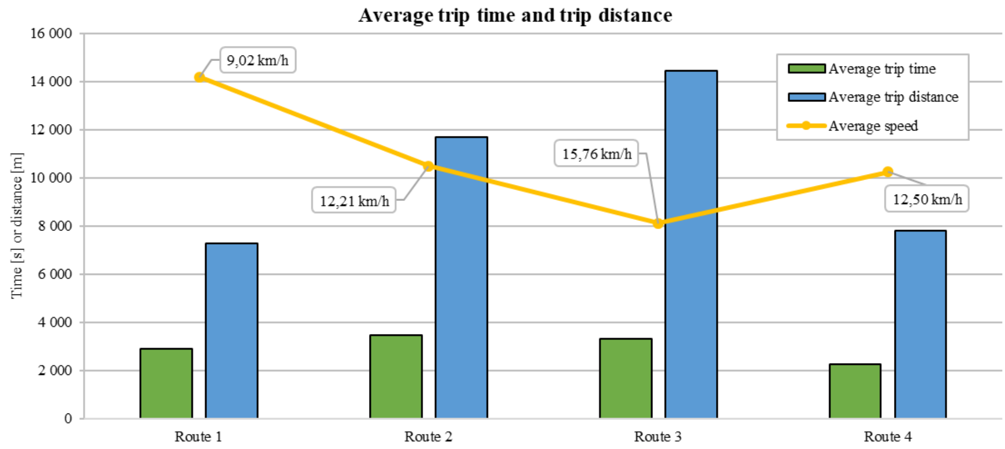


Figure 10 - Average trip time and trip distance

The energy consumption was not only used to calculate the energy cost, but also for the battery dimensioning. And when it comes to the battery dimensioning, DOD was set to 40 % (SOC from 40 – 80 %) for opportunity charge and 60 % (SOC from 20 – 80 %) for overnight charge. However, in the case of opportunity charging, the battery dimensioning was done as presented in 4.2, i.e. a safety factor was used to make it possible for buses to skip one charging point, and still stay in the chosen DOD. The calculated battery sizes for opportunity charging, best case for overnight charging, and maximum km case for opportunity charging are presented in Table 16.

Table 16 - Battery dimensioning for all routes and charging strategies

	Route 1	Route 2	Route 3	Route 4
Opportunity Charge	53	71	86	57
Overnight Charge Low*	383	424	605	345
Overnight Charge High**	492	556	680	345

All values in kWh, *) Based on best case, **) Based on max. km case

If the values presented in Table 16 is compared with the literature presented in 2.2 for the same auxiliary load, i.e. 6 kW, one can see that the battery sizes for the routes in this master's thesis are larger than for Lajunen (2018), except for Route 4. This depends on the energy consumption per km, distance per bus per day, and duration, but also heavily on the chosen DOD. In this master's thesis the DOD for overnight charged buses was set to 60 % compared with 95 % in Lajunen (2016). However, if the values are compared with Bi, Kleine and Keoleian (2016), one can see that the 458 kWh battery they used for overnight charging is larger than the batteries for route 1, 2 and 4 from the best case in this master's thesis.

The findings presented in this chapter indicates that electric buses seem to be most energy efficient at routes with a higher average driving speed, as the auxiliary power has a great impact on the energy consumption. On the other hand, the most energy efficient route might not be route with the lowest TCO since there are several other costs that has to be considered. Furthermore, the findings imply that there is a great difference in the battery size needed between the routes, especially for overnight charging. The following chapters will present the findings and analysis of TCO, where the energy consumption and battery dimensioning from this chapter were used for the calculations.

6.2 Findings and analysis of TCO for Opportunity Charge

The aim with section 6.2 is to present the findings and analysis associated with TCO for opportunity charged buses.

6.2.1 Route 1 - Opportunity Charge

The findings from simulation 1 on the first route is found in Figure 11.The figure illustrates how much the total annual cost have changed when the charge time decreases from 10 min to 3 min. For more detailed numbers, see Appendix A – Findings for Route 1.

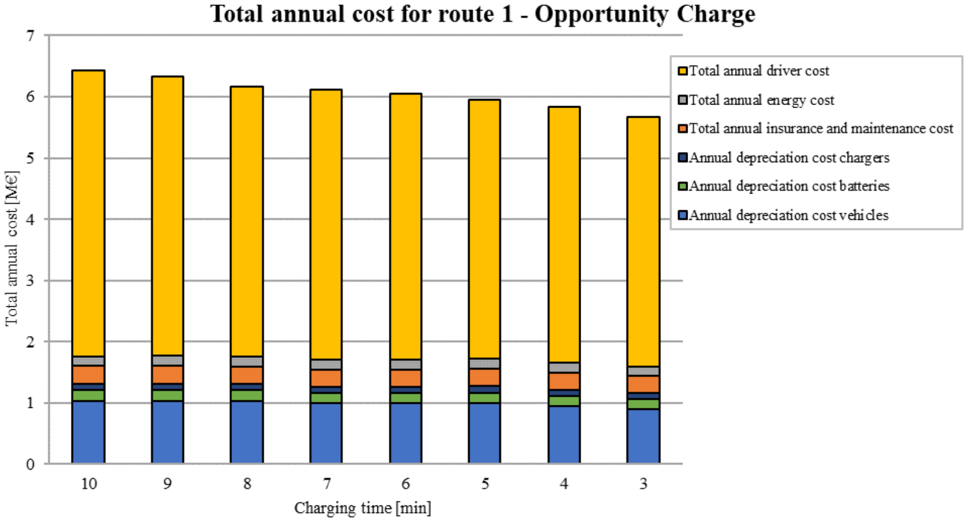


Figure 11 - Total annual cost for Route 1 in the first simulation

As seen in Figure 11, the total annual cost is at its peak at 10 min charge time and decreases when the charging time is reduced, reaching its minimum at 3 min charge time. Table 17 shows a break-down of the total annual costs of the worst case and the best case, i.e. the charge time with the highest total cost and the charge time with the lowest total cost. The total annual cost is reduced from € 6427 K, with a charging time of 10 min, to € 5673 K when the charging time is 3 min, corresponding to a reduction of 11,73 %. The vast majority of the decreased cost can be attributed to the decrease in total annual driver cost, from 124 326 hours to 109 217 hours see Table 18, this equals to an annual cost reduction of € 586 K or 12,56 %.

Table 17 - Change in annual costs for opportunity charged buses for Route 1

Annual costs	Worst Case	Best Case	Change	Change
Total annual depreciation cost	1 315	1 163	-151,57	-11,53 %
Total annual insurance and maintenance cost	287	274	-13,93	-4,84 %
Total annual energy cost	162	159	-2,87	-1,77 %
Total annual driver cost	4 663	4 077	-585,53	-12,56 %
Total annual cost	6 427	5 673	-753,89	-11,73 %

[k€] if nothing else is stated

The total annual cost for insurance and maintenance as well as the total annual energy cost decreases between the worst and best case. In order to understand why, one have to look at the parameters behind these costs. Both depend on the number of chargers and buses, and Table 18 shows the different parameter values for the worst and best run. The total charge effect increases from 415 kW to 463 kW, resulting in a small increase in the cost for charger maintenance and installation since this is based on the number of chargers and charge effect. The majority of the € 14 K reduction in annual insurance and maintenance can however be derived from the reduced number of vehicles, from 24 to 21.

Table 18 – Parameter values Route 1: opportunity charge

Charge time [min]	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	Change*
Number of chargers	6	6	4	4	4	4	3	2	-66,67 %
Total charge effect [kW]	415	463	348	397	462	556	518	463	11,57 %
Number of buses	24	24	24	23	23	23	22	21	-12,50 %
Annual driver time [h]	133 416	130 336	126 486	126 355	124 149	120 931	199 481	116 662	-12,56 %

*) Change between the worst and best case

To achieve a greater understanding of how the different costs behave, one have to analyze the entire dataset. The annual costs do not follow a linear downward pattern as one might expect, Figure 12 illustrates the cost progress for the different runs and there are several different trends to observe. It should be noted that there is a correlation between the costs, e.g. the energy cost and insurance and maintenance cost are both a product of the total charge effect, but Figure 12 represent the change relative to the index value, hence the magnitude of the changes should not be put in comparison to the other costs. The total annual cost is represented by the blue dashed line, and the total annual driver cost is represented by the yellow line, both of which are decreasing for every run. An interesting trend to note here is what happens to the costs between charge time 7 and 5, where the total annual insurance and maintenance, deprecation and energy cost is increasing. These costs are derived from the number of vehicles and chargers, and if one investigates the number of the chargers more closely, one can see that the number of opportunity chargers remains constant, but the total charge effect is increasing, see Table 18. Since the number of vehicles remains the same, the sudden jump in the aforementioned costs can be explained by the increased total effect.

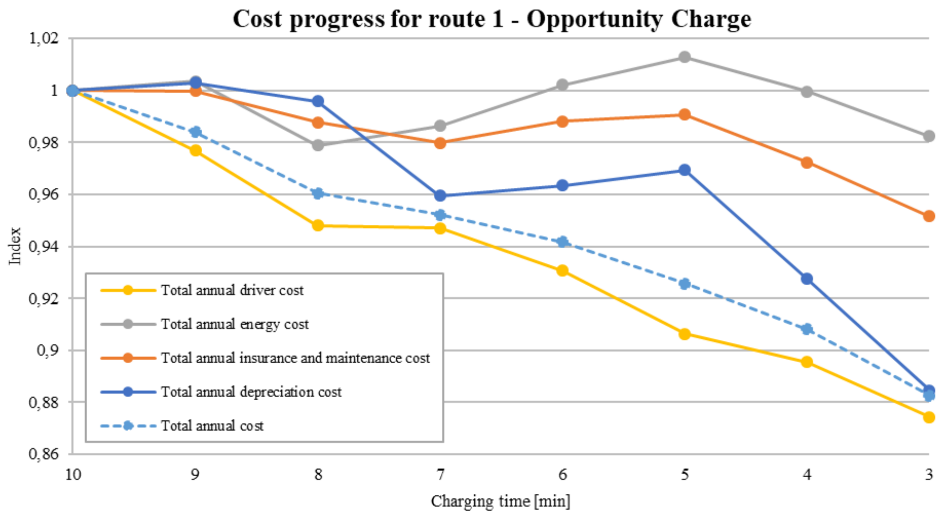


Figure 12 - Cost progress Route 1

To understand the changes in the annual costs, one must take a deeper look into the drivers of the parameters values that is presented in Table 18. The reduced charge time at the end-stops essentially changes the entire bus schedule. When the bus spends less time at the end-stop, new options regarding the route optimization for each bus emerge. In the best case, the bus can be assigned to a new trip right when the charging is completed, avoiding unnecessary time to be spent and thereby reducing the required driving time. Additionally, when the time spent at the end-stop is reducing, the assigned trips are being pressed together and thus the buses can run more trips during the day, eventually reducing the number of buses as can be seen in Table 18.

The number of opportunity chargers is decided by the occupancy rate, which in turn depends on the bus schedule. The more time spent at the chargers, the higher the odds of two or more buses being charged simultaneously, resulting in a higher occupancy rate. It should be noted, that the charging time only decreases by 1 minute between each run, but the required number of chargers can decrease significantly, e.g. from 6 to 4 chargers when the charge time goes from 9-8 min.

To summarize the result from 6.2.1, the total annual cost decreased by 11,73 % when the charge time was reduced from 10 min to 3 min. The driving factor was the reduction of the driver cost, which was reduced by 12,15 %. Furthermore, the number of buses was reduced by 12,5 % due to a higher utilization rate of each bus. To reduce the charge time the effect of the chargers must be increased, and thus the effect per charger increased from 69 kW to 231 kW. However, the total charge effect only increases by 11% due to the reduced number of required chargers.

6.2.2 Route 2 – Opportunity Charge

In a similar way as for Route 1, this subsection will present the result and analysis from simulation 1 and Route 2, when it comes to the total annual cost for opportunity charge. For more detailed numbers, see Appendix B – Findings for Route 2.

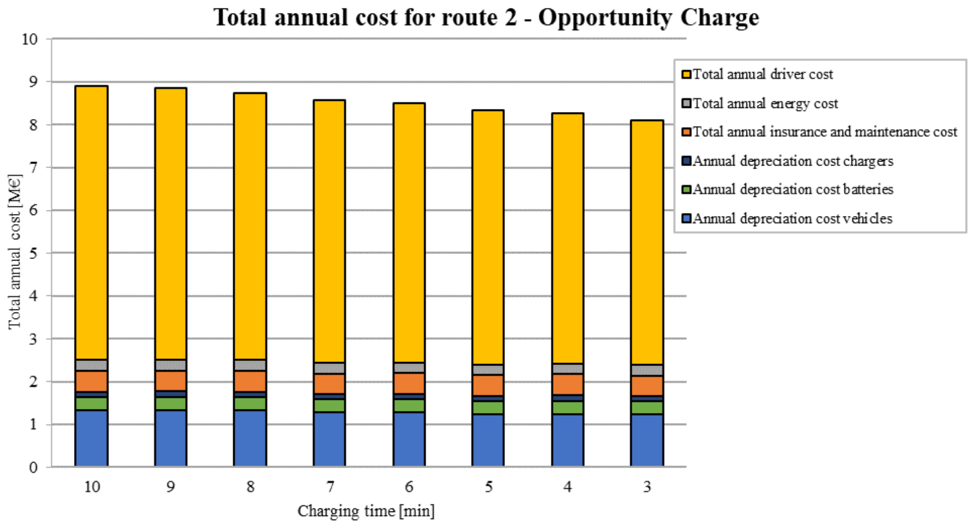


Figure 13 - Total annual cost for Route 2 in the first simulation

Figure 13 illustrates how much the total annual cost for Route 2 have changed when the charge time decreased from 10 min to 3 min. As seen in the figure, the total cost decreased when the charging time was reduced, and it reached its lowest point when the charging time was 3 min. Table 19 shows a break-down of the total annual costs of the worst case and the best case. The total annual cost was reduced by 9,16 %, and the majority of the reduced total annual cost was traced to the 10,94% decrease in driver time, accounting for an annual cost reduction of € 701 K. Additionally, the total annual depreciation cost was reduced by 5,89%, accounting for a total annual decrease of € 104 K. The total annual cost for energy was reduced by 0,62%, while the cost for insurance and maintenance was reduced by 1,98%. The reduction in the total annual cost was slightly higher on Route 1. The reason for this is that, in addition to a slightly higher reduction of the driver cost, the annual depreciation cost was reduced by 11,53% which is almost twice the amount of Route 2.

Table 19 - Change in annual costs for opportunity charged buses for Route 2

Annual costs	Worst Case	Best Case	Change	Change
Total annual depreciation cost	1 766	1 662	-103,98	-5,89 %
Total annual insurance and maintenance cost	488	478	-9,67	-1,98 %
Total annual energy cost	250	248	-1,54	-0,62 %
Total annual driver cost	6 406	5 705	-701,11	-10,94 %
Total annual cost	8 909	8 093	-816,30	-9,16 %

[k€] if nothing else is stated

Table 20 contains the parameter values for each run and the percentage change between the worst and best case. The reduction in the annual depreciation cost can be derived to the decreased number of vehicles and total charge effect. The number of vehicles was reduced from 31 to 29, corresponding to a reduction of 6,45%, and the charge effect was increased by 11,22 %. In comparison, the equivalent numbers for Route 1 was 12,50% for the buses and 11,57% for the total charge effect. Just like Route 1, the number of chargers could be reduced from 6 to 2, but the charge effect of per charger is higher on Route 2 (292,5 kW) compared to Route 1 (231,5 kW).

Table 20 - Parameter values Route 2: opportunity charge

Charge time [min]	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	Change*
Number of chargers	6	6	5	4	4	4	4	2	-66,67 %
Total charge effect [kW]	526	585	540	501	584	701	876	585	11,22 %
Number of buses	31	31	31	30	30	29	29	29	-6,45 %
Annual driver time [h]	183 294	181 576	178 179	175 367	173 566	169 909	167 124	163 233	-10,94 %

*) Change between the worst and best case

To get a better understanding of the behavior of each annual cost, Figure 14 shows an illustration over the cost progress of each annual cost.

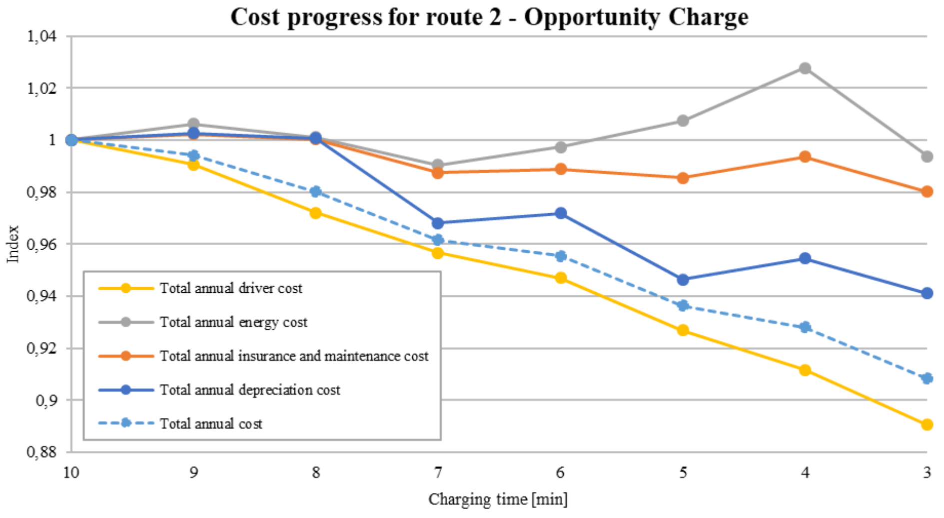


Figure 14- Cost progress Route 2

The annual driver cost and the total annual cost both have a downward trend and reaches its lowest point when the charge time is 3 min, the same trend was observed on Route 1. The upward pattern in the energy cost (grey line) between charge time 7-4 occurs because the number of chargers remain constant while the charge effect per charger increases, resulting in an increase in total charge effect from 584 kW to 876 kW. The zigzag downward pattern in the depreciation cost is a result of the variations in the required number of buses and total charge effect. When the number of chargers remains constant the total charge effect increases, and therefore the depreciation cost increases. Meanwhile, the sudden decrease in the depreciation cost occur when either the number of chargers or vehicles is reduced, or a combination of the two. Moreover, just like Route 1, the driver time steadily decreases when the charge time is reduced, allowing for a total annual reduction of 10,94 %.

6.2.3 Route 3 – Opportunity Charge

As for route 1 and 2, this subsection presents the result and analysis from simulation 1 for Route 3, when it comes to the total annual cost for opportunity charge. For more detailed numbers, see Appendix C – Findings for Route 3.

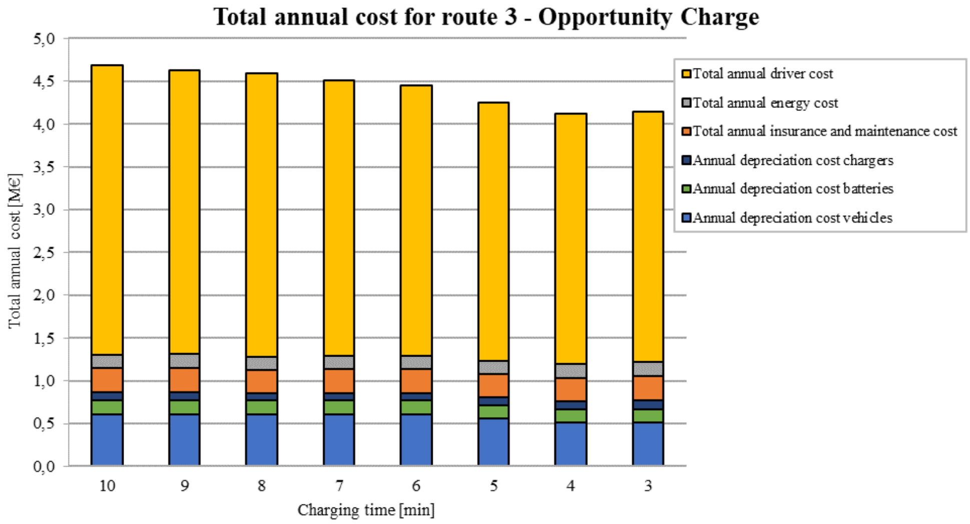


Figure 15 - Total annual cost for Route 3 in the first simulation

Figure 15 illustrates how much the total annual cost for Route 3 have changed when the charge time decreases from 10 min to 3 min. An interesting finding here is that the lowest total annual cost is achieved with a charging time of 4 min, not 3 min like route 1 and 2. The reason for this will be discussed later in this chapter. Table 21 shows an annual cost breakdown of the worst case and the best case. The total annual cost decreases by 11,88 % when the charge time goes from 10 min to 4 min. The majority of the reduction can be derived to the reduced depreciation and driver cost. The total annual cost for energy, insurance and maintenance only changes marginally.

Table 21 - Change in annual costs for opportunity charged buses for Route 3

Annual costs	Worst Case	Best Case	Change	Change
Total annual depreciation cost	862	759	-103,89	-12,05 %
Total annual insurance and maintenance cost	285	277	-8,07	-2,83 %
Total annual energy cost	156	156	0,20	0,13 %
Total annual driver cost	3 379	2 935	-444,77	-13,16 %
Total annual cost	4 683	4 126	-556,53	-11,88 %

[k€] if nothing else is stated

Table 22 shows the parameter values for the whole dataset. The number of vehicles and chargers can be decreases by 14 % and 50 % respectively, and the annual driver time is reduced by 13%. The total charge effect increased by 25 % and compared to the other two routes, the increase in total charge effect is much higher on Route 3 since the number of chargers is only reduced by 50%. However, Route 3 has the highest reduction in driver time, followed by Route 1 and then Route 2.

Table 22 - Parameter values Route 3: opportunity charge

Charge time [min]	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	Change*
Number of chargers	4	4	2	2	2	2	2	2	-50,00 %
Total charge effect [kW]	436	485	273	311	363	436	546	727	25,23 %
Number of buses	14	14	14	14	14	13	12	12	-14,29 %
Annual driver time [h]	96 697	95 143	94 717	92 321	90 193	86 206	83 971	83 861	-13,16 %

*) Change between the worst and best case

Further looking into the parameter values for the 3 min charge time in Table 22, an interesting finding is that driver time still decreases when the charge time goes from 4 to 3 min, but only marginally from 83 971 to 83 861 h. Since the lowest TCO was achieved with a charge time of 4 min, the reduced driver time when shifting from 4 to 3 min was not sufficient to decrease the TCO. Meaning that the changes in the other cost were greater that the reduction in the driver cost. To get a better understanding of the behavior of each annual cost, Figure 16 illustrates the cost progress for Route 3 when using opportunity charge.

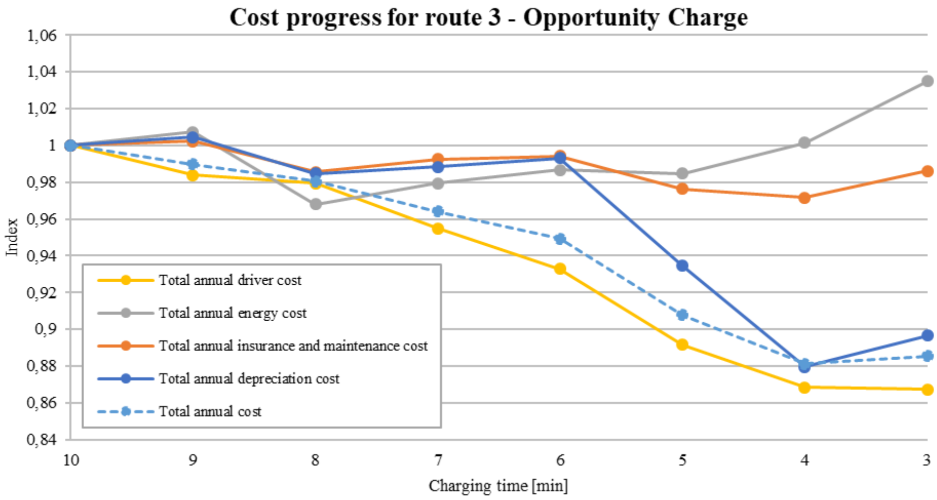


Figure 16- Cost progress Route 3

The dashed line in light blue in Figure 16 illustrates the total annual cost, and just as noted before, the total annual cost increased when the charge time goes from 4 min to 3 min. The marginal increase in driver cost does not make up for the increase in depreciation, energy and insurance and maintenance cost. The increase in these costs can be attributed to the increase in the total charge effect, as can be seen in Table 22. Unlike the previous routes, the number of chargers reached its' minimum at a charge time of 8 min. As a consequence, the costs associated with the chargers follows a linear pattern when the charge time is reduced further since they are now solely a product of the total charge effect. Furthermore, the sudden drop in the depreciation cost between charge time 6-4 is a result of the decrease number of vehicles, that reduced from 14 to 12.

6.2.4 Route 4 – Opportunity Charge

In a similar way as for the previous three routes, this subsection presents the result and analysis of simulation 1 for Route 4 using opportunity charge. For more detailed numbers, see Appendix D – Findings for Route 4.

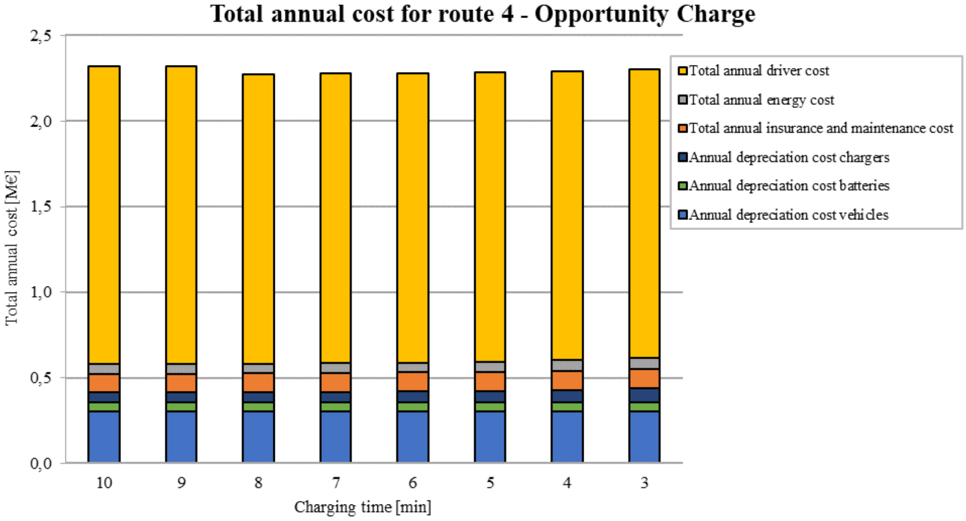


Figure 17 - Total annual cost for Route 4 opportunity charging

Figure 17 illustrates the total annual cost for Route 4 using opportunity charging. There is only a slight difference in the total annual cost between the different charge times, and compared to the other three routes, there is no clear trend of reduced total annual cost following a reduction in charge time. The lowest total annual cost was achieved with an 8 min charge time, and the highest with 9 min charge time.

Table 23 - Change in annual costs for opportunity charged buses for Route 4

Annual costs	Worst Case	Best Case	Change	Change
Total annual depreciation cost	415	417	1,36	0,33 %
Total annual insurance and maintenance cost	109	109	0,38	0,35 %
Total annual energy cost	56	56	0,49	0,87 %
Total annual driver cost	1 739	1 693	-45,87	-2,64 %
Total annual cost	2 319	2 275	-43,65	-1,88 %

[k€] if nothing else is stated

Table 23 shows the difference in annual cost between the worst and best case. The annual driver cost was only reduced by 2,64% while it decreased by 11-13% on the other routes. The depreciation, energy, insurance and maintenance cost increased slightly and thus the total annual cost was only reduced by 1,88% on Route 4. This is by far the lowest reduction achieved among the four routes. To understand why, each cost must be analyzed further and therefore the cost progress was calculated.

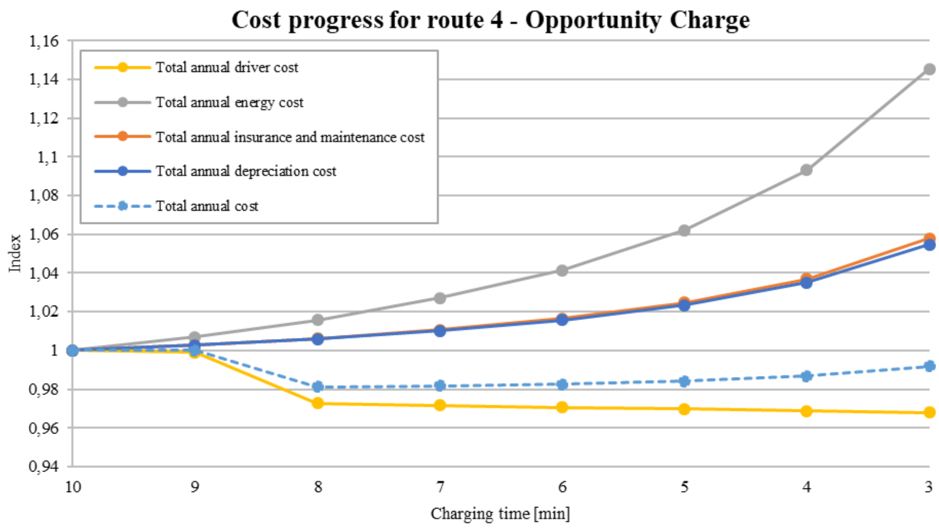


Figure 18 - Cost progress Route 4

Figure 18 shows the cost progress for Route 4 using opportunity charging. The total cost for energy, depreciation, insurance and maintenance follows an upward pattern, and the driver cost stagnates when the charge time decreases from 8 min. The explanation for these trends can be found in the parameter values for Route 4 which are shown in Table 24. The number of buses and chargers remains constant, while the total charge effect is steadily increasing. Since the depreciation, energy, insurance and maintenance costs are a product of the charge effect, the upward pattern in these costs can be attributed to the increasing total charge effect.

However, in order to understand why the number of vehicles and chargers remain constant, one have to analyze the route characteristics and the schedule on this route. The route characteristics on Route 4 differs from the other routes since all the dimensions are ranked low. Since there are relatively few trips per day and the trip frequency is low, the option in terms of assigning new trips to the buses are limited. Meaning that when the charge time is reduced, few new assignment options emerge and thus the schedule could remain unaltered. As a consequence, the number of buses and chargers cannot be reduced, and the total driver time remain unchanged. A more thorough discussion of the driver time can be found in subsection 6.2.5.

Table 24 - Parameter values Route 4: opportunity charge

Charge time [min]	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	Change*
Number of chargers	2	2	2	2	2	2	2	2	0,00 %
Total charge effect [kW]	119	133	149	171	199	239	299	399	12,03 %
Number of buses	7	7	7	7	7	7	7	7	0,00 %
Annual driver time [h]	49 803	49 745	48 441	48 393	48 344	48 297	48 249	48 201	-2,62 %

*) Change between the worst and best case

6.2.5 Comparative analysis of routes – Opportunity Charge

To understand the total annual cost for opportunity charging further, the outcomes from the different routes was compared by calculating the cost per km and cost per hour for each route. The cost per km was calculated by dividing the total annual cost by the length of the daily trips, i.e. excluding the distance driven from and to the depot. Figure 19 illustrates the cost per km for each charge time and route.

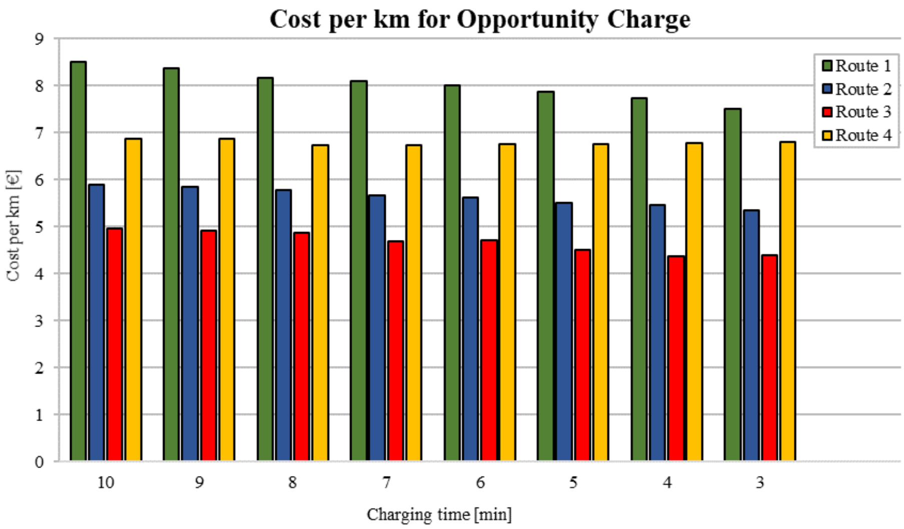


Figure 19 - Cost per km for the first simulation

Route 1 had the highest cost per km while Route 3 had the lowest, suggesting that Route 3 might have the lowest TCO. However, according to Lajunen (2018) the cost per km ratio may not present the lifecycle cost in a fair way, hence by calculating the cost per hour, one might achieve a more profound understanding of what route has the lowest TCO for opportunity charging.

Figure 20 shows the cost per hour per route for each charging time using opportunity charging. The cost per hour ratio is calculated using the total annual cost and the time spent actually driving on the route, i.e. the aggregated duration of the trips.

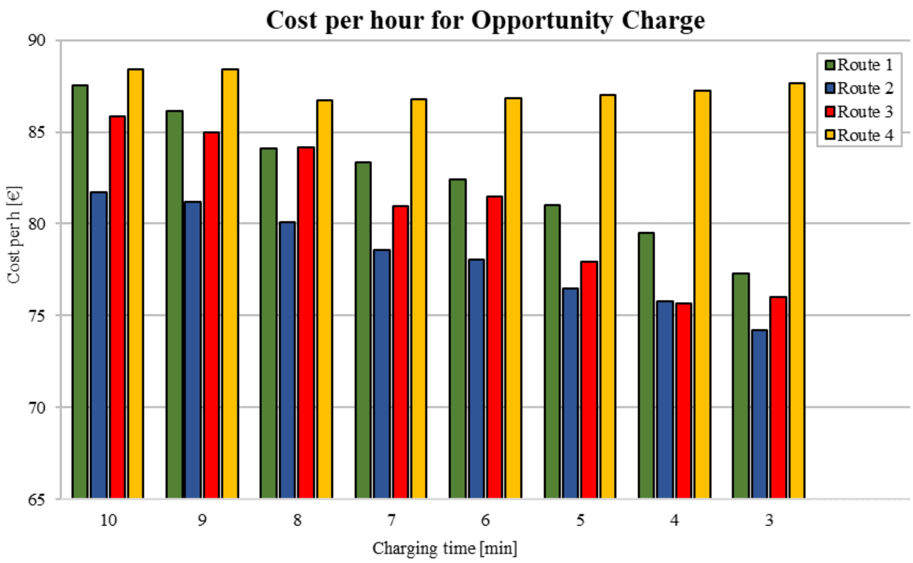


Figure 20 - Cost per hour for the first simulation

Lajunen (2018) found that difference between the routes that he investigated was smaller when the TCO was measured as cost per hour compared with cost per km. The findings from this master's thesis indicates the same thing, as the difference between the routes has now decreased significantly. Another thing that differed from when the TCO was measured as cost per km was that Route 2 has the lowest cost per hour while Route 4 remains the most expensive route, however it should be noticed that the difference between route 1, 2 and 3 is relatively small, see Figure 20, ranging from € 74,2 per hour to € 77,3 per hour. The cost per km and cost per hour from the best case for each of the routes with opportunity charging is presented in Table 25.

Table 25 - Cost per km and cost per hour for all routes for opportunity charging

	Route 1	Route 2	Route 3	Route 4
Cost per km [€/km]	7,51	5,35	4,37	6,74
Cost per hour [€/hr]	77,28	74,20	75,64	86,73

If the costs in Table 25 is compared with previous studies, the result for cost per km is higher. One reason for this is that most of the previous studies chose to exclude the driver cost. Olsson, Grauers and Pettersson (2016) calculated the cost per km with the driver cost included, and for opportunity charging the cost was € 3,23 per km. This means that the result for the route with the lowest cost per km in this master's thesis was still higher than for previous studies, even for studies with driver cost included. If the driver cost is excluded from the cost per km, the result was € 2,11 for Route 1, followed by € 1,58 for Route 2, € 1,26 for Route 3 and € 1,72 for Route 4. This can be compared with a result between € 0,6 and € 1,0 from Lajunen (2018), between € 0,8 and € 0,9 from Philatie et al. (2014), between € 0,68 and € 1,43 from Bloomberg NEF (2018), and about € 1 from Transport & Environment (2018). However, it is hard to make any fair conclusions regarding the TCO by comparing the TCO from different studies as the assumptions are not the same. Another thing that affects the result is how the calculations is performed, e.g. in this master's thesis the investment cost was calculated into a yearly depreciation cost, as presented in 4.1.1, while some of the previous studies instead discounted the operating costs and technology replacement cost. Still, the cost per km from previous studies can be used as a sanity check as it is hard to know how appropriate the result is without having anything to compare with. On average, the cost per km in this master's thesis without driver cost was about 70 % higher than the average from previous studies. A more in-depth analysis of how an excluded driver cost will affect the TCO, for both opportunity charging, and overnight charging is presented in 6.5.

Considering the energy consumption of these routes, see Figure 9, Route 3 has a higher average driving speed, resulting in a higher energy consumption per hour and a higher travelled distance per hour. Inevitably translating into a higher annual energy cost, and insurance and maintenance cost per hour as can be seen in Table 26.

Table 26 - cost breakdown all routes opportunity charge

Costs per hour	Route 1	Route 2	Route 3	Route 4
Depreciation vehicles per hour	12,33	11,46	9,48	11,50
Depreciation batteries per hour	2,15	2,67	2,66	2,15
Depreciation chargers per hour	1,37	1,10	1,77	2,23
Total depreciation cost per hour	**15,85**	**15,23**	**13,91**	**15,88**
	20,5 %	20,5 %	18,4 %	18,3 %
Total insurance and maintenace cost per hour	**3,73**	**4,39**	**5,08**	**4,17**
	4,8 %	5,9 %	6,7 %	4,8 %
Total energy cost per hour	**2,17**	**2,28**	**2,86**	**2,15**
	2,8 %	3,1 %	3,8 %	2,5 %
Total driver cost per hour	55,54	52,31	53,80	64,53
	71,9 %	70,5 %	71,1 %	74,4 %
Total cost per hour	**77,28**	**74,20**	**75,64**	**86,73**
	100 %	100 %	100 %	100 %

[€/hr] if nothing else is stated, the percentage below the costs represent the percentage the cost constitutes of the total cost

Table 26 shows a breakdown of the cost/hour for each route, as mentioned earlier, the difference in total annual cost per hour between route 1, 2 and 3 is relatively small, but with a cost per hour of € 86,73 Route 4 differs significantly from the other three. Although Route 4 scores relatively good in the annual cost for depreciation, energy, maintenance and insurance, the annual cost for the drivers is much higher than the other three routes. The explanation for this is the operating conditions, where a low trip frequency and a low number of daily trips restricts the reduction of the driver time subsequent to a decreased charge time. Furthermore, the lowest total annual depreciation cost is achieved by Route 3, meaning that the investment in batteries, vehicles and chargers in relation to the driver time would be more favorable/benign compared to the other routes. By calculating the usage rate of the vehicles for route 1 and 3, see Figure 21, it can be concluded that the vehicles have a higher usage rate on Route 3. A discussion of why the usage rate differs between the routes can be found in subsection 6.3.6

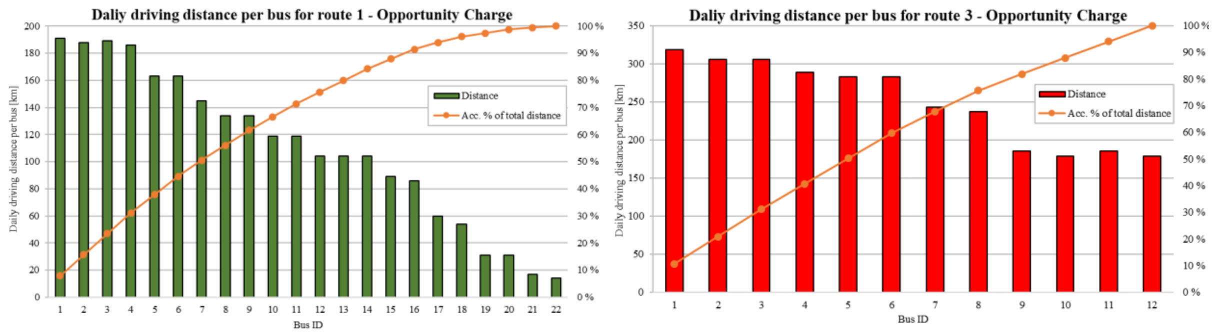


Figure 21 – Left: Usage rate for Route 1, Right: Usage rate for Route 3

The total driver time consist of four components – inactive time, empty driving, trip time and charge and dwell time. The empty driving is the time spent driving to and from the bus depot, seen in grey in Figure 22, and the trip time is the accumulated duration of each trip (blue boxes). The charge and dwell time (orange boxes) is the time that the bus spends adjusting for the chargers and charging. The inactive time (in white) is the time spent waiting for departure at the end-stops.

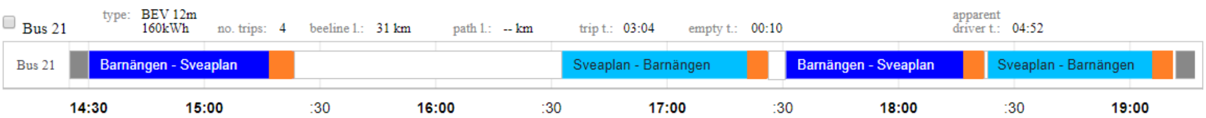


Figure 22 – Driver time components

Figure 23 shows each components share of the total driving time. The trip time (in blue) is the time spent actually transporting passengers, ideally this is the time component that should be maximised. As expected, the trip time for Route 4 accounts for a relatively small share of the overall driver time, explaining the high total annual driver cost per hour for Route 4. The lowest total annual driver cost per hour is € 52,31, achieved by Route 2. The explanation for this can be found in Figure 23, where the trip time for Route 2 accounts for 83,52 % of the total driver time, scoring the highest of the four routes. Intuitively, if the charge and dwell time would remain constant, and the trip duration becomes longer, the charge and dwell component relative to the trip time would decrease. This relationship is demonstrated by route 1 and 2, where both routes have a charge and dwell time of 4 min, but the trip duration is 27 to 48 min and 36 to 59 min. It should be noted that the charge and dwell time for Route 3 is 5 min and 9 min for Route 4, whereby the charge and dwell time accounts for 8,11 % of the total driver time for Route 3. In comparison to Route 2 and 3, Route 1 has a relatively high driver cost per hour at € 55,54. The reason for this is the high share of inactive time, as is illustrated in Figure 23.

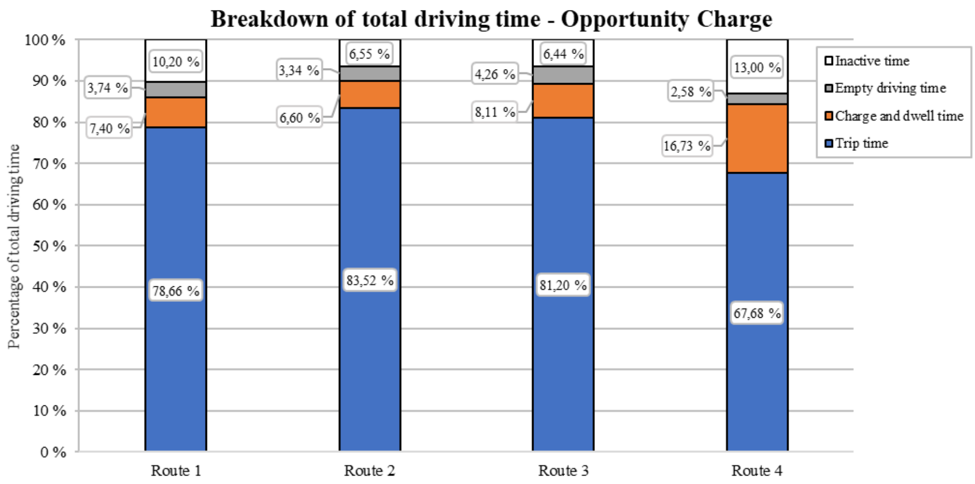


Figure 23 - Breakdown of total driving time

To summarize section 6.2, even though the operating conditions differ between the routes, the total annual cost per hour only vary marginally between route 1, 2 and 3, while Route 4 being the exception with a significantly higher cost per hour. The operating conditions on Route 4 did not allow for the same reduction of the TCO following the reducing charge time, resulting in a significantly higher driver cost per hour relative to the other routes. The high average driving speed on Route 3 results in an increased energy, insurance and maintenance cost. But a high usage rate of the vehicles and relatively low driver cost per hour makes this the route with the second lowest total annual cost per hour.

The result indicates that there are several factors that need to be considered in order to decide what kind of route characteristics that are favorable for opportunity charged buses. Route 3 had the lowest total annual depreciation rate due to a high usage rate of the vehicles. Route 1 had the lowest insurance, maintenance and energy cost due to a low average driving speed. But since the driver cost accounts for the majority of the total annual cost, reducing the driver time is critical in order to achieve a low TCO. This explains why the lowest TCO occurred on Route 2, implying that the route characteristics on this route are favorable when compared to the other four routes. In contrast, the route characteristics on Route 4 resulted in a high total driver time relative to the trip time, see Figure 23, and hence the TCO became much higher than the other three routes. Route 2 has a high trip frequency, high number of daily trips, intermediate trip length and high trip duration, see Table 14, while Route 4 scored low on all characteristics. The route characteristics on Route 2 allow for a high percentage trip time, which translates into a lower driver cost per hour and thus resulting in a lower TCO.

6.3 Findings and analysis of TCO for Overnight Charge

The aim with section 6.3 is to present the findings and analysis associated with TCO for overnight charged buses.

6.3.1 Route 1 - Overnight Charge

When it comes to the total annual cost for overnight charge, the findings from simulation 2 is found in Figure 24, which illustrates the total annual cost for a bus system dimensioned for maximum kilometer in the left bar, and each of the other bars represent the result when maximum number of trips per bus per day was limited. For more detailed numbers, see Appendix A – Findings for Route 1.

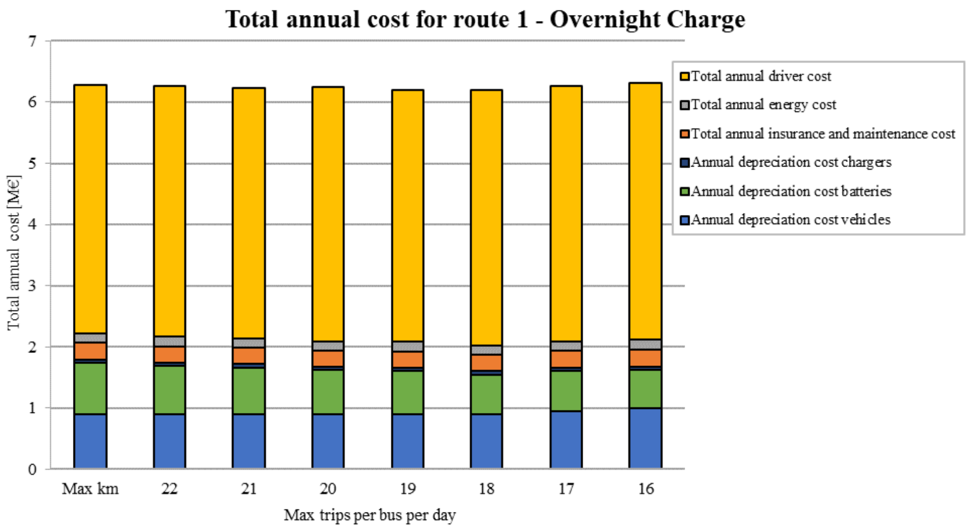


Figure 24 - Total annual cost for Route 1 in the second simulation

As presented in Figure 24, and Table 27, the total annual cost for a bus system optimized to be able to drive the maximum amount of kilometer per day was € 6 287 K. When the maximum number of trips per bus per day was limited, the total annual cost decreased to its minimum cost at 18 trips with a total annual cost of € 6 190 K. This reduction corresponds to a cost saving of € 96 K, i.e. 1,53 % in savings and the main driver behind this is that a lower number of trips will reduce the driving distance per day, which leads to a lower energy consumption. With this lower energy consumption for the bus that acted as the dimensioning case, smaller batteries could be used which decreased the annual battery depreciation cost with € 182 K, i.e. a 22 % decrease. However, the reason why the decrease in total annual cost was € 96 K and not € 182 K is the counteract of driving time. When the maximum number of trips per bus per day was limited, the buses needed to be assign to other trips than what is optimal when it comes to driving time. For Route 1 this led to an increase of annual driver cost of € 95 K, but still a lower total annual cost due to the decrease in annual battery depreciation cost.

The annual battery depreciation cost decreased even more when the maximum number of trips per bus per day was limited to 17 and 16 trips. However, when limited to 17 trips, there was a need for an additional bus to manage the time schedule, and for 16 trips one more bus was needed. So, after 18 trips, the cost for the additional buses and the extra driving time needed had a more negative impact on the total annual cost than the positive impact of decreased battery cost.

Besides previous mentioned changes in costs, the total annual cost was also affected by changes in total annual cost for insurance and maintenance, and total annual energy cost. However, these changes only had a minor effect on the total annual cost, as the changes was small, and insurance and maintenance accounted for 4,26 % of the total annual cost in the maximum kilometer case, and energy accounted for 2,42 %. The increase in total annual insurance and maintenance cost was due to a longer total driving distance, caused by the bus schedule optimization needed to reduce the maximum number of trips per bus per day. Even if the total driving distance was longer, the total annual energy cost was decreased and the reason for this is that the decrease in power fee due to lower installed charge effect, see Table 28, was greater than the increase in energy consumption.

Table 27 - Change in annual costs for overnight charged buses for Route 1

Annual costs	Max km	Best max trips	Change	Change
Total annual depreciation cost	1 794	1 602	-191,95	-10,70 %
Total annual insurance and maintenance cost	268	270	1,87	0,70 %
Total annual energy cost	152	151	-1,19	-0,78 %
Total annual driver cost	4 072	4 167	94,88	2,33 %
Total annual cost	6 287	6 190	-96,39	-1,53 %

[k€] if nothing else is stated

The parameters behind the cost described in the previous paragraphs is presented in Table 28. For both maximum kilometer and the best run for maximum trips per bus per day, i.e. 18 trips, it was found that the lowest total annual cost was found for the same amount of buses, 21 units. As soon as more buses were needed, the increase in vehicle cost offset the decrease in battery cost for overnight charging for Route 1. Except the maximum driving distance per bus per day that was the single major parameter for this cost decrease, it was also found that some cost decrease was achieved as the chargers could operate at a lower effect and still recharge the energy consumed during the day, resulting in a lower investment cost for charging infrastructure and a lower power fee. However, both the decreased battery capacity needed, and the total charge effect are due to the lower driving distance, 145 km for 18 trips instead of 191 km for the maximum kilometer case.

Table 28 - Parameter change for overnight charged buses for Route 1

Parameter	Max km	Best max trips	Change
Vehicles [#]	21	21	0,00 %
Max trips per bus per day [#]	25	18	-28,00 %
Max driving distance per bus per day [km]	191	145	-24,08 %
Battery capacity [kWh]	492	383	-22,15 %
Total driver time per year [hrs]	116 511	119 226	2,33 %
Chargers in depot [#]	21	21	0,00 %
Total charge effect [kW]	1 092	840	-23,08 %

Furthermore, in simulation 2, all of the buses were dimensioned to manage to drive the dimensioning case, i.e. have the most occupied driving schedule when it comes to number of kilometer per day. This will affect the usage rate for the buses. The usage rate measured in km and kWh for the maximum kilometer case is presented in Figure 25.

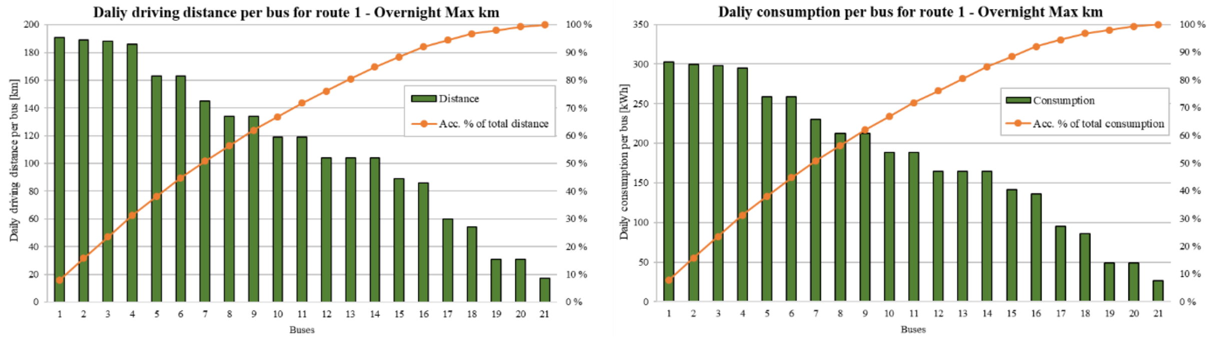


Figure 25 – Left: Usage rate kilometer for Route 1, Right: Usage rate kWh for Route 1

As all buses are dimensioned with respect to the bus with the highest driving distance per day, bus number 1 can be said to have a 100 % usage rate in this case. From this analysis it was found that overnight charged buses at Route 1 had a usage rate of 60 %. This means that 40 % of the feasible driving distance, and thereby also the battery capacity is unused. In practical applications, it would not be a cost-efficient solution to have the same battery dimension for all buses. Instead, the total annual cost will be lower if different battery sizes are used for different buses. However, if that approach is used, it is important to make sure that the correct buses are assigned to the right trips, as all buses cannot travel the maximum kilometer case. Another approach could be to use the buses on more routes to better utilize the buses. Last mentioned solution might be more feasible for overnight charged buses than opportunity charged buses, as overnight charged buses does not require any charging infrastructure along the routes. However, the prerequisite for using the buses at other routes is that other routes have a demand for buses at the same time when the demand is low for Route 1.

To investigate how the usage rate affects the total annual cost, two analyses was performed. In the first analysis it was assumed that the buses only were used at Route 1, and the analysis focused on battery optimization, so the battery size for the whole fleet was calculated for 60, 70, 80, 90 and 100 % usage rate of the battery capacity. The result from this analysis is presented in Figure 26. The difference from this analysis compared with the initial analysis was that the annual cost of battery depreciation was calculated for the new battery size.

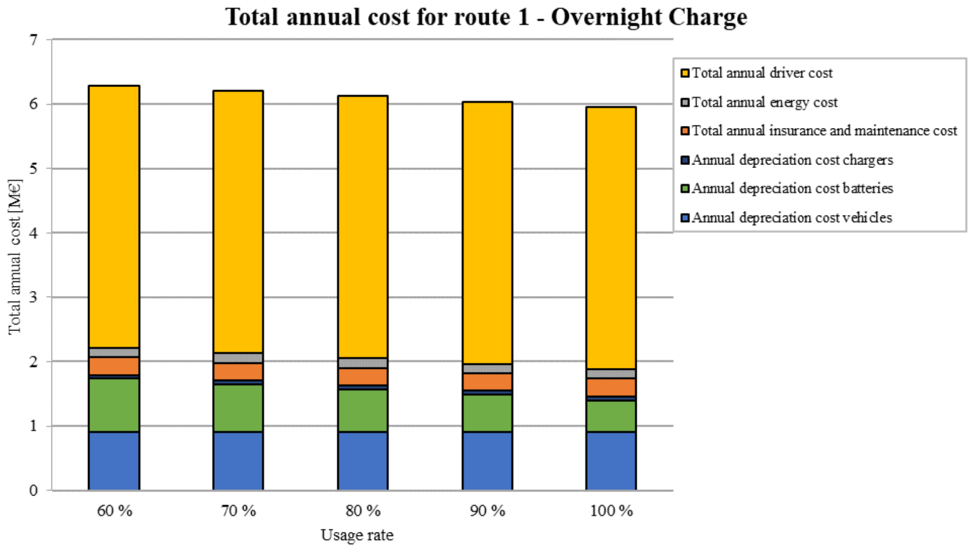


Figure 26 - Analysis of how an alternative battery dimensioning affects the TCO

From this analysis, it was found that the total annual cost decreased from € 6 287 K to € 5 956 K, i.e. an 5,26 % decrease, when going from 60 to 100 % usage rate. The total annual cost at 100 % usage rate is also 3,93 % lower than for the best trip presented in Table 27. However, in practical applications this requires that the buses drive exactly the same trips as they were assigned to in this analysis. Furthermore, it requires that the batteries can be purchased in the size that was calculated here, this is not always the case which will increase the cost as the batteries need to be purchased in a size near but over the calculated value to manage the driving distance. Still, this analysis showed that the battery optimization has a great impact on the TCO and that a usage rate of the battery capacity that goes from 60 % to 72 % will have the same effect as decreasing the number of trips to the optimal point according to Table 27. And if a usage rate higher than 72 % can be achieved, this seems to be a better way to use the overnight charged buses in a cost-efficient way than to only limit the maximum number of trips per bus per day.

In the second analysis of the usage rate, it was assumed that the buses could be used at other routes. And therefore, the annual depreciation cost for vehicles, charging infrastructure and batteries, vehicle insurance cost and maintenance cost for chargers was calculated for 60, 70, 80, 90 and 100 % usage rate of the battery capacity. The result from this analysis is presented in Figure 27.

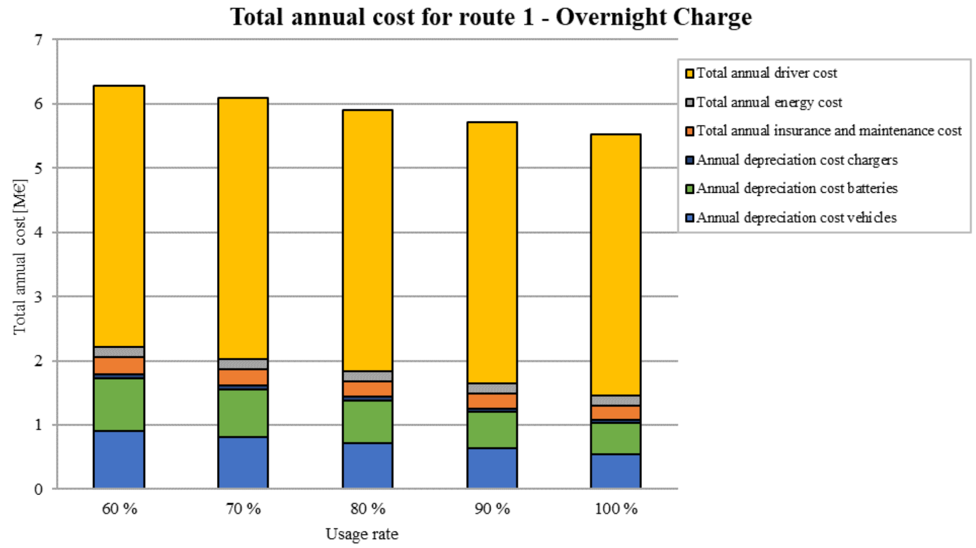


Figure 27 - Analysis of how alternative usage of unused bus capacity affects the TCO

It was found that a higher usage rate of the buses, i.e. the possibility to use buses on other routes to increase the total usage rate, not only for the battery but also for vehicles and charging infrastructure has a great potential to decrease the total annual cost. When going from the initial usage rate of 60 % to 100 % a decrease of total annual cost from € 6 287 K to € 5 531 K, i.e. a decrease of 12 %. However, a usage rate of 100 % of the whole fleet might not be a realistic scenario, but if this is compared with the previous analysis of the battery dimensioning, at 78 % the shared fleet will reach the same total annual cost as 100 % usage of the battery capacity in the previous analysis.

6.3.2 Route 2 – Overnight Charge

In a similar way as for Route 1, this subsection will present the result and analysis from simulation 2 and Route 2, when it comes to the total annual cost for overnight charge. For more detailed numbers, see Appendix B – Findings for Route 2.

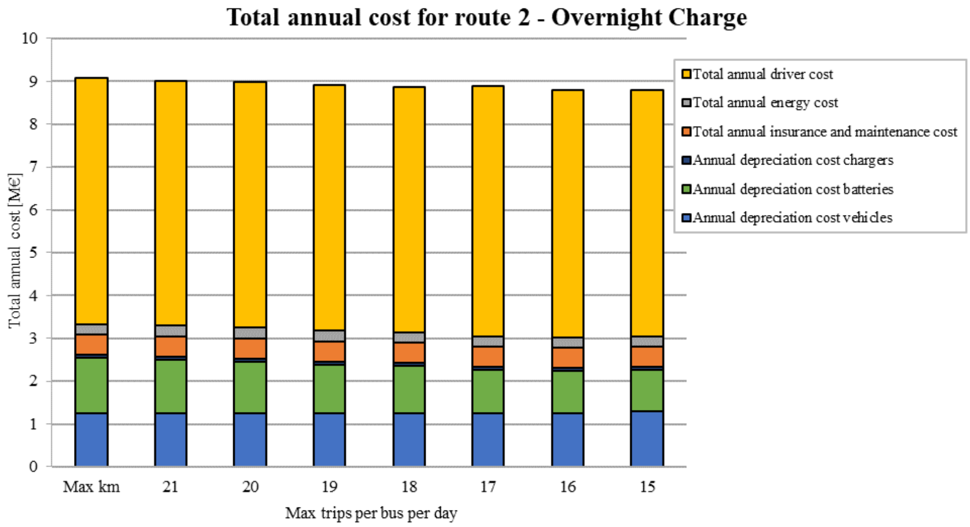


Figure 28 – Total annual cost for Route 2 in the second simulation

From simulation 2, as presented in Figure 28 and Table 29, it was found that the total annual cost for an overnight charged bus system at Route 2, dimensioned to drive the maximum number of kilometers was € 9 069 K. The maximum number of trips per bus per day was limited and the lowest total annual cost was found at 16 trips, with a total annual cost of € 8 796 K. This decrease corresponds to 3,01 %, compared with 1,52 % for Route 1. The main driver of this decrease is the same as for Route 1, i.e. decreased driving distance for the bus used for battery dimension, which leads to smaller batteries and a lower annual battery depreciation cost. However, the decrease in total annual cost for Route 2 is greater than for Route 1 and the main reason for this is that on Route 1, the driver time increased with 2,33 %, while Route 2 only had an increased driver time of 0,90 %.

When it comes to the annual battery depreciation cost, the same pattern was found for Route 2 as for Route 1, i.e. the battery cost decreased even more after the run with the lowest total annual cost. However, when going below 16 trips per bus per day, an additional bus was needed and the investment cost for that bus was greater than the cost reduction for batteries.

For Route 2, the total annual cost for insurance and maintenance did not increase as for Route 1, instead there was a minor decrease by 0,05 %. Even for this route, the total driving distance was longer when maximum trip per bus per day was decreased. However, the decrease in maintenance of charging infrastructure was greater than the increase in maintenance of vehicles and tire wear, both depending on the driving distance. When it comes to the total annual energy cost, this cost decreased when the maximum number of trips per bus per day was decreased, and as for Route 1, this was due to a decrease in power fee due to a lower installed charger effect, see Table 30, that decreased more than the increase in energy consumption.

Table 29 - Change in annual costs for overnight charged buses for Route 2

Annual costs	Max km	Best max trips	Change	Change
Total annual depreciation cost	2 618	2 299	-319,81	-12,21 %
Total annual insurance and maintenance cost	472	472	-0,22	-0,05 %
Total annual energy cost	242	237	-4,37	-1,81 %
Total annual driver cost	5 737	5 789	51,66	0,90 %
Total annual cost	9 069	8 796	-272,75	-3,01 %

[k€] if nothing else is stated

Table 30 present some the parameters behind the total annual cost. As for Route 1, Route 2 also had its lowest total annual cost for maximum kilometer and maximum number of trips per bus per day at the same number of buses, 29 units. For maximum number of trips, 16 trips had the lowest total annual cost, then the additional vehicle cost offset the saving in battery cost for overnight charging for Route 2. At 16 trips per day, the maximum driving distance per bus per day decreased from 281 km to 203 km, a slightly higher decrease than for Route 1.

Table 30 - Parameter change for overnight charged buses for Route 2

Parameter	Max km	Best max trips	Change
Vehicles [#]	29	29	0,00 %
Max trips per bus per day [#]	23	16	-30,43 %
Max driving distance per bus per day [km]	281	203	-27,76 %
Battery capacity [kWh]	556	424	-23,74 %
Total driver time per year [hrs]	164 168	165 646	0,90 %
Chargers in depot [#]	29	29	0,00 %
Total charge effect [kW]	1 450	1 073	-26,00 %

As mentioned, all the buses in simulation 2 were dimensioned to manage to drive the dimensioning case. The usage rate measured in km and kWh for the maximum kilometer case is presented in Figure 29.

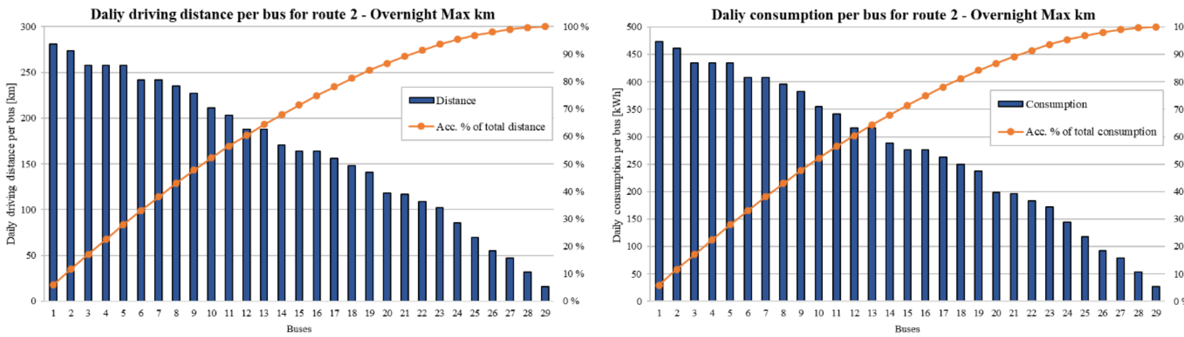


Figure 29 – Left: Usage rate kilometer for Route 2, Right: Usage rate kWh for Route 2

From the analysis of the findings from Figure 29, it was found that the overnight charged buses on average had a usage rate of 58 %. This usage rate is quite similar to Route 1, which had a usage rate of 60 %. Different ways on how to increase this usage rate will not be discussed here, as that was done in 6.3.1. However, to investigate how the usage rate affects the total annual cost, the two analysis that was performed in 6.3.1 was performed also for Route 2. The result from the first analysis is presented in Figure 30.

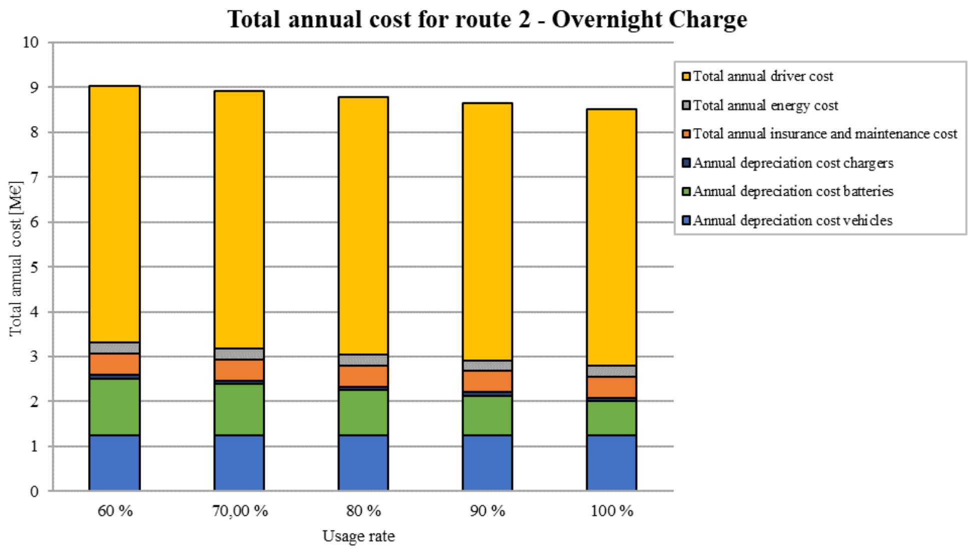


Figure 30 - Analysis of how an alternative battery dimensioning affects the TCO

From this analysis, it was found that the total annual cost decreased with 5,71 %, from € 9 043 K at 60 % usage rate to € 8 527 K at 100 % usage rate. If € 8 527 K is compared with the total annual cost for the best run when maximum trips per bus per day was used, i.e. € 8 769 K, the fleet with a fully optimized battery size have an 2,76 % lower total annual cost. However, in practical applications, the same difficulties discussed for Route 1 will be present also for Route 2. Yet, this analysis showed that the battery optimization has a great impact on the total annual cost also for Route 2, and that a usage rate of the battery capacity that goes from 58 % to 81 % will have the same effects as decreasing the number of trips to the optimal point according to Table 30. And when the usage rate for the battery capacity is higher than 81 %, the total annual cost will be lower, and considering that, this way to use overnight charged buses seems to be a more cost-efficient way than only to limit the maximum trips per bus per day also for Route 2.

In the second analysis of the usage rate for Route 2, as for Route 1, it was assumed that the buses could be used at other routes. The result from this analysis is presented in Figure 31.

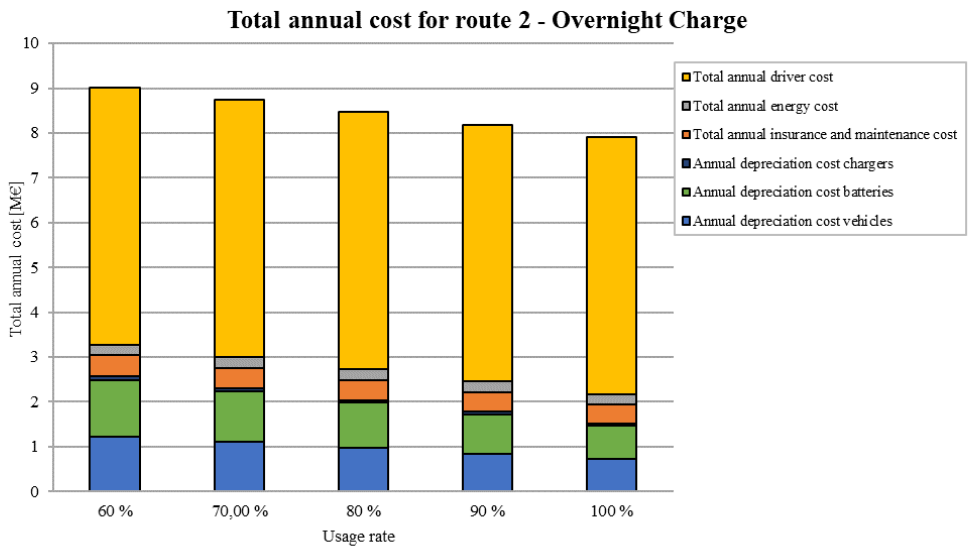


Figure 31 - Analysis of how alternative usage of unused bus capacity affects the TCO

It was found that a higher usage rate of the buses, i.e. the possibility to use buses on other routes to increase the total usage rate, not only for the battery but also for vehicles and charging infrastructure has a great potential to decrease the total annual cost also for Route 2. At 60 % usage rate, the total annual cost was € 9 014 K, but for 100 % usage rate the total annual cost decreased to € 7915 K, which corresponds to an 12,19 % decrease. The same difficulties to achieve a high usage rate for the whole fleet is the same for Route 2 as for Route 1. However, at a usage rate for the whole fleet of 77 %, the total annual cost will be the same as for 100 % usage of the battery capacity, investigated in the previous analysis.

6.3.3 Route 3 – Overnight Charge

As for route 1 and 2, this subsection presents the result and analysis from simulation 2 for Route 3, when it comes to the total annual cost for overnight charge. For more detailed numbers, see Appendix C – Findings for Route 3.

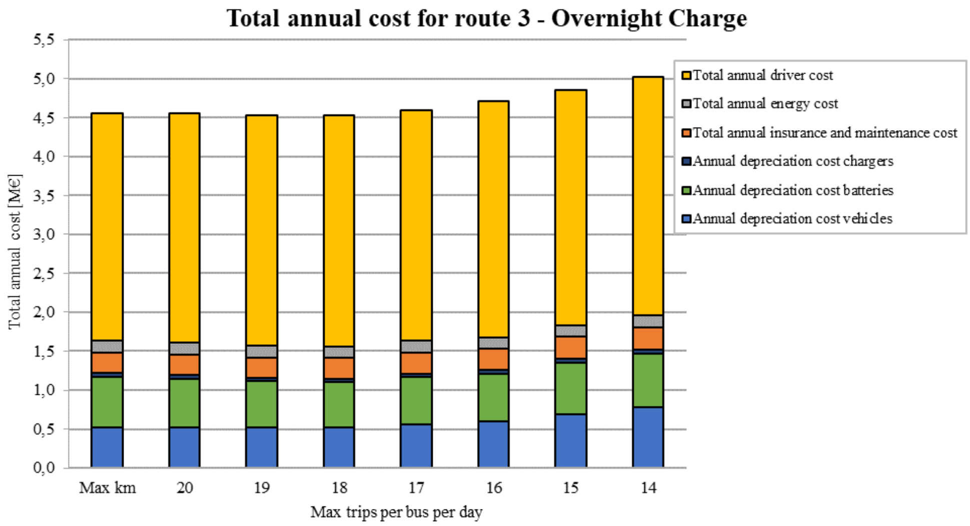


Figure 32 – Total annual cost for Route 3 in the second simulation

From simulation 2, as presented in Figure 32 and Table 31, it was found that the total annual cost for an overnight charged bus system at Route 2, dimensioned to drive the maximum amount of kilometer was € 4 558 K. The lowest total annual cost for Route 3 was found at 18 trips per bus per day, and the total annual cost for that run was € 4 523. This corresponds to an 0,78 % decrease, compared to a decrease with 3,01 % and 1,52 % for route 1 and 2. The reason behind this is easier to understand when looking at Figure 33, i.e. the average usage of the buses at Route 3 are higher, and due to that there are less room for improvement if only limiting the maximum number of trips per bus per day.

For the annual battery depreciation cost, Route 3 differs from route 1 and 2 after the point were the lowest total annual cost was found. For route 1 and 2, the battery depreciation cost decreased even more after this point, while the battery depreciation cost increased after this point for Route 3. This is the reason why the increase in total annual cost, that can be seen in Figure 32 is quite steep after 18 trips. After 18 trips, one additional bus is needed, which also was the reason why the total annual cost increased for route 1 and 2. However, the bus fleet at Route 3 is smaller, and this together with a larger battery size per bus leads to that the battery cost for an additional bus is higher than the decrease in cost due to a decrease in battery size per bus.

As presented in Table 31, the total annual cost for insurance and maintenance increased by 0,72 % due to a slightly longer travel distance when the maximum trips per bus per day was limited to 18 trips. Even for this route, the cost for maintenance of charger decreased, but not enough to offset the increased cost due to the longer travel distance. The annual energy cost was almost the same and the small increase by

0,25 % was due to that the increase in energy consumption was greater than the cost reduction due to a lower power fee caused by the lower installed charge effect.

Table 31 - Change in annual costs for overnight charged buses for Route 3

Annual costs	Max km	Best max trips	Change	Change
Total annual depreciation cost	1 215	1 140	-74,76	-6,15 %
Total annual insurance and maintenance cost	268	270	1,94	0,72 %
Total annual energy cost	148	149	0,37	0,25 %
Total annual driver cost	2 927	2 964	36,99	1,26 %
Total annual cost	4 558	4 523	-35,46	-0,78 %

[k€] if nothing else is stated

Some of the parameters behind the total annual cost is presented in Table 32. What can be found is that Route 3 had its lowest total annual cost for maximum kilometer and maximum number of trips per bus per day at the same number of buses, 12 units. This result is in line with the result from route 1 and 2, were the cost of add additional buses offset the decrease in battery cost. At 18 trips per day, the driving distance went from 318 km to 283 km causing a battery size reduction from 680 kWh to 605 kWh. This decrease corresponds to 11 %, which is approximately half of the decrease found for route 1 and 2. One major reason behind this is the same as for the lower decrease in the total annual cost, i.e. the higher usage rate in the max kilometer case.

Table 32 - Parameter change for overnight charged buses for Route 3

Parameter	Max km	Best max trips	Change
Vehicles [#]	12	12	0,00 %
Max trips per bus per day [#]	21	18	-14,29 %
Max driving distance per bus per day [km]	318	283	-11,01 %
Battery capacity [kWh]	680	605	-11,03 %
Total driver time per year [hrs]	83 751	84 810	1,26 %
Chargers in depot [#]	12	12	0,00 %
Total charge effect [kW]	648	576	-11,11 %

As mentioned, all the buses in simulation 2 were dimensioned to manage to drive the dimensioning case. The usage rate measured in km and kWh for the maximum kilometer case is presented in Figure 33.

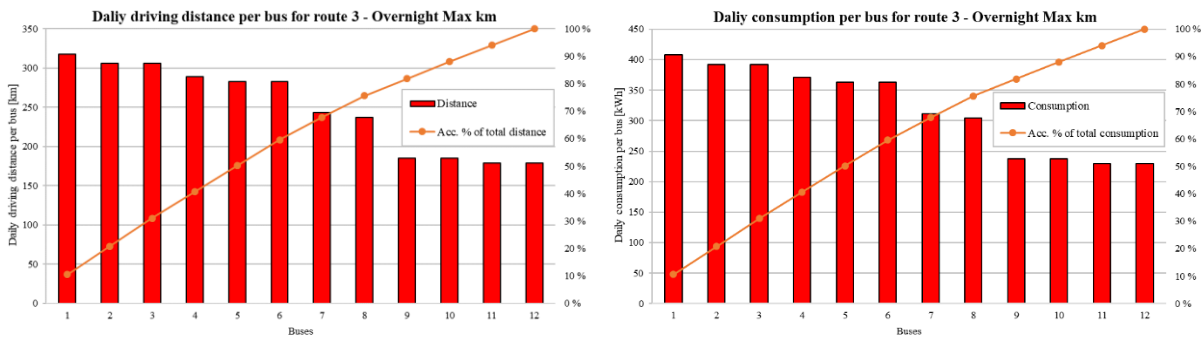


Figure 33 – Left: Usage rate kilometer for Route 3, Right: Usage rate kWh for Route 3

From the analysis of usage rate for Route 3, it was found that the overnight charged buses on average had a usage rate of 78 %. Which means that the usage rate for Route 3 is higher than for route 1 and 2, were the usage rate was 60 % and 58 %. One thing that affect the usage rate of the buses is the difference in demand during peak times and non-peak times. This has a great impact since the bus system needs to be dimensioned to manage peak times and this leads to the fact that some of the buses used during peak times will not be used during non-peak times, causing a low average usage rate for the fleet. How the usage rate will affect the total cost per km and total cost per hour, which are numbers that can be used to compare the cost between different route will be presented in 6.3.6.

Different ways on how to increase this usage rate will not be discussed here, as that was done in 6.3.1. However, to investigate how the usage rate affects the total annual cost, the two analysis that was performed for route 1 and 2 was performed also for Route 3. The result from the first analysis is presented in Figure 34. Notice that the usage rate for the maximum kilometer case was 78 %, and not lower or the same as the first bar as for previous routes.

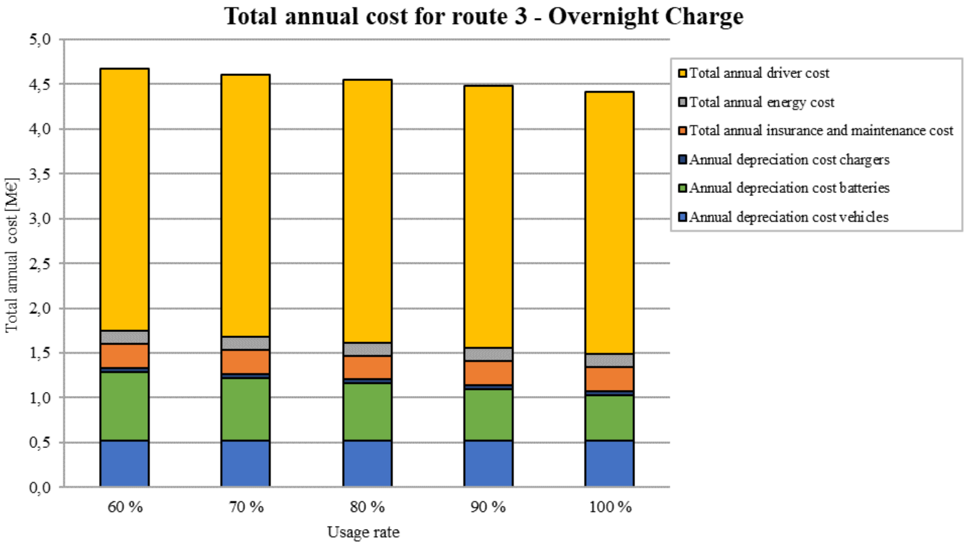


Figure 34 - Analysis of how an alternative battery dimensioning affects the TCO

From Figure 34 it can be found that the total annual cost decreased from € 4 676 K to € 4 414 K, i.e. an 5,59 % decrease when going from 60 % to 100 % usage rate. When comparing the result with an 100 % usage rate with the best run when maximum trips per day was used, i.e. € 4 523 K, the total annual cost was decreased with 2,41 %. To achieve the same total annual cost as for the best run for maximum trips per day, the usage rate of the battery capacity need to increase from 78 % to 83 %. The result follows the same pattern as for route 1 and 2, that there seems to be more cost saving to achieve by optimize the total battery capacity for the fleet, than only limit the maximum number of trips per day

In the second analysis of the usage rate for Route 3, as for route 1 and 2, it was assumed that the buses could be used at other routes. The result from this analysis is presented in Figure 35.

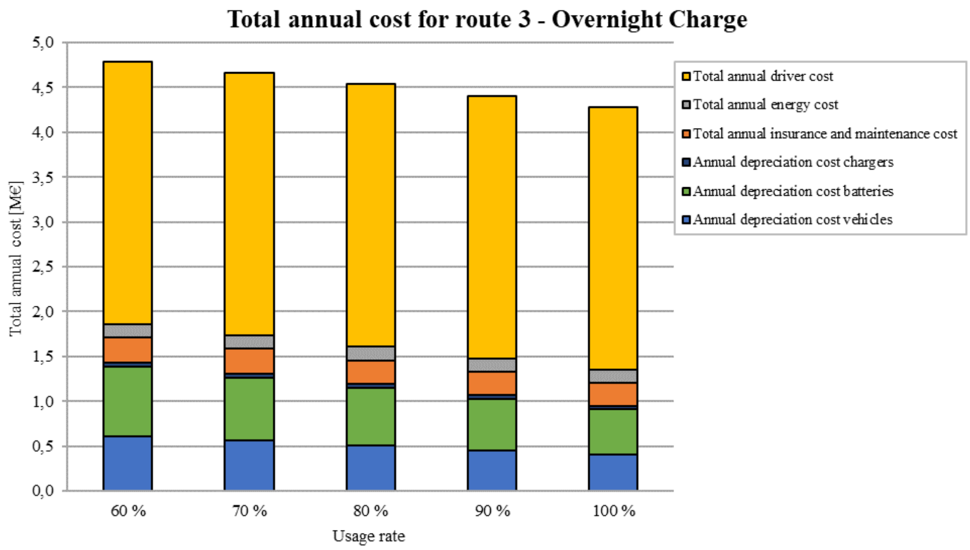


Figure 35 - Analysis of how alternative usage of unused bus capacity affects the TCO

Here, it was found that an increase from 60 % usage rate to 100 % usage rate will decrease the total annual cost by 10,60 %, going from € 4 786 K to € 4 279 K. However, it should be mentioned also here that the initial usage rate for the maximum kilometer case was 78 % for Route 3. This means that the decrease that can be achieved for Route 3 is as decrease by 6,12 %, when going from 78 % usage rate to 100 %. As for route 1 and 2, there are difficulties to reach a high usage rate for the whole fleet in practical applications. However, by increasing the usage rate for the whole fleet from 78 % to 89 %, the total annual cost will be the same as for 100 % usage of the battery capacity.

6.3.4 Route 4 – Overnight Charging

In a similar way as for the previous three routes, this subsection presents the result and analysis from simulation 2 for Route 4, when it comes to the total annual costs for overnight charge. For more detailed numbers, see Appendix D – Findings for Route 4.

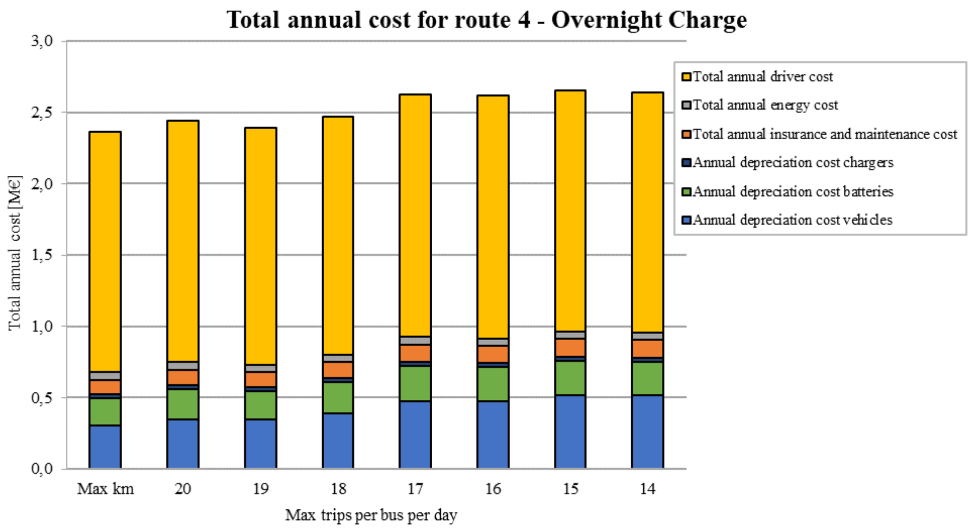


Figure 36 – Total annual cost for Route 4 in the second simulation

The result from simulation 2 is presented in Figure 36, and it was found that Route 4 differs when it comes to the lowest total annual cost compared to route 1, 2 and 3. For Route 4, the lowest total annual cost was found for the maximum kilometer case and not when the maximum number of trips per bus per day was limited. For the maximum kilometer case the total annual cost was € 2 362 K, while the best run when maximum trips per bus per day was € 2 394 K, i.e. 1,37 % higher. The reason for this is that the usage rate for Route 4 is high, see Figure 37, and already when maximum number of trips goes from the initial 21 trips to 20 trips, an additional bus is needed. For 19 trips, the same number of buses are needed as for 20 trips, and the lower battery size here leads to a lower total annual cost due to lower battery cost. However, when the number of trips is decreased to 18, one more additional bus is needed and the total annual cost increase again. This pattern follows all the runs when the maximum number of trips per bus per days was limited for Route 4. One deviation from this pattern is between 18 trips and 17 trips, where the total annual cost continued to increase due to the need of two additional buses.

Table 33 which presents the total annual cost for Route 4 looks slightly different compared with the other routes, due to that the lowest annual cost was found for the maximum kilometer case. What can be found is that the annual depreciation cost increased with 9,63 % when going from 21 trips to 19 trips, because the decrease in battery cost was offset by the increase in cost for an additional bus. For the same reason, the annual cost for insurance and maintenance increased. The annual energy cost was almost unchanged, only a minor decrease with 0,02 %. Moreover, the total annual driver cost was decreased with 1,28 %.

Table 33 - Change in annual costs for overnight charged buses for Route 4

Annual costs	Max km	Best max trips	Change	Change
Total annual depreciation cost	521	571	50,18	9,63 %
Total annual insurance and maintenance cost	106	110	3,75	3,54 %
Total annual energy cost	51	51	-0,01	-0,02 %
Total annual driver cost	1 685	1 663	-21,63	-1,28 %
Total annual cost	2 362	2 394	32,29	1,37 %

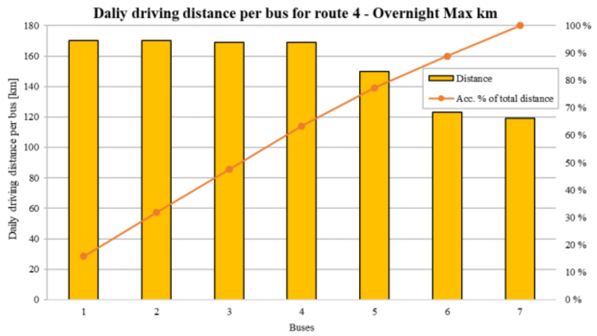
[k€] if nothing else is stated

Table 34 presents some of the drivers behind the total annual costs. What can be found here is that Route 4 did not have the same number of buses for maximum kilometer and maximum number of trips per bus per day for the lowest total annual cost. For all other routes, this was true but for Route 4 an additional bus was needed already when the number of trips was limited with one trip. However, when the number of trips per bus per day was limited, the maximum driving distance went from 170 km to 312 km, resulting in an increase in battery capacity from 312 kWh to 345 kWh. From a practical perspective this might be interesting even if the total annual cost was higher, as e.g. Yutong and BYD offers buses with 324 kWh battery capacity (Bloomberg NEF 2018; ZeEUS 2017a). On the other hand, MAN offers a solo bus with 480 kWh in battery capacity (MAN 2018).

Table 34 - Parameter change for overnight charged buses for Route 4

Parameter	Max km	Best max trips	Change
Vehicles [#]	7	8	14,29 %
Max trips per bus per day [#]	21	19	-9,52 %
Max driving distance per bus per day [km]	170	154	-9,41 %
Battery capacity [kWh]	345	312	-9,57 %
Total driver time per year [hrs]	48 201	47 582	-1,28 %
Chargers in depot [#]	7	8	14,29 %
Total charge effect [kW]	189	200	5,82 %

As mentioned, all the buses in simulation 2 were dimensioned to manage to drive the dimensioning case. The usage rate measured in km and kWh for the maximum kilometer case is presented in Figure 37.



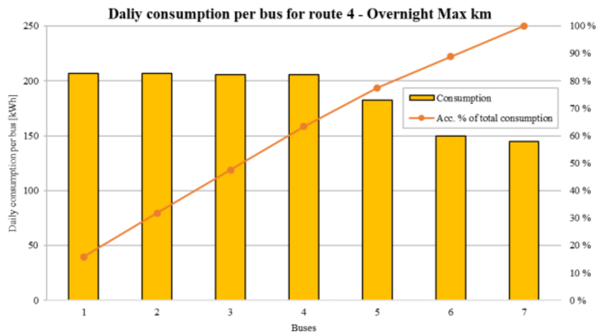


Figure 37 – Left: Usage rate kilometer for Route 4, Right: Usage rate kWh for Route 4

From the analysis of usage rate for Route 4, it was found that overnight charged buses on average had a usage rate of 90 %. This means that Route 4 had the highest usage rate of all investigated routes, as route 1, 2 and 3 had a usage rate of 60 %, 58 % and 78 %. As mentioned in 6.3.3, the difference in demand during peak times and non-peak times has a great effect on the usage rate. How this demand differs between the different routes and how this affect the total cost per km and total cost per hour will be presented in 6.3.6.

As the discussion about how to increase the usage rate was done in 6.3.1, it will not be discussed here. However, to investigate how the usage rate affects the total annual cost, the two analysis that was performed for the previous three routes was performed also for Route 4. The result from the first analysis is presented in Figure 38. Notice that the usage rate for the maximum kilometer case was as high as 90 %, and not lower or the same as the first bar as for route 1 and 2.

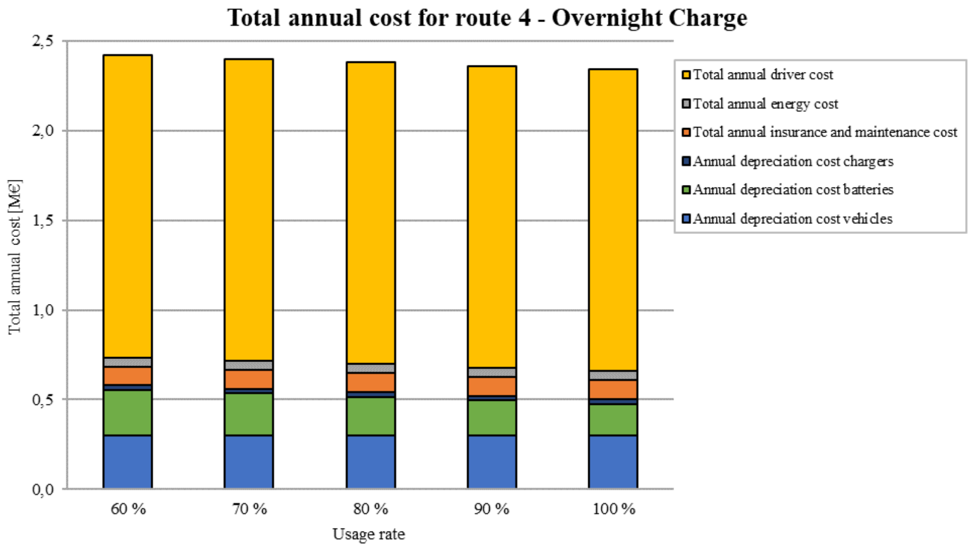


Figure 38 - Analysis of how an alternative battery dimensioning affects the TCO

Figure 38 shows that when going from 60 % usage rate to 100 % for Route 4, the total annual cost will decrease from € 2 420 K to € 2 343 K, i.e. an 3,19 % decrease. This was the lowest decrease in total annual cost for all routes, as the decrease was 5,26 %, 5,71 % and 5,59 %. One reason for this is the number of buses and battery capacity and Route 4 had both the lowest number of buses and smallest battery size. Due to that, the cost saving when the usage rate of battery capacity increased was some 2 % lower than for the other routes. However, the usage rate for Route 4 was already 90 %, and the potential decrease in total annual cost when going from € 2 362 K at 90 % to € 2 343 K at 100 % is 0,82 %. On the other hand, the high usage rate might indicate that Route 4 is a potential candidate for a route to be electrified, since it both has a high usage rate and a total energy consumption that seems to make not only opportunity charging, but overnight charging practical possible. The reason why the usage rate might do Route 4 to a potential candidate is that electric buses has a high investment cost compared to buses with combustion engines, but instead a lower running cost (Olsson, Grauers & Pettersson 2016). And with a high usage rate of the buses, the running costs are likely to be lower. However, this will be further analyzed in 6.3.6 and 6.5.

In the second analysis of the usage rate for Route 4, as for all previous routes, it was assumed that the buses could be used at other routes. The result from this analysis is presented in Figure 39.

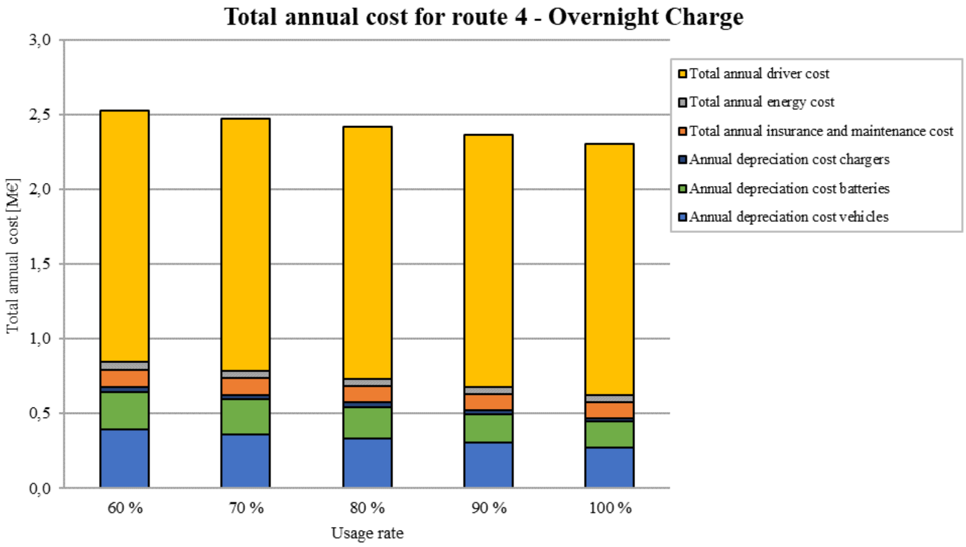


Figure 39 - Analysis of how alternative usage of unused bus capacity affects the TCO

Here, it was found that an increase from 60 % usage rate to 100 % usage rate for the fleet will decrease the total annual cost from € 2 527 K to € 2 307 K, i.e. an 8,71 % decrease. For the same reason as mentioned in the previous analysis, this is a lower decrease than for the other routes. As mentioned, the usage rate for Route 4 is 90 % and when going from a usage rate of 90 % to 100 %, the total annual cost decreased from € 2 362 K to € 2 307 K, i.e. an 2,33 % decrease. For Route 4, the total annual cost for 60 % is higher than for 60 % from the previous analysis of usage rate for battery capacity. The reason for this is that a 60 % usage rate here will add additional costs for buses, charger, insurance and maintenance, besides the battery cost. To achieve the same total annual cost as for 100 % usage rate of the battery capacity, a usage rate for the whole fleet of 93 % was required, i.e. 3 % higher than in the maximum kilometer case.

6.3.5 Depth of Discharge - Overnight Charge

From the previous four subsections, the needed battery capacities presented in Table 35 was found. These battery capacities were calculated with a lower SOC of 20 % and an upper SOC of 80 %, which corresponds to an 60 % DOD.

Table 35 - Battery capacity and costs for overnight charge

	Route 1	Route 2	Route 3	Route 4
Battery capacity per bus [kWh]	492	556	680	345
Battery capacity per fleet [kWh]	10 332	16 124	8 160	2 413
Battery investment cost [k€]	5 567	8 696	4 398	1 301
Annual battery depreciation cost [k€]	827	1 292	653	193
Percentage of total annual cost	13,15 %	14,24 %	14,33 %	8,18 %

Moreover, as we can see in Table 35, the annual battery depreciation cost accounted for between 8,18 % to 14,33 % of the total annual cost. Hence, it is of interest to investigate if an increased DOD which leads to smaller batteries also leads to a lower battery depreciation cost, and thereby a lower total annual cost. To see how the DOD will affect the battery depreciation cost, it is important to calculate the life time for the battery which will affect the battery depreciation time. For this, the model presented by Hoke et al. (2011) in 2.2 was used, and the result for battery life and number of batteries needed during a contract life of 10 years is presented in Figure 40.

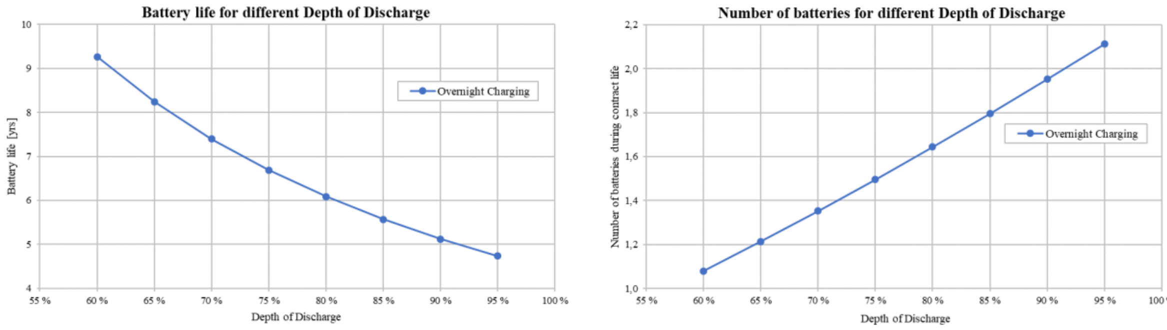


Figure 40 – Left: Battery life for different DOD, Right: Number of batteries during contract time

From this analysis, it was found that at a 60 % DOD, the battery life is 9,3 years while a 95 % DOD will reduce the battery life to 4,7 years according to the model by Hoke et al. (2011). In simulation 2, were 60 % DOD was used it was assumed that the battery life was 8 years, which is a slightly more conservative time than with this model. Moreover, how the DOD will affect the battery size per bus for all four routes is presented in Figure 41.

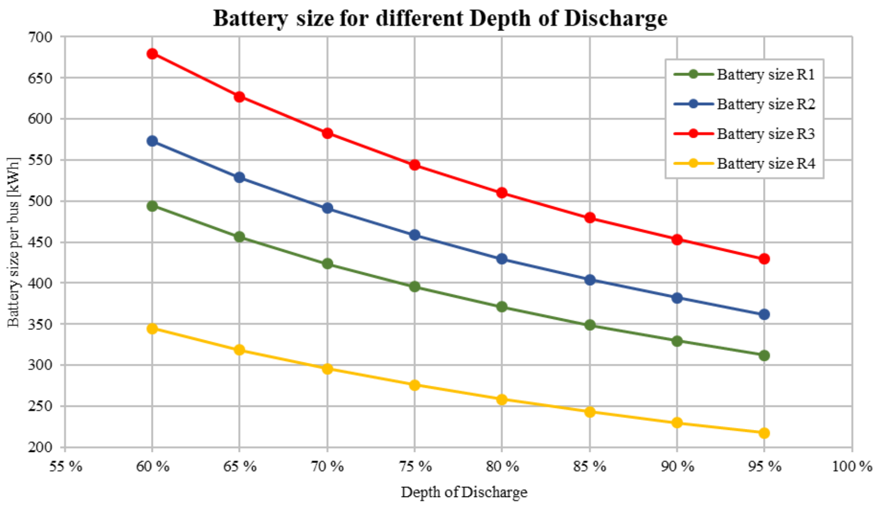


Figure 41 - How the DOD will affect the battery size

This analysis shows that the battery size can be reduced from 494 kWh to 312 kWh for Route 1, from 573 kWh to 362 kWh for Route 2, from 680 kWh to 429 kWh for Route 3 and from 345 kWh to 218 kWh for Route 4. To use 95 % DOD is an extreme case, however as mentioned in the theoretical framework, Lajunen (2018) used a 95 % DOD for overnight charged buses. What is interesting from this analysis is not only if the decrease in battery size lead to a lower total annual cost, but also if it is possible to decrease the battery size to sizes that are available on the market today. One example of a solo bus with a high battery capacity is MAN Lion's City E with 480 kWh (MAN 2018). And from Figure 41 it can be found that Route 1 can use this battery size with 65 % DOD, Route 2 with 75 % DOD, Route 3 with 85 % DOD and Route 4 can use this battery size even with a smaller DOD than 60 %.

However, a decreased battery size will decrease the initial investment cost for batteries, but not necessary the annual cost of battery depreciation. The reason for this is as mentioned that a decreased battery size, ceteris paribus, leads to a higher DOD which will decrease the battery life. When the model by Hoke et al. (2011) was used to see how the annual cost of battery depreciation changed for different DOD, the result in Figure 42.

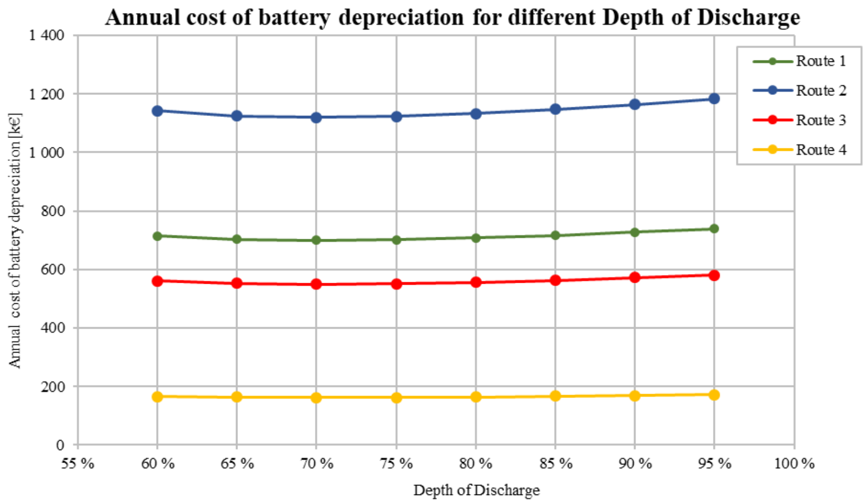


Figure 42 - Annual cost of battery depreciation for different DOD

In this analysis, it was assumed that the battery price today was the same as in previous analysis, i.e. € 540 per kWh and that the annual price reduction was 5 %. With these assumptions the result shows that the annual cost of battery depreciation will remain quite stable for different DOD. For all the routes it was a small decrease in cost when increasing the DOD, due to that the reduction in size had a greater impact than the reduction in battery life. Then the battery cost starts to increase due to a decreases battery life, and the total annual cost of battery deprecation increased by 3,55 % when going from 60 % to 95 % DOD. How this affect the total cost per kilometer is presented in Figure 43.

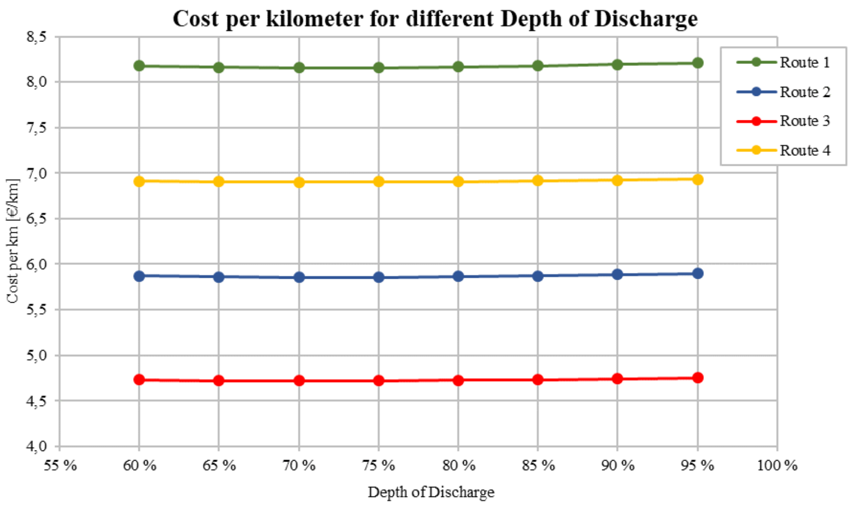


Figure 43 - Cost per kilometer for different DOD

From this analysis it was found that the effect on total cost per km was small for different DOD. When going from 60 % to 100 % DOD the total annual cost for Route 1 increased with 0,41 %, followed by 0,46 %, 0,45 % and 0,25 % for Route 2, 3 and 4. However, before the cost per km increase, there is a small decrease in cost per km for all routes when going from 60 % to 75 % DOD, where the lowest total cost per km was found. One outcome from this analysis is that there seems to be only small changes in total annual cost by decreasing the battery size by increasing the DOD, if the model by Hoke et al. (2011) is valid. Another outcome is that the battery capacity needed for overnight charging for route 1, 2 and 3 was higher than what is currently available on the market, i.e. 480 kWh (MAN 2018). However, this analysis showed that by increasing the DOD, ceteris paribus, for all investigated routes the battery size can be reduces to this number. Also, for this outcome, it is important that the model by Hoke et al. (2011) is valid. These two outcomes together, that batteries available at the market today could be used for approximately the same total annual cost as in the analysis presented in previous four sections also strengthen the practical implications of this master's thesis.

6.3.6 Comparative analysis of routes – Overnight Charge

In the previous five subsections of section 6.3, overnight charging has been analyzed to find the drivers behind the total annual cost and how it differs between different routes and why. Furthermore, the DOD was investigated to see how it affected the total annual cost. In this subsection, the findings from all of these analyses will be presented together with a more comparative analysis between the routes. The result from the first analysis of cost per km is presented in Figure 44.

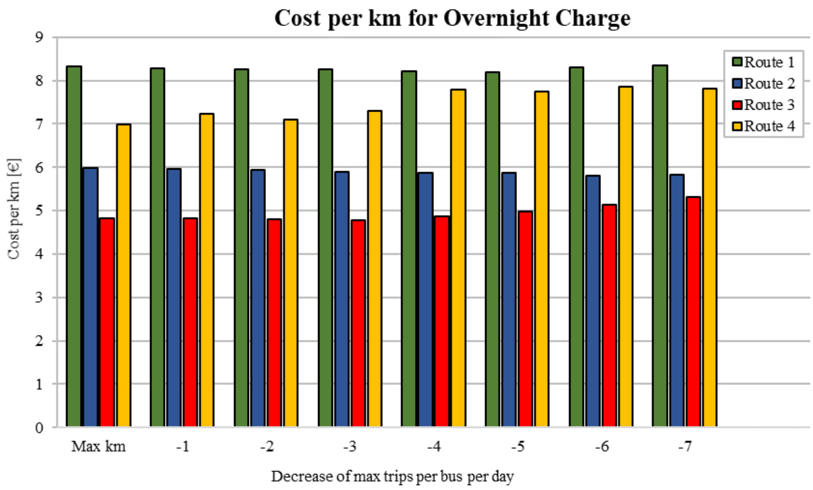


Figure 44 - Cost per km for Overnight Charge

From this analysis it was found that the mutual order between the routes when it comes to cost per km for overnight charged buses was not changed during the runs. The route with the lowest cost per km was Route 3, followed by Route 2, 4 and 1. In 6.3.4 it was mentioned that Route 4 might be a great candidate to electrify as the usage rate was high, as electric buses are known to have high initial capital expenditures but a lower operating cost than buses with internal combustion engines (Olsson, Grauers & Pettersson 2016). However, according to this result it seems to be more parameters than the usage rate that effect as Route 4 with the highest usage rate was the second most expensive route when looking at cost per km. On the other hand, Route 3, with the second highest usage rate had the lowest cost per km of the investigated routes. It should also be mentioned that electric buses can still have a lower total annual cost at Route 4 than buses with combustion engines, as this comparison was not done in this master's thesis.

Moreover, as in 6.2.5, an analysis was also performed for cost per hour as cost per km might not be a fair measure to use when analyzing city buses (Lajunen 2018). The result from this analysis is presented in Figure 45.

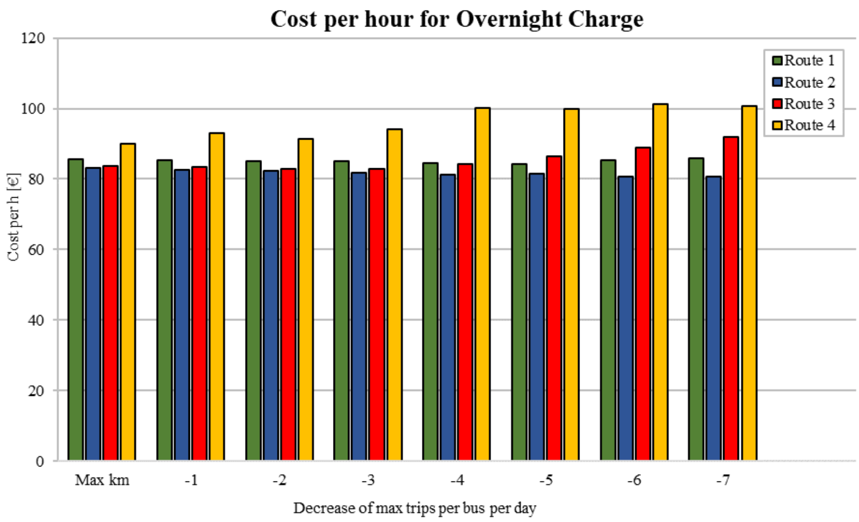


Figure 45 - Cost per hours for Overnight Charge

According to the result in Figure 45, the differences between the routes seems to be smaller measured in cost per hour than in cost per km. The mutual order between the routes for cost per km did not change during the runs, and this was also true the cost per hour. However, when looking at the cost per hour, Route 2 had the lowest cost per hour, followed by Route 3, 1 and 4. So, when measure cost per hour, the route with the highest usage rate was the route that was most expensive to drive with opportunity charged buses. When the result from the dimensioning case for maximum kilometer was analyzed, the values presented in Table 36 was found for cost per km, cost per hour and usage rate.

Table 36 - Cost per hour, cost per km and usage rate for Overnight Charge

	Route 1	Route 2	Route 3	Route 4
Cost per km [€/km]	8,32	5,99	4,83	6,99
Cost per hour [€/hr]	85,63	83,16	83,56	90,04
Usage rate	60 %	58 %	78 %	90 %

If the costs in Table 36 is compared with previous studies, the result for cost per km is higher also for overnight charging. One reason for this is, as mentioned in 6.2.5, that most of the previous studies chose to exclude the driver cost. Olsson, Grauers and Pettersson (2016) calculated the cost per km with the driver cost included, and for overnight charging the cost was € 3,56 per km. This means that the result for the route with the lowest cost per km for overnight charging in this master's thesis was still higher than for previous studies. If the driver cost is excluded from the cost per km, the result was € 2,86 for Route 1, followed by € 1,99 for Route 2, € 1,65 for Route 3 and € 2,01 for Route 4. This can be compared with a result between € 0,8 and € 1,4 from Lajunen (2018), approximately € 1,1 from Philatie et al. (2014), between € 0,78 and € 1,73 from Bloomberg NEF (2018), and about € 1 from Transport & Environment (2018). However, as mentioned in 6.2.5, it is hard to make any fair conclusions regarding the TCO by comparing the TCO from different studies as the assumptions are not the same. On average, the cost per km in this master's thesis without driver cost was about twice as high as the average from previous studies A more in-depth analysis of how an excluded driver cost will affect the TCO, for both overnight charging and opportunity charging is presented in 6.5.

To be able to find the parameters that drives the TCO, the total cost per hour was divided into annual depreciation cost, annual insurance and maintenance cost, energy cost, driver cost and the total annual cost. The result is presented in Table 37, where the result is the percentage each cost category constitutes to of the total annual cost.

Table 37 - Breakdown of total annual cost presented in cost per hour and percentage of total annual cost

Costs per hour	Route 1	Route 2	Route 3	Route 4
Depreciation vehicles per hour	12,33	11,46	9,48	11,50
Depreciation batteries per hour	11,26	11,84	11,98	7,37
Depreciation chargers per hour	0,85	0,71	0,82	1,00
Total depreciation cost per hour	**24,44**	**24,01**	**22,27**	**19,86**
	28,5 %	28,9 %	26,7 %	22,1 %
Total insurance and maintenace cost per hour	**3,65**	**4,33**	**4,91**	**4,04**
	4,3 %	5,2 %	5,9 %	4,5 %
Total energy cost per hour	**2,07**	**2,22**	**2,72**	**1,93**
	2,4 %	2,7 %	3,3 %	2,1 %
Total driver cost per hour	55,47	52,61	53,66	64,21
	64,8 %	63,3 %	64,2 %	71,3 %
Total cost per hour	**85,63**	**83,16**	**83,56**	**90,04**
	100 %	100 %	100 %	100 %

[€/hr] if nothing else is stated, the percentage below the costs represent the percentage the cost constitutes of the total cost

Earlier in this report it was presented that Route 1 and Route 4 had the highest total annual cost, for both cost per km and cost per hour. If Table 37 is walked through, it can be found that the total annual depreciation cost is quite similar between Route 1 and Route 2, both measured as cost per hour and the percentage they constitute of the total cost. Route 3 had a depreciation cost per hour that was between the two beforementioned routes and Route 4. The reason why this cost was lower than for route 1 and 2 was a lower depreciation cost for vehicles, while the cost for battery depreciation was almost at the same level. Route 4 on the other hand had the lowest total annual depreciation cost. What can be found here is that there is a correlation between the total annual depreciation cost and the usage rate, i.e. the route with the highest usage rate had the lowest total annual depreciation cost, measured as the percentage of the total annual cost and cost per hour. The importance of a high usage rate for a low TCO is also supported by Pihlatie et al. (2014), and Olsson, Grauers and Pettersson (2016), as mentioned in 2.5.3.

When it comes to the total annual insurance and maintenance it differs 1,6 % between the route with the highest cost measured as a percentage of the total annual cost and lowest cost. For the total annual energy cost, the difference was 1,2 % and the lowest percentage was found for Route 4 which had the highest total annual cost.

However, when it comes to the last cost category, i.e. total annual driver cost, there are a major difference in how large of the total annual cost it constitutes. Between Route 4 with the highest percentage, and Route 2 with the lowest percentage, there is a difference of 8 %. One major finding from this analysis is that there is a correlation between the total annual driver cost and the total annual cost measured in cost per hour and cost per km, as the rank between the four routes for total cost per hour, total cost per km and total driver cost per hour is the same. That the driver cost is an important cost to consider is also supported by Olsson, Grauers and Pettersson (2016), as their result indicated that operator costs was a significant cost. The annual driver cost depends on the driver time and cost per hour, and since the cost was assumed the same between the different routes, the parameter behind the difference is the driver time. The reasons why the driver time differs between these routes was discussed in 6.2.5 for opportunity charging, and since there were only minor changes of the driver time between opportunity charged with 3 min charge time and overnight charging, this will not be discussed again. For all routes, the driver cost was the largest cost, constituted from 63,3 % to 71,3 % of the TCO.

As mentioned, it was found that there was a correlation between the total depreciation cost and the usage rate. The usage rate was discussed in previous sections and the main reason for that was peaks in demand during the day. A visualization of the demand for the investigated routes during the day is presented in Figure 46.

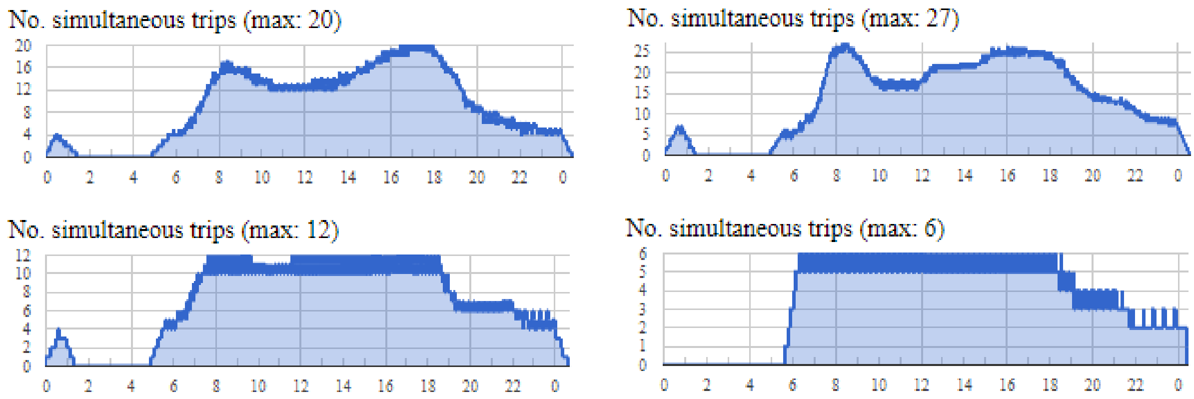


Figure 46 – Plot of trips during the day, Upper left: Route 1, Upper right: Route 2, Lower left: Route 3, Lower right: Route 4

It was found from Figure 46, the main reason why the usage rate differs between the routes can be found. What can be found is that both Route 1 and Route 2 has two major peaks, one at 08:00 and one at 17:00. This means that for both these routes, the bus system need to have a number of buses large enough to manage these two peaks, and during the time between these peaks, these buses are unused. For Route 3 there are no peaks, however between 10:00 and 12:00 there is a slight decrease in demand which affects the usage rate. Moreover, it was found that Route 4 has a very uniform demand the major part of the day. This is the main reason why Route 4 has the highest usage rate followed by Route 3, and that Route 1 and 2 has an approximately 20 % lower usage rate than Route 4.

As mentioned, it is important with a high usage rate for a low TCO (Olsson, Grauers & Pettersson 2016; Philatie et al. 2014), and If it is possible to increase the usage rate, e.g. by optimizing the battery capacity or use the buses on other routes when they are not needed for the particular route, the cost per hour for the four routes will be as presented in Figure 47. Where the figure to the left presents the cost per hour for different usage rates for batteries, while the right figure presents cost per hour for different usage rates for the fleet. Notice that the y-axis does not start at 0 € per hour, but 70 € per hour for both figures.

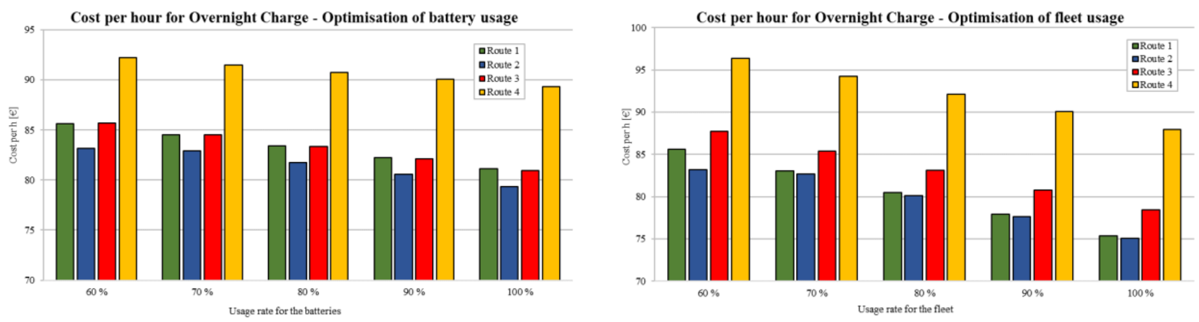


Figure 47 – Left: Cost per hour for different battery usage rates, Right: Cost per hour for different fleet usage rates

What was found from this analysis, and also presented for each route separate earlier was that the total annual cost can be reduced by increasing the usage rate for either the batteries or the whole fleet. However, both these options might be hard to perform in practical applications, depending on e.g. which battery sizes can be purchased and if there is a demand for the buses on other routes when not used on the particular routes. The fleet usage rate is not only dependent on the demand from other routes, but also the charging infrastructure available on that routes. In the case with opportunity charging, there must be charges connected to the other routes where the buses will be used, leading to additional costs and it might also be hard to have this charging infrastructure on some routes depending on e.g. space. However, for overnight charging, this charging infrastructure is not needed. From this analysis is was found that a 10 % increase in usage rate of batteries will decrease the cost per hour with between 0,8 %

and 1,4 %, while a 10 % increase in usage rate of the fleet will decrease the cost per hour with between 2,2 % and 3,0 %, assuming the initial usage rate as a base, and a linear cost reduction between 60 % and 100 % usage rate.

To summarize section 6.3, the major cost category for overnight charged buses is the driver cost and the rank between the driver cost as a percentage of the total annual cost was also the same as the rank of total cost per hour and total cost per km. The driver cost constituted between 63,3 % and 71,3 % of the total cost per hour for all routes. The second largest cost category was deprecation cost, that constituted between 22,1 % and 28,9 % of the total annual cost. In this category, vehicle cost and battery cost were the two major costs, see Table 37. Another finding was that the usage rate of the bus fleet, which affect the depreciation cost, is greatly affected by the peak in demand during the day, as the bus system needs to be dimensioned to manage these peaks.

Two ways of increasing the usage rate was analyzed, and if the usage rate of batteries was increased with 10 % the total annual cost was reduced with between 0,8 % and 1,4 %, while a 10 % increase in usage rate for the whole fleet results in a decrease in total annual cost between 2,2 % and 3,0 %. Moreover, it was also found that the annual maintenance and insurance cost, and the energy cost together counts for between 6,6 % to 9,1 % of the total annual cost. Lastly, the findings from section 6.3 implies that the route characteristics on Route 2 seems to be most favorable for overnight charging, closely followed by Route 3 when looking at the cost per hour. The main reason for this was a lower driving cost for Route 2, for the same reason as for opportunity charging, i.e. a time schedule that allows a high percentage of trip time of the total driving time, see Figure 23. And for Route 3, a high usage rate of the bus fleet but a slightly lower percentage of trip time of the total driving time than for Route 2. The findings and analysis from this chapter will be used and compared with opportunity charged buses in section 6.5.

6.4 Auxiliary load

Previous analysis was done at an auxiliary load of 6 kW, corresponding to mild weather according to Lajunen (2018), who also used 6 kW auxiliary load for the base-case in his study. However, in this chapter the findings from when different levels of auxiliary load was investigated will be presented. The energy consumption for opportunity charging is presented left in Figure 48, while the energy consumption for overnight charging is presented to the right.

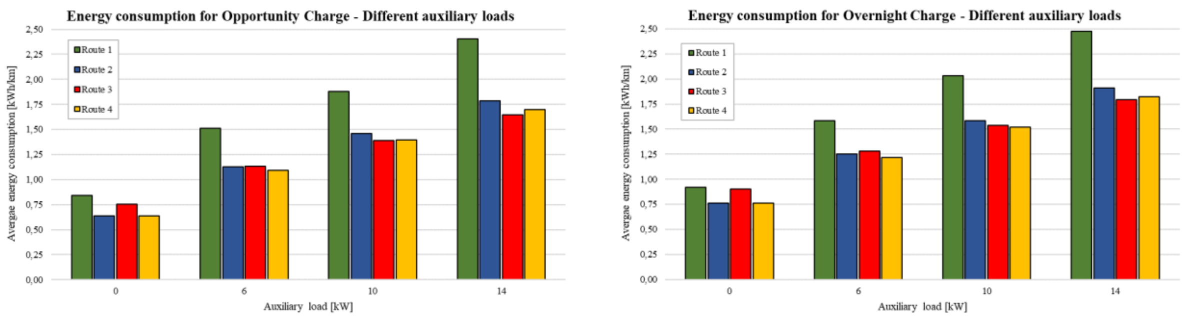


Figure 48 – Left: Energy consumption for opportunity charge, Right: Energy consumption for overnight charge

It was found from Figure 48 that the effects of a higher auxiliary load, for example, the energy consumption for Route 1 increases from 0,85 kWh/km to 2,35 kWh/km when the auxiliary load changes from 0 to 14 kW. The energy consumption for opportunity charge is the highest for Route 1, while it is somewhat similar for the other three routes. The same trend was found for overnight charge, where Route 1 also had the highest energy consumption and the other three routes has rather similar consumption. An interesting pattern displayed is that the relative difference between the routes changes, i.e. the increase in auxiliary load impacts the routes differently. For example, Route 3 does not maintain the second highest energy consumption when the auxiliary load increases. Instead, Route 2 goes from third place to second place, meaning that the auxiliary load has a higher effect on this route. The energy consumption for opportunity charge on Route 3 increased by 45% when the auxiliary load increased from 6 kw to 14, in the meantime, the increase on Route 2 is 58 %. The energy model consists of different variables, e.g. driving distance, time, and vehicle performance. Since the auxiliary load is a product of time, the difference in the increase of the energy consumption can partially be explained by the difference in average driving speed, as discussed in section 6.1. Since the auxiliary load is a function of time, a lower average driving speed results in a higher energy consumption per km. On average, the energy consumption increased by 54 % for opportunity charge and 49% for overnight charge when the auxiliary load increased from 6 kw to 14 kw. The reason why the average differs between the two charging strategies is because the overnight charged buses has a higher consumption constant (Cs_{dim}) than the opportunity charged buses.

Figure 49 illustrates the cost per hour for each route when the auxiliary load differs. The result for both charging strategies follow a similar trend, where Route 4 has the highest cost per hour, and Route 2 the lowest. The highest relative increase when using opportunity charging occur on Route 2, where the cost per hour increases by 6,6 % when the auxiliary load increases from 0 kW to 14 kW. The equivalent case for overnight charge is Route 1 where the cost per hour increased by 14 %. If we use our previous analysis as a reference, shifting from 6 kW to 14 kW would on average result in a 3,23 % increase in cost per hour for opportunity charge, and a 6,58 % increase for overnight charge.

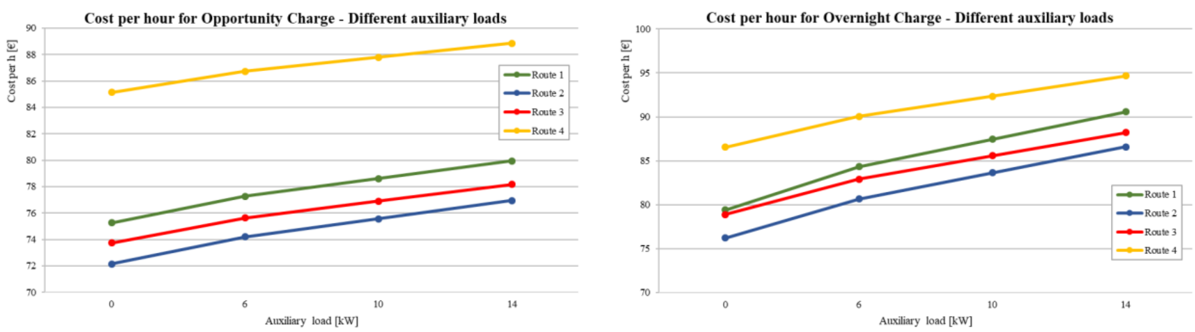


Figure 49 – Left: Cost per hour for opportunity charge, Right: Cost per hour for overnight charge

The majority of the increased cost can be attributed to the higher battery capacity. Table 38 and Table 39 shows the how the battery capacity changes with an increasing auxiliary load. The battery size increase by an average of 25 % when shifting from 6 kW to 10 kW, and by 50 % when shifting from 6 kW to 14 kW, for both opportunity and overnight charge. A 1 kW increase in the auxiliary load results in an average battery capacity increase of 4,16 kWh for opportunity charged buses. With a cost of € 950/kWh, this results in a cost of approximately € 3 952/kW/bus. The equivalent number for overnight charge is 26,44 kWh/kW/bus, and with a cost of € 540/kWh, this translates into € 14 278/kW/bus which is 3,6 times the number for opportunity charge. Implying that hot or ambient cold conditions could be adverse for overnight charged buses.

Table 38 - Battery size opportunity charge

	Battery capacity [kWh]			
kW	**0**	**6**	**10**	**14**
Route 1	29	53	69	85
Route 2	42	71	91	111
Route 3	59	86	104	122
Route 4	38	57	70	83

Table 39 - Battery size overnight charge

	Battery capacity [kWh]			
kW	**0**	**6**	**10**	**14**
Route 1	217	375	481	586
Route 2	257	424	536	647
Route 3	425	605	725	845
Route 4	215	345	431	517

To summarize, Lajunen (2018) concluded that an increase in auxiliary load can increase the lifecycle cost with as much as 10 % for end station charging buses. This was not in this master's thesis, where the cost for opportunity charged buses increased on average by 6,6 % when the auxiliary load went from 0 to 14 kW. For overnight charged buses the cost per hour increased by 14 % under the same condition. Furthermore, the average increase in cost per hour was 3,23 % for opportunity charge and 6,58 % for overnight charge when the auxiliary load went from 6 to 14 kW. Most of the cost can be attributed to the increase in battery capacity, with a cost of € 14 278/kW/bus for overnight charge and € 3 952/kW/bus for opportunity charge. This suggests that a high auxiliary load seems particularly adverse for overnight charged buses.

6.5 Comparative analysis of charging strategies

Here, the findings from previous sections in chapter 6 will be presented and analyzed with respect to the differences between opportunity charging and overnight charging. The cost per hour for all routes and both charging strategies is presented in Figure 50, where both the result from opportunity charging and overnight charging is from the run with the lowest total annual cost.

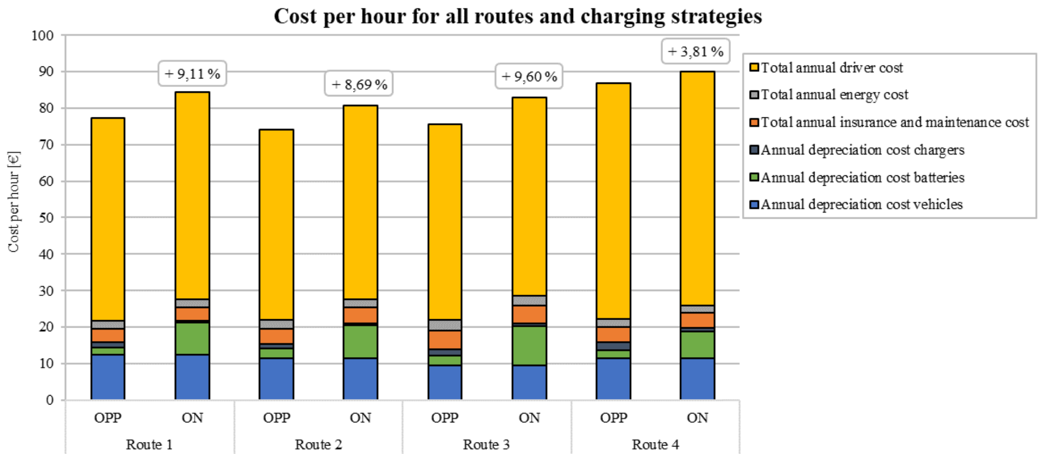


Figure 50 - Cost per hour for all routes and charging strategies

From the result presented in Figure 50 it was found that overnight charging had an approximately 9 % higher total annual cost than opportunity charging for route 1, 2 and 3. It was also found that the cost per hour for the most expensive route for opportunity charging, when looking at route 1, 2 and 3 was lower than the least expensive route for overnight charging. Moreover, for Route 4, the previous pattern is not demonstrated, instead, opportunity charging had a cost per hour that was higher than overnight charging for route 1, 2 and 3. However, the cost per hour for overnight charging for Route 4 was higher than for opportunity charging, but 3,85 % higher compared with 9,11 %, 8,69 % and 9,60 % for the other routes. To be able to see what costs that differs between opportunity charging and overnight charging, but also between the routes, a breakdown of the cost per hour is presented in Table 40.

Table 40 - Breakdown of cost per hour for all routes and charging strategies

Costs per hour	Route 1		Route 2		Route 3		Route 4	
	OPP	ON	OPP	ON	OPP	ON	OPP	ON
Depreciation vehicles per hour	12,33	12,33	11,46	11,46	9,48	9,48	11,50	11,50
Depreciation batteries per hour	2,15	8,78	2,67	9,04	2,66	10,66	2,15	7,37
Depreciation chargers per hour	1,37	0,72	1,10	0,58	1,77	0,76	2,23	1,00
Total depreciation cost per hour	**15,85**	**21,82**	**15,23**	**21,08**	**13,91**	**20,90**	**15,88**	**19,86**
	20,5 %	25,9 %	20,5 %	26,1 %	18,4 %	25,2 %	18,3 %	22,1 %
Total insurance and maintenace cost per hour	**3,73**	**3,68**	**4,39**	**4,32**	**5,08**	**4,95**	**4,17**	**4,04**
	4,8 %	4,4 %	5,9 %	5,4 %	6,7 %	6,0 %	4,8 %	4,5 %
Total energy cost per hour	**2,17**	**2,06**	**2,28**	**2,18**	**2,86**	**2,73**	**2,15**	**1,93**
	2,8 %	2,4 %	3,1 %	2,7 %	3,8 %	3,3 %	2,5 %	2,1 %
Total driver cost per hour	55,54	56,76	52,31	53,08	53,80	54,34	64,53	64,21
	71,9 %	67,3 %	70,5 %	65,8 %	71,1 %	65,5 %	74,4 %	71,3 %
Total cost per hour	**77,28**	**84,32**	**74,20**	**80,66**	**75,64**	**82,91**	**86,73**	**90,04**
	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %

[€/hr] if nothing else is stated, the percentage below the costs represent the percentage the cost constitutes of the total cost

When comparing opportunity charging with overnight charging, opportunity charging had the lowest total annual costs for all routes. The smallest difference in TCO between the two strategies occur on Route 4 since the difference in total depreciation cost per hour is relatively small compared to the other routes. The depreciation cost for the opportunity chargers is higher on Route 4 in relation to the other three routes, resulting in a higher total depreciation cost. Meanwhile, the lowest total depreciation cost per hour for overnight charge was achieved on Route 4 due to the high usage rate. Thereby, the difference in cost per hour between the two strategies is only 3,81 %.

The greatest difference in TCO between the two strategies occurred on Route 3, see Figure 50. A relatively low driver cost combined with a high usage rate meant that the TCO for the opportunity charged alternative ranked second of the four routes. The operating conditions on Route 3 is characterized by a long trip distance, high average speed and intermediate energy consumption. This requires a high battery capacity per bus which in turn translates into a high depreciation cost for the batteries, see Table 40. However, Route 3 still achieved the second lowest TCO for overnight charge due to the high usage rate. But the difference between the two strategies were still 9,60 %, which is the greatest of the four routes.

The usage rate of the battery capacity and the bus fleets was investigated earlier in chapter 6, where it was discussed that it might be easier to increase the usage rate for the whole bus fleet for overnight charging as the system does not require charging infrastructure at end stations. Moreover, the usage rate of the batteries varies between the two charging strategies. While the opportunity charged batteries are dimensioned based on the energy consumption of a single trip, the overnight charged buses must be dimensioned based on the energy consumption of a whole day. Meaning that the overnight charged batteries are significantly over-dimensioned in comparison to the opportunity charged batteries, and as a consequence, the usage rate between the two charging strategies vary significantly. Thereby, adjusting the battery capacity usage rate for overnight charging would enable a more just comparison between the two. As the usage rate for the fleet was at 90 % for Route 4, a new TCO for the three other routes was calculated using a 90 % usage rate of the battery capacity. The result is illustrated in Figure 51.

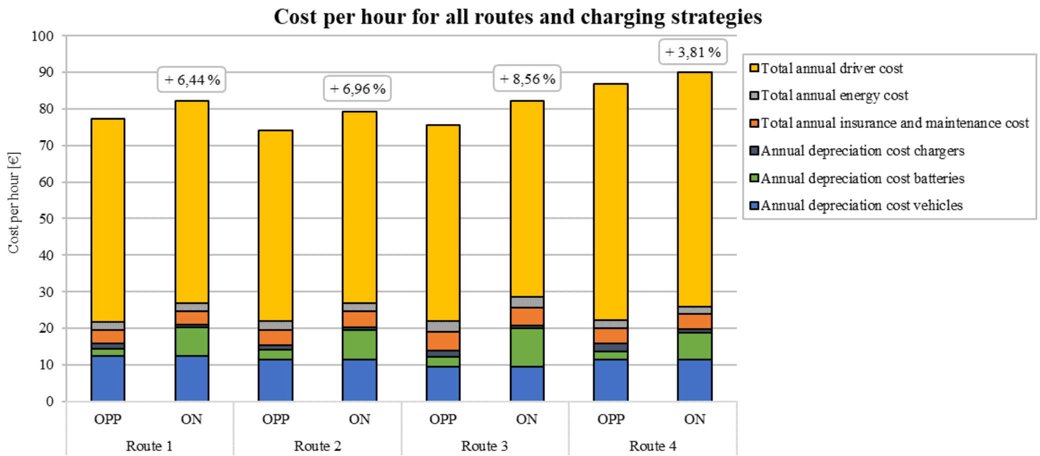


Figure 51 - Change in difference due to an increased battery capacity usage rate for overnight charged buses

The difference between opportunity charging and overnight charging has now been reduced, but overnight charge still has a slightly higher TCO than opportunity charge. As mentioned in subsection 2.3.2, since no charging infrastructure is needed along the route, overnight charge buses offer somewhat similar operating characteristics as combustion engine buses (Olsson, Grauers & Pettersson 2016). Consequently, overnight charged buses offers a greater flexibility in terms of operating on other routes than the one they are originally dimensioned for. Thus, the ability to use overnight charged buses on other routes, and thereby increasing the usage rate, is more favourable in comparison to opportunity charging. The economic implications of this ability are difficult to estimate since the operating conditions vary significantly. Thereby, an assumption is made that the buses on the route 1, 2 and 3 can achieve a similar usage rate as Route 4. If the usage rate for the overnight charged buses increased to 90 %, while the usage rate for the opportunity charged buses remains the same, one can calculate a new cost per hour, this result is illustrated in Figure 52.

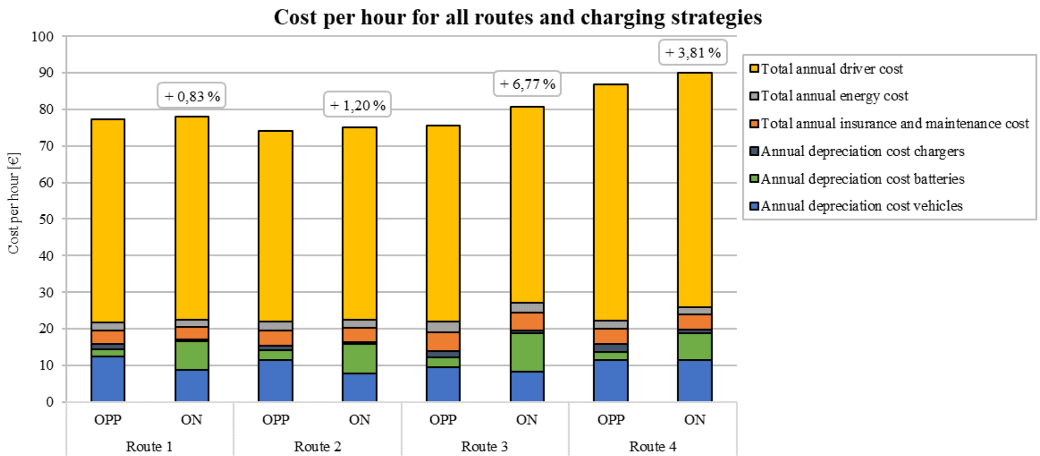


Figure 52 - Change in difference due to an increase in the usage rate for the whole overnight charged bus fleet

By applying a 90 % usage rate for the whole overnight bus fleet, the difference between the two charging strategies could be reduced further. The difference is now only 0,83% on Route 1 and 1,20% on Route 2. The difference was only reduced slightly on Route 3, from 8,56% to 6,77%, due to a high usage rate beforehand.

The driver cost accounts for the vast majority of the total annual cost. Most of the previous studies presented in subsection 2.5.3 assumes that the driver cost remains unchanged when shifting from e.g. diesel buses to electric buses and can therefore be excluded in the analysis. Thus, it could be of interest to see how this assumption affects the result and subsequently if this impact the previous TCO ranking of the routes. The result excluding the driver cost is presented in Figure 53.

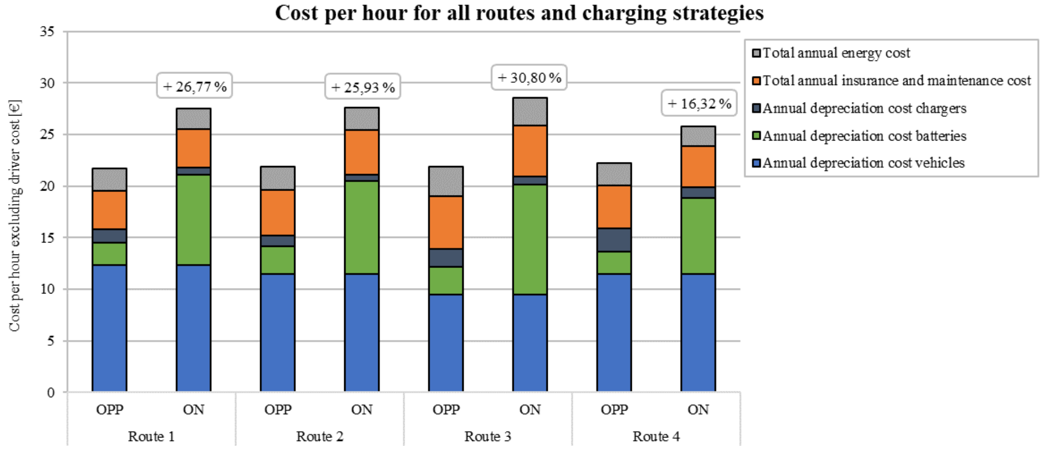


Figure 53 - Cost per hour for all routes and charging strategies excluding the driver cost

By excluding the driver cost, it was found that the cost per hour ranking of the routes changed. Additionally, when analyzing each charging strategies separately, the route with the lowest cost per hour changed from previous analysis. For opportunity charge, the lowest cost per hour was found for Route 1 at € 21,74, followed by Route 3 at € 21,84, Route 2 at € 21,90 and lastly Route 4 at € 22,20. For overnight charge, the lowest cost per hour was found for Route 4, at € 25,83, followed by Route 1 at € 27,56, Route 2 at € 27,57 and lastly Route 3 at € 28,57. This ranking can be compared with the previously calculated total cost per hour that included the driver time, see Figure 52, where Route 2 had the lowest cost per hour for both charging strategies, followed by Route 3, 1 and 4. Additionally, the difference between the two charging strategies have now become even greater, where the average difference is now 25 % compared to the initial 7,8 %. The analysis demonstrates the importance of being aware of how the operating schedule affect the TCO when comparing different routes, as the assumption of a constant driver cost completely changed the outcome of the analysis.

To summarize section 6.5, opportunity charge achieved a lower cost per hour on all the routes when compared to overnight charge. The greatest difference between the two strategies was 9,60 % and achieved on Route 3, the smallest difference was 3,81 % and occurred on Route 4. The operating characteristics of overnight and opportunity charged buses differs, and one could argue that overnight charged buses has a greater flexibility in terms of the ability of utilizing the vehicles on different routes. Thereby, an analysis was conducted were the overnight charged buses was assumed to have a higher usage rate than the previous analysis. The result showed that the difference in TCO between the two charging strategies had now been reduced to as little as 0,83%, which was achieved on Route 1. Furthermore, an analysis was made where the driver time was assumed to remain constant and thus excluded from the TCO calculation. The result differed from the previous analysis with respect to the TCO ranking of the routes. For opportunity charging, the lowest cost per hour occurred on Route 1 instead of Route 2, and for overnight charging, Route 4 had the lowest cost per hour instead of Route 2.

The comparative analysis conducted in this section demonstrates the difficulties of comparing opportunity charge and overnight charge. Depending on what assumptions that are being made, the difference in cost per hour between the two charging strategies could e.g. for Route 1 be reduced from 9,11 % to as little as 0,83%. In previous studies, the difference between opportunity charge and overnight charge varied, in the study by Lajunen (2018) the cost per hour for opportunity charge was between € 14 and € 18 for the different routes, while the difference for overnight charge was between € 16 and €

28, i.e. the difference between opportunity charge and overnight charge was greater than in this master's thesis. Other studies, e.g. Transport & Environment (2018) showed a similar result between the two charging strategies, while the result from Bloomberg NEF (2018) indicated that opportunity charging has a lower TCO when the annual driving distance per bus is longer, and that overnight charging has a lower TCO when the annual driving distance per bus is shorter.

6.6 Sensitivity analysis

In the previous sections, the analyses were done without changing the value of the cost parameters, except the battery cost in 6.3.5. In this section, a sensitivity analysis was performed for five different costs to observe the behavior of the total annual cost.

The sensitivity analysis was performed for the vehicle cost, battery cost, charger cost, insurance and maintenance cost, energy cost and the driver cost. This sensitivity analysis was performed by decreasing previous mentioned costs by 10 % to see how this decrease affects the total annual cost. The result from the sensitivity analysis for opportunity charging is presented in Figure 54, while the result for overnight charging is presented in Figure 55.

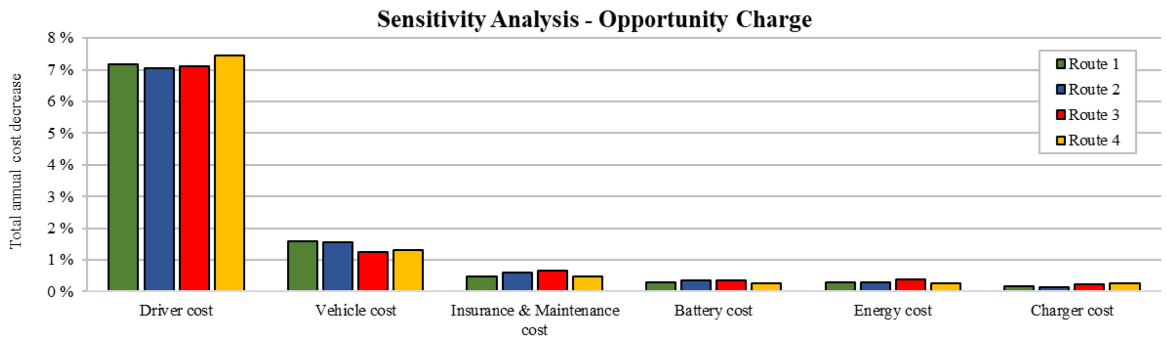


Figure 54 - Sensitivity analysis for opportunity charging

As presented in Figure 54, it was found that a change in driver cost will have the greatest impact on the total annual cost. A 10 % decrease in driver cost will give a decrease in total annual cost of approximately 7 %. The cost with the second highest impact was the vehicle cost, here the effect for a 10 % decrease in vehicle cost was some 1,5 % decrease in total annual cost. Insurance and maintenance had the third highest impact where a 10 % decrease gives approximately a 0,5 % decrease in total annual cost. The battery cost, energy cost and charger cost had the lowest and similar impact on the total annual cost, about 0,3 % for battery and energy cost, and even lower for charger cost. These numbers cannot be directly compared with previous studies as most studies that included a sensitivity analysis did not included driver cost in their TCO analysis. However, from Lajunen (2018) it was found that a change in vehicle cost had the greatest affect followed by a change in maintenance cost. So, with the driver cost excluded, the two cost changes that affected the TCO most for opportunity charging was the same. Important to notice is that the percentage change in TCO, if the driver cost was excluded in this master's thesis, would have increased significantly compared to Figure 54. When it comes to overnight charging, the result from the sensitivity analysis is presented in Figure 55.

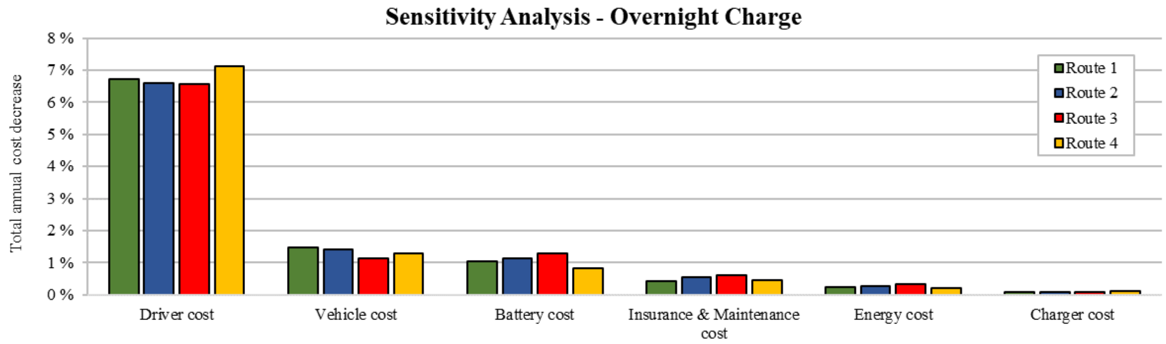


Figure 55 - Sensitivity analysis for overnight charging

From the analysis in Figure 55, it was found that a change in driver cost will have the greatest impact also for overnight charging. However, the impact was slightly lower than for opportunity charging. The reason for this is that driver cost has a greater percentage of the total annual cost for opportunity charging than for overnight charging, see Table 40. Also, for overnight charging, a change in vehicle cost had the second highest impact on the total annual cost. A difference from opportunity charging is that the change in battery cost had third greatest impact on the total annual cost for overnight charging. A 10 % decrease in battery cost will lead to about 1 % in decrease of the total annual cost, compared with some 0,3 % for opportunity charging. The reason for this is that the battery size is larger for overnight charging, leading to that the battery cost constitutes a larger percentage of the total annual cost and hence, a 10 % decrease will affect overnight charging more than opportunity charging. The price of lithium-ion batteries has declined with 79 % since 2010 (Bloomberg NEF 2018), and hence decline in price can be especially interesting for overnight charging, as the effect from a price change affects the TCO more than for opportunity charging. A change in insurance and maintenance cost had almost the same effect on the total annual cost for overnight charging as for opportunity charging and the same was found for the energy cost. The least affecting category for overnight charging was the same as for opportunity charge, i.e. the charger cost. As for opportunity charging, the values cannot be compared directly with previous studies for the same reason, however the pattern is the same as in the study by Lajunen (2018), i.e. a change in vehicle cost will ha the greatest impact followed the battery cost. That the battery cost will have a great impact on the TCO is also supported from the study by Bi, Kleine & Keoleian (2016), where the sensitivity analysis showed that the battery cost will have the greatest impact.

To summarize section 6.5, it was found that a change in driver cost had the greatest impact on the total annual cost for both opportunity charging and overnight charging, followed by the vehicle cost. The cost with the third most impact on the total annual cost for opportunity charging was insurance and maintenance, while a change in battery cost had the third greatest impact on the total annual cost for overnight charging. For opportunity charging the two least affecting costs was the battery cost and energy cost, respectively insurance and maintenance cost and energy cost for overnight charging. It was also found some variations between different routes, e.g. Route 3 for overnight charging, where a change in battery cost will have a greater impact than a change in vehicle cost. The reason for the changes between the routes is the same as the differences between opportunity charging and overnight charging, i.e. it depends on how large percentage of the total annual cost each cost category constitutes.

6.7 Summary of findings

The findings from the analysis of the energy consumption indicated that a high average driving speed seem to be beneficial if one wants to achieve a lower energy consumption for electric buses. A high average driving speed contributes to lowering the effects of the auxiliary load which is time dependent. Following this reasoning, Route 3 should have had the lowest energy consumption, but this was not the case. The energy model used in this thesis accounts for the topography of the route, and since Route 3 had the highest cumulative elevation gain and loss, the topography had the highest impact on the energy consumption on this route. Resulting in the second highest energy consumption of the four routes. Furthermore, the result showed that the required battery size varied significantly between the routes, especially for overnight charge. The calculated battery size was put in relation to previous studies, and it could be concluded that the battery size used in this thesis are generally larger than the ones used previously. However, the analysis in 6.3.5 indicated that the DOD could be increased, and thereby decreasing the battery to practical possible sizes without any major cost increases.

The result in section 6.2 presented the TCO of opportunity charged buses that was utilized on four different routes. Eight different runs on each route were conducted during simulation 1, where the charge time was reduced by one unit for each run, from 10 min to 3 min. The lowest cost per hour was achieved on Route 2, see Table 21, and Route 4 had the highest cost per hour. While the TCO of route 1, 2 and 3 only differed marginally, Route 4 had a significantly higher TCO than the other routes when the TCO was defined as cost per hour.

The total annual driver cost is the largest cost category for both charging strategies, and it is a product of the driver time and driver salary. The driver time constitutes of 4 components – Inactive time, Charge and dwell time, Empty driving and Trip time, see Figure 22. To accomplish a low driver cost per hour the trip time component should be maximized. Since the trip time remains constant, one must lower either the inactive time, charge and dwell time or the empty driving. The second highest cost was the depreciation cost, where the majority of the cost was constituted by the vehicle and battery cost, followed by the cost for insurance and maintenance, and finally the cost for energy.

When investigating how adjustments in the charge time for opportunity charge affected the TCO, it was found that a decrease in charge time from 10 min to 3 min could lower the TCO with as much as 11,73 % on Route 1. The reduced charge time allowed for fewer vehicles and chargers, and it decreased the total driver time thus resulting in a lower driver cost per hour. These effects where demonstrated on all routes, however, it was discovered that the extent of these effects varied since the minimum TCO for each route was attained using different charge times. For Route 1 and 2, the minimum TCO was attained with a charge time of 3 min, for Route 3 with a charge time of 4 min and for Route 4 with a charge time of 8 min. This could be explained by the differences in the route characteristics of the routes. Since Route 2 had the lowest TCO, a high trip duration and frequency combined with an intermediate trip length and a high number of daily trips seem to be favorable route characteristics for opportunity charged buses. In contrast, the highest TCO occurred on Route 4, which scored low on all characteristics.

Section 6.3 presented the result of the TCO calculation for overnight charged buses. The TCO ranking of the routes remained the same as when using opportunity charged buses. The major cost category was the driver cost, followed by the depreciation cost, insurance and maintenance cost, and finally the energy cost. It was discovered that the usage rate had a great impact on the TCO of the routes, however it was not the most important parameter as the route with the highest usage rate had the highest TCO. The variance in the usage rate could be explained by the differences in demand during the day. The result implies that the route characteristics on Route 2 seem most favorable for overnight charge due to the low driver cost, closely followed by Route 3 and Route 1.

From the analysis in 6.4 it was discovered that an increased auxiliary load will have a greater impact on routes with a low average speed and/or high length. Additionally, a route with a high auxiliary load proved to be more adverse for overnight charge due to the rising battery cost. On average, the battery size increases by 25 % when shifting from 6 kW to 10 kW, and by 50 % when shifting from 6 kW to 14 kW, for both opportunity and overnight charge.

When comparing the TCO of between the two strategies, it was discovered that the difference could vary significantly based on what assumptions that are being made. The initial analysis resulted in a 3,81% to 9,60 % TCO difference depending on what route that was analyzed. The smallest difference occurred on Route 4 and the largest difference occurred on Route 3. Since the usage rate of the batteries vary between the two charging strategies, where overnight charge has a significantly lower usage rate, an assumption was made to increase the usage rate of the battery capacity to 90%. This resulted in a reduced difference in TCO between the charging strategies, where the greatest difference occurred on Route 1, from the initial 9,11% to 6,44%.

Compared to opportunity charge, overnight charged buses offer greater flexibility in terms of adopting the buses on other routes. The monetary value of this ability is difficult to estimate, but an argument could be made that one can achieve a higher usage rate of the bus fleet using overnight charge, and thereby lowering the depreciation cost. An analysis was conducted where the usage rate of the overnight charged bus fleet was assumed to be 90%, which was achieved on Route 4. The outcome was that the difference between the two charging strategies was reduced further and was lowered to as little as 0,83% on Route 1 and 1,20% on Route 2.

Previous studies have assumed that the driver cost remains unchanged when shifting from e.g. diesel buses to electric buses and can therefore be excluded in the analysis. Based on this assumption, a new TCO calculation was conducted, and it could be concluded that the cost per hour ranking of the routes changed. The route with the lowest TCO was now Route 1 for opportunity charge and Route 4 for overnight charge, and not Route 2 as the previous result. When the driver cost was removed from the TCO, the usage rate had a higher impact as a higher usage rate of vehicles lead to a lower depreciation cost per hour. The analysis demonstrated the importance of being aware of how the operating schedule affect the TCO when comparing different routes, as the assumption of a constant driver cost completely changed the outcome of the analysis. This result also indicated the importance of being aware of what costs that are included, and which assumptions that are done when analyzing results from a TCO analysis.

The sensitivity analysis showed that changes in driver time has the greatest impact on TCO. On average, a 10 % decrease in driver cost gave a 7 % decrease in total annual cost. A 10% reduction in vehicle cost resulted in approximately 1,5 % decrease in total annual cost, making it the cost with the second highest impact after the driver cost. The cost with the third highest impact differs between the two charging strategies, for opportunity charging it is the insurance and maintenance cost, and for overnight charging it is the battery cost.

7 Conclusions and discussion

The following chapter will start with the conclusions from this master's thesis, where the four research questions will be answered. This will be followed by a discussion of the methodology and a discussion of further studies.

7.1 Conclusions regarding the Total Cost of Ownership

Section 7.1 aims to answer the research questions, and it will do so in the same order as the research questions was stated in.

RQ 1 – What parameters to include in the TCO calculation for an electric bus system?

Parameters that were found to be important to include in the TCO calculation was gathered through the literature review and from the EAEB project. The major cost categories included was depreciation cost for vehicles, batteries and charging infrastructure, insurance and maintenance cost, energy cost, and driver cost. The major parameters used in these cost categories are presented in Table 41.

Table 41 - Parameters to include in the TCO calculation

Investment parameters	Operating parameters	Energy model parameters
Vehicle cost	Driver cost	Vehicle weight
Battery cost	Maintenance cost vehicles	Consumption constant
Charger cost	Insurance cost vehicles	Auxilary power
Grid connection cost	Tire cost	Efficiency
Grid connection substation cost	Maintenance cost chargers	HVO consumption
Cable installation cost	Annual energy fee	
Depreciation time buses	Power fee	
Depreciation time chargers	Variable energy fee	
Depreciation time batteries	Consumption cost	
Interest	HVO cost for heating	

RQ2 – What parameters seems to have greatest impact on the TCO for each charging strategy?

Figure 56 illustrates the relationship between the TCO and the parameters that had the greatest impact on the TCO. The TCO was divided into four major cost categories: Depreciation cost, Insurance and maintenance cost, Energy cost and Driver cost. The pie-chart in the upper right corner of each box illustrate how large a share the category constitutes of the TCO. All four categories can somehow be derived to the operating conditions, and the Depreciation cost, Insurance and maintenance cost and Energy cost also depend on the vehicle performance.

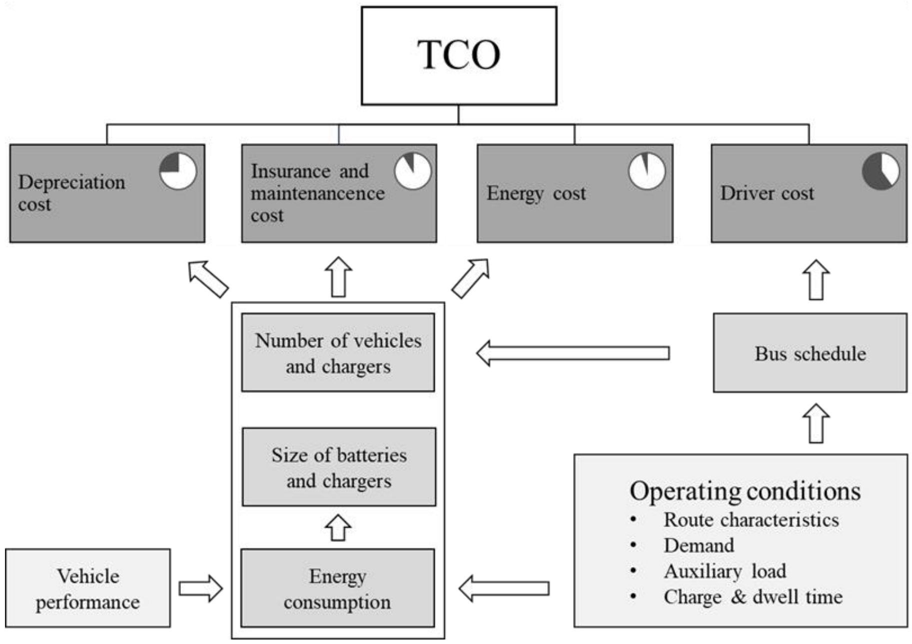


Figure 56 – Conclusions regarding the TCO

The majority of the TCO for both charging strategies can be attributed to the driver cost and more precisely to the total driver time. The total driver time is based on the bus schedule, which in turn is determined by the operating conditions. In the analysis it was discovered that the ratio between the trip time and the total driver time was a vital factor in minimizing the TCO since the lowest driver cost per hour occurred on the route with the highest percentage trip time. It was discovered that adjustments in the charge time for opportunity charge could reduce the TCO with up to 11,73 % on Route 1, when going from a 10 min to a 3 min charge time. This reduction was derived by a 12,56 % reduction in driver cost, and in addition to that, the reduced charge time enabled a more optimized bus schedule that required less vehicles and chargers.

When it comes to the depreciation cost of the vehicles, it was found to be the second highest cost category for both charging strategies. The deprecation cost for the vehicles is a result of the number of vehicles and the usage rate of the vehicles, which in turn can be derived to the demand during the day. The findings showed that a 10 % increase in the usage rate of the fleet could decrease the total annual cost with between 2,2 % and 3,0 %. Since the bus fleet and chargers are dimensioned based on the peak in daily demand, a uniform demand allowed for a higher usage rate and subsequently a reduced TCO.

The third highest cost differed between the two charging strategies. For opportunity charge, it was the insurance and maintenance cost, and for overnight charge, the depreciation cost of the batteries. The insurance and maintenance cost depend on the number of vehicles and chargers, size of the chargers, and the driving distance. The findings showed that routes with a higher average driving speed had a slightly higher insurance and maintenance cost per hour, due to a greater amount of driven km per hour. The driving speed is derived from the bus schedule, which in turn is defined by Route characteristics. When it comes to the depreciation cost for the batteries, it depends on the battery capacity, i.e. battery size, and the usage rate of the battery capacity. The battery capacity can be derived from the energy consumption, which depends on the operating conditions and vehicle performance. Considering that, the driving distance per bus per day and usage rate has a great impact on the TCO for overnight charging.

It was discovered that the battery capacity per bus varied significantly between the routes, but a high battery capacity per bus did not necessarily result in a higher battery depreciation cost per hour as will be discussed below. However, it was discovered that the auxiliary load had a significant impact on the TCO. An increase in auxiliary load from 6 kW to 14 kW resulted in an average increase in energy consumption of 54 % for opportunity charge and 49 % for overnight charge, resulting in average increase of 3,23 % in TCO for opportunity charge and a 6,58 % increase in TCO for overnight charge.

RQ3 – What operating conditions seems to be most favourable for each charging strategy?

Previous section outlined what parameters that had the greatest impact on the TCO. In turn, favourable operating conditions are those that minimize the magnitude of these parameters. The lowest driver cost per hour was achieved on Route 2, and the findings showed that this was due to the operating conditions on Route 2. It could be concluded that the route characteristics on this route enabled a high ratio between the trip time and total driver time, resulting in a lower driver cost per hour relative to the other routes. The route conditions on this route could be characterised by a high number of daily trips, high trip frequency, high trip duration and an intermediate trip length. The significance of each of these characteristics was not investigated in detail in this thesis, but this topic will be discussed further in section 7.2.

As mentioned earlier, the usage rate played an important part in minimizing the TCO. A high usage rate was achieved on the routes with a uniform demand during the day. Since number of chargers and buses are dimensioned based on the peaks, a high difference between the peak and bottom demand means that the vehicles remain unused a larger part of the time. Additionally, the findings indicated that a high usage rate was especially important for overnight charge in order to achieve a competitive TCO in comparison to opportunity charge.

The analysis showed that changes in auxiliary load had major impacts on the TCO. The greatest increase in TCO occurred for overnight charge since the size of the batteries are significantly higher than that of opportunity charge. Hence, it can be concluded that routes with hot or ambient cold conditions is particularly adverse for overnight charge.

RQ4 – How does the TCO differ between the two charging strategies?

When the two charging strategies was compared, opportunity charge achieved a lower TCO on all the routes, and for Route 1, 2 and 3 the difference between the two charging strategies was about 9,60 %, and on Route 4 the difference was 3,81 %. However, depending on what assumptions that was made, the difference between the two charging strategies could be reduced. Overnight charged buses offer a greater flexibility in terms of being operated on several routes, hence one could make the argument that the usage rate of these buses could become higher than the opportunity charged buses. The monetary value of this ability is difficult to estimate, but an assumption was made that the usage rate was higher for overnight charge. The new result showed that the difference in TCO between the two charging strategies became as little as 0,83 % on Route 1, while it varied between 1,20 % and 6,77 % on the other routes.

An analysis where made with the assumption that the driver time was constant and thus could be excluded. The analysis demonstrated the importance of being aware of how the schedule affect the TCO when comparing different routes, since the assumption of a constant driver cost completely changed the outcome of the analysis. Route 2 was no longer the route with the lowest TCO, and the average difference in TCO between the charging strategies increased to 25 % from the initial 7,8 %.

7.2 Discussion of methodology

This master's thesis was performed with a quantitative research strategy and a multiple case study was chosen as research design. Four different cases, i.e. four routes were investigated. Here it can be discussed both if a lower number of routes would have facilitated time for a deeper analysis, or if a greater number of routes would have been better to facilitate a more statistically correct study. However, according to the authors, these four routes enabled both time for a deep analysis of the parameters, which operating conditions that seems to be most favorable, and how the TCO differ between the two charging strategies.

As mentioned in 3.5, three important quality criteria are reliability, replication, and validity (Bryman & Bell 2015). Starting with the reliability of this thesis, i.e. if the measures are consistent and if the result is repeatable, this thesis used the same calculations, assumptions, and same costs for all investigated route to ensure consistent measures. It was mentioned that it is important to not only have consistent measures, but also correct calibrated measures, as inaccurate measures can lead to invalid conclusions (Pruzan 2016). From this thesis it was found that measures were higher than in previous studies, some reasons for this were which costs that were included in the TCO analysis, if the result is compared for cost per km or cost per hour, assumptions, and how the calculations are performed. However, considering the aim and purpose with this thesis, the authors argues that the conclusions are reliable.

The replication of this study can be said to be high due since the methodology chapter presents a thorough review of the used methodology, in combination will additional chapters that presents the used calculations, assumptions and parameter values. The authors of this master's thesis believed that it was important to achieve a high transparency of the methodology to enhance the credibility of the thesis, and to show that the results and conclusions are not affected by the collaboration with Scania CV AB.

When it comes to the validity of this thesis, the measurement validity can be said to be high, as TCO is as it reflects the concept it is supposed to measure well. However, different assumptions can affect the TCO, which is discussed in the next paragraph. It was found that a system for electric buses is a complex system to investigate. There are many parameters that are connected to each other, and hence it can be hard to analyze the causality, which is related to the internal validity according to Bryman and Bell (2015). Yet, the authors argue that the parameters behind the variations in costs was investigated to ensure the internal validity of the conclusions. To find how the different parameters relates to each other was also strongly connected to the purpose and research questions in this thesis. Moreover, the external validity was strengthened by the multiple case study design, i.e. several routes were investigated with the same methodology.

The practical implications of this thesis should be exercised with great care. The purpose with this thesis was not to pick a winner between the two charging strategies. There are other dimensions that must be considered when dimensioning an electric bus system, e.g. the robustness of the system. For example, Route 1 had the lowest difference between the two charging strategies, and the required number of chargers on Route 1 was two, meaning that there is one charger at each end-stop. In the event that one of the chargers break, and some of the buses arrive late to the end-stop, the situation would quickly become problematic. If more chargers would be added, the difference between the two charging strategies on Route 1 would decrease further, with the likely outcome that the difference could become insignificant or even that the TCO of overnight charge could become lower than that of opportunity charge.

Important to consider, especially for practitioners reading this thesis are the assumptions that were made and values that were used. One example of this is that all battery sizes and charger sizes was set to the theoretical values, while these only can be purchased in fixed sizes. However, these assumptions enabled a way to observe how incremental changes in different parameters affected the TCO, which would be difficult if practical available sizes were used. Another assumption was that the bus schedule was optimized in a fair way in the EAEB tool. As driver time was found to constitute a clear majority of the TCO, the schedule optimization has an important role.

However, the authors are satisfied with the used methodology and believe that its' design was more than adequate to achieve a greater understanding of opportunity charging and overnight charging when it comes to the TCO, and thereby achieve the purpose with this thesis. The used methodology and the result from this these raised some issues that would be interesting to do further studies about.

7.3 Discussion of further studies

This thesis was based on four different routes. Therefore, it would be interesting to see if and how the result would differ if more routes were investigated. Furthermore, a study with more routes included could be used in combination with some statistical models to see if it possible to make any statistically significant conclusions about different parameters and its effect on the TCO.

Another interesting study would be to do a qualitative analysis of an electric bus system to see what the different stakeholders' values. For example, is the TCO the most important measure in the decision of which charging strategy to use, or are there any other qualitative factors that have a great impact on the decisions? A such study can include interviews with e.g. public transport authorities, operators and manufacturers, but also studies of recent bus tenders. It was also found in this thesis that the result varied when using cost per km or cost per hour. Hence, it would be interesting the see what performance metrics different stakeholders use, and if they look at different performance metrics in different purchase situations.

In this thesis, the cost side was investigated but not the revenue side. As electric buses are considered as an environmentally friendly transport alternative, people might be more inclined to travel by bus or pay more to travel compared to diesel buses. Hence, it would be interesting to compare the Total Operating Economy between electric buses and diesel buses, i.e. taking consideration to both the revenue and the cost side.

Moreover, it was found that time schedules had a great influence on the driver time. And considering the fact that the driver cost constituted the vast majority of the total annual cost, it would be of interest to do a study about implementation of electric buses and time scheduling. Should the implementation be optimized based on the current operating schedule or the technical compatibility of the chargers and buses? Or can routes and scheduling be optimized for a greater fit with the technical aspects for electric buses?

It was found that the usage rate of buses and vehicles had an important impact, especially for overnight charged buses. Hence, it would be interesting to do a study about how different bus manufacturers work with this issue, and how bus fleets can be optimized to increase the usage rate of the batteries. Should all buses have the same battery size? Should all buses be bought with the same battery size? Or is it possible to use modularization to increase the usage rate of the batteries?

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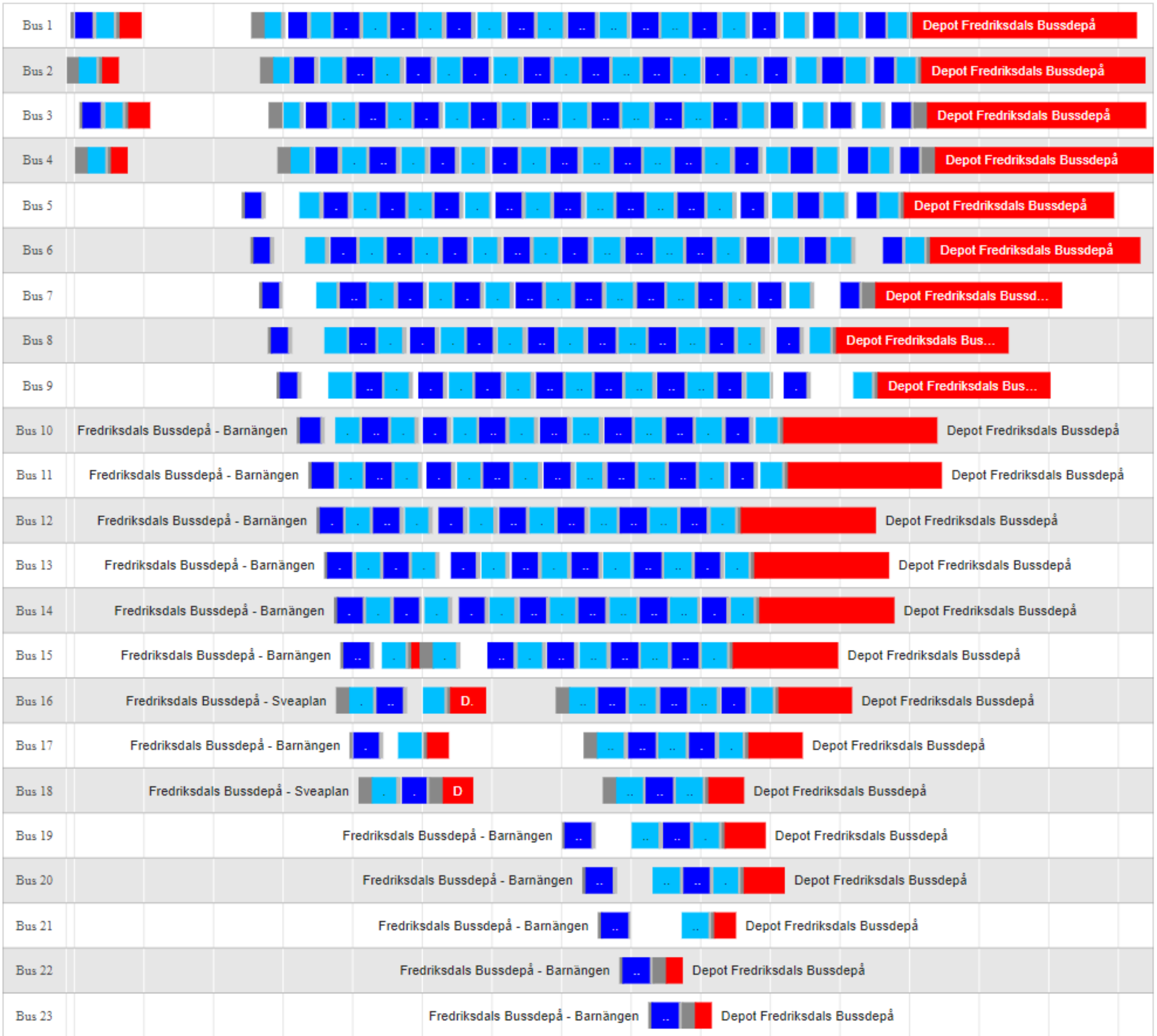
Appendix

Appendix A – Findings for Route 1

Appendix A includes:

- Example of bus schedule for Route 1 from the EAEB-tool for Overnight Charge
- Total annual cost: Route 1 all runs for Opportunity Charge – Simulation 1
- Total annual cost: Route 1 all runs for Overnight Charge – Simulation 2

Example of bus schedule for Route 1 from the EAEB-tool for Overnight Charge



Total annual cost: Route 1 for all runs Opportunity Charge – Simulation 1

All costs are presented in k€ if nothing else is stated - Opportunity Charge

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment costs								
Vehicle investment	8 388	8 388	8 388	8 038	8 038	8 038	7 689	7 339
Battery investment	1 214	1 214	1 214	1 163	1 163	1 163	1 112	1 062
Infrastructure investment	1 118	1 161	1 057	1 088	1 146	1 231	1 183	1 120
Total investment cost	**10 719**	**10 762**	**10 658**	**10 289**	**10 348**	**10 432**	**9 984**	**9 521**
Annual costs								
Depreciation vehicles	1 034	1 034	1 034	991	991	991	948	905
Depreciation batteries	180	180	180	173	173	173	165	158
Depreciation chargers	101	104	95	98	103	111	106	101
Total annual depreciation cost	**1 315**	**1 319**	**1 309**	**1 262**	**1 267**	**1 274**	**1 220**	**1 163**
Insurance vehicles	94	94	94	90	90	90	86	82
Maintenance vehicles	163	162	161	162	163	161	161	161
Tyres vehicles	14	14	13	14	14	14	13	13
Maintenance chargers	17	18	16	17	18	20	19	17
Total annual insurance and maintenance cost	**287**	**287**	**284**	**282**	**284**	**285**	**279**	**274**
Annual electricity fee	2	2	2	2	2	2	2	2
Electricity subscription fee	0	0	0	0	0	0	0	0
Electriciy power fee	33	34	31	31	33	36	34	32
Electricity variable fee	9	9	9	9	9	9	9	9
Consumption	95	95	94	95	95	94	94	94
HVO for heating	24	24	23	24	24	24	23	23
Total annual energy cost	**162**	**163**	**159**	**160**	**162**	**164**	**162**	**159**
Total annual driver cost	4 663	4 555	4 420	4 416	4 339	4 226	4 176	4 077
Total annual cost	**6 427**	**6 324**	**6 172**	**6 119**	**6 052**	**5 950**	**5 837**	**5 673**
Cost per km [€]	**8,51**	**8,37**	**8,17**	**8,10**	**8,01**	**7,88**	**7,73**	**7,51**
Cost per hour [€]	**87,55**	**86,14**	**84,08**	**83,35**	**82,44**	**81,05**	**79,51**	**77,28**
Other relevant data								
Total number of vehicles [units]	*24*	*24*	*24*	*23*	*23*	*23*	*22*	*21*
Total driver time per yr [hrs]	*133 416*	*130 336*	*126 486*	*126 355*	*124 149*	*120 931*	*119 481*	*116 662*
Total number of charger [units]	*6*	*6*	*4*	*4*	*4*	*4*	*3*	*2*
Total charger effect [kw]	*415*	*463*	*348*	*397*	*462*	*556*	*518*	*463*

Total annual cost: Route 1 for all runs Overnight Charge – Simulation 2

All costs are presented in k€ if nothing else is stated - Overnight Charge

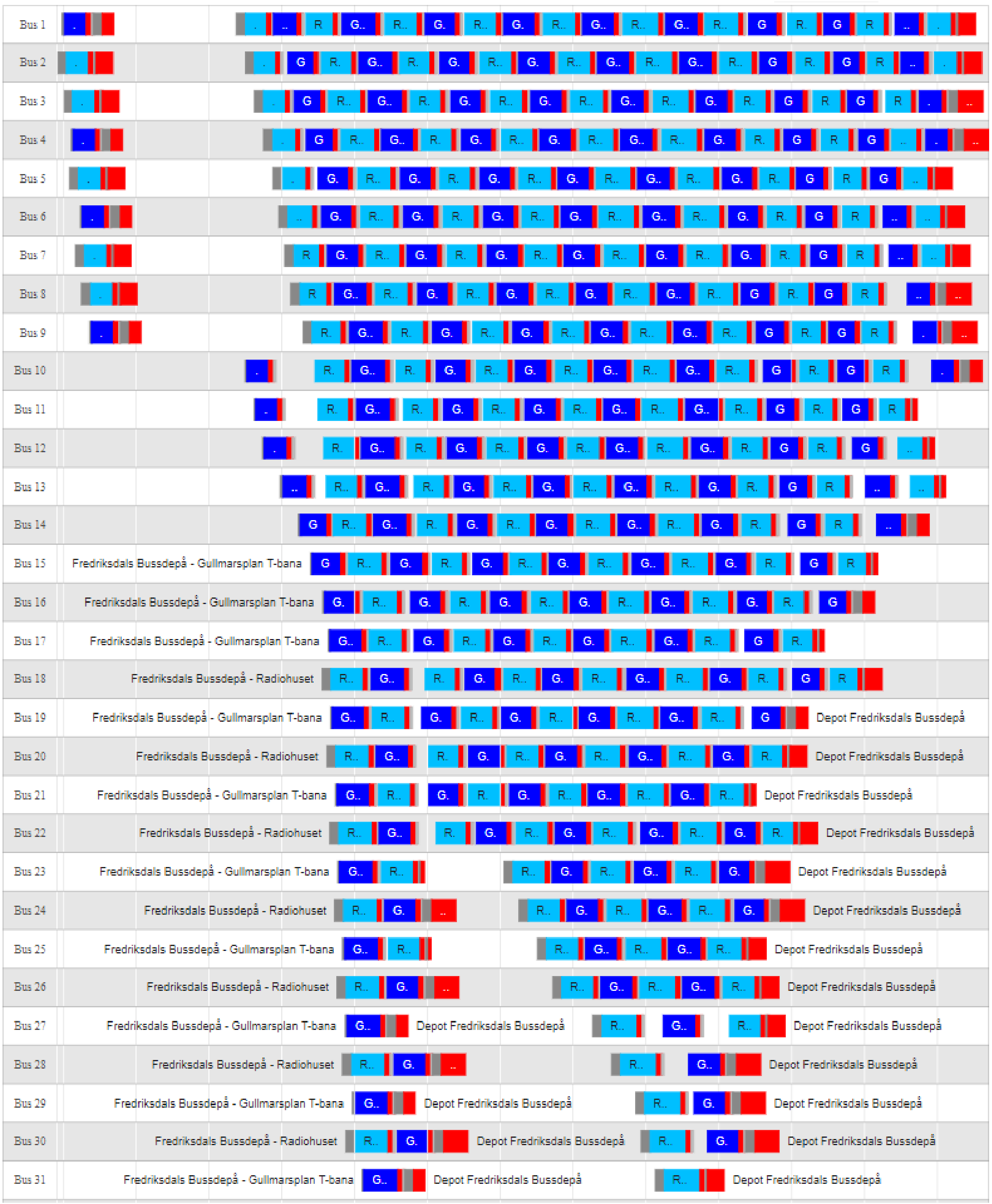
Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment costs								
Vehicle investment	7 339	7 339	7 339	7 339	7 339	7 339	7 689	8 038
Battery investment	5 567	5 238	5 118	4 789	4 699	4 340	4 453	4 294
Infrastructure investment	694	665	654	625	618	586	596	582
Total investment cost	**13 600**	**13 242**	**13 112**	**12 753**	**12 656**	**12 265**	**12 737**	**12 914**
Annual costs								
						182		
Depreciation vehicles	905	905	905	905	905	905	948	991
Depreciation batteries	827	778	760	711	698	645	661	638
Depreciation chargers	62	60	59	56	56	53	54	52
Total annual depreciation	**1 794**	**1 743**	**1 724**	**1 672**	**1 658**	**1 602**	**1 663**	**1 681**
Insurance vehicles	82	82	82	82	82	82	86	90
Maintenance vehicles	161	161	161	163	164	165	165	167
Tyres vehicles	13	14	14	14	14	14	14	14
Maintenance chargers	12	11	11	11	10	10	10	9
Total annual insurance and maintenance cost	**268**	**268**	**268**	**269**	**270**	**270**	**274**	**280**
Annual electricity fee	1	1	1	1	1	1	1	1
Electricity subscription fee	0	0	0	0	0	0	0	0
Electriciy power fee	21	20	19	18	18	16	17	16
Electricity variable fee	9	9	9	9	9	9	9	9
Consumption	98	99	99	100	100	101	101	102
HVO for heating	23	24	24	24	24	24	24	24
Total annual energy cost	**152**	**152**	**151**	**151**	**151**	**151**	**152**	**152**
Total annual driver cost	4 072	4 095	4 092	4 150	4 117	4 167	4 180	4 197
Cost per km [€]	**8,32**	**8,29**	**8,26**	**8,27**	**8,20**	**8,20**	**8,30**	**8,35**
Cost per hour [€]	**85,63**	**85,24**	**84,93**	**85,04**	**84,41**	**84,32**	**85,39**	**85,95**
Other relevant data (no costs)								
Total number of vehicles [units]	*21*	*21*	*21*	*21*	*21*	*21*	*22*	*23*
Total driver time per yr [hrs]	*116 511*	*117 171*	*117 081*	*118 752*	*117 810*	*119 226*	*119 597*	*120 079*

Appendix B – Findings for Route 2

Appendix B includes:

- Example of bus schedule for Route 2 from the EAEB-tool for Opportunity charge
- Total annual cost: Route 2 all runs for Opportunity Charge – Simulation 1
- Total annual cost: Route 2 all runs for Overnight Charge – Simulation 2

Example of bus schedule for Route 2 from the EAEB-tool for Opportunity Charge



Total annual cost: Route 2 for all runs Opportunity Charge – Simulation 1

All costs are presented in k€ if nothing else is stated - Opportunity Charge

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment costs								
Vehicle investment	10 834	10 834	10 834	10 484	10 484	10 135	10 135	10 135
Battery investment	2 099	2 099	2 099	2 032	2 032	1 964	1 964	1 964
Infrastructure investment	1 311	1 364	1 324	1 276	1 350	1 442	1 600	1 337
Total investment cost	**14 245**	**14 298**	**14 257**	**13 792**	**13 866**	**13 541**	**13 698**	**13 436**
Annual costs								
Depreciation vehicles	1 336	1 336	1 336	1 293	1 293	1 250	1 250	1 250
Depreciation batteries	312	312	312	302	302	292	292	292
Depreciation chargers	118	123	119	115	121	130	144	120
Total annual depreciation cost	**1 766**	**1 770**	**1 767**	**1 709**	**1 716**	**1 671**	**1 685**	**1 662**
Insurance vehicles	121	121	121	117	117	113	113	113
Maintenance vehicles	318	318	318	317	316	316	316	316
Tyres vehicles	27	27	27	27	26	26	26	26
Maintenance chargers	22	24	23	21	23	26	29	23
Total annual insurance and maintenance cost	**488**	**489**	**488**	**482**	**483**	**481**	**485**	**478**
Annual electricity fee	2	2	2	2	2	2	2	2
Electricity subscription fee	0	0	0	0	0	0	0	0
Electriciy power fee	42	44	42	41	43	45	51	42
Electricity variable fee	14	14	14	14	13	13	13	13
Consumption	146	146	146	146	145	145	145	145
HVO for heating	46	46	46	46	46	46	46	46
Total annual energy cost	**250**	**251**	**250**	**247**	**249**	**252**	**257**	**248**
Total annual driver cost	6 406	6 346	6 227	6 129	6 066	5 938	5 841	5 705
Total annual cost	**8 909**	**8 857**	**8 732**	**8 567**	**8 513**	**8 342**	**8 267**	**8 093**
Cost per km [€]	**5,89**	**5,85**	**5,77**	**5,66**	**5,63**	**5,51**	**5,46**	**5,35**
Cost per hour [€]	**81,69**	**81,21**	**80,06**	**78,55**	**78,06**	**76,49**	**75,81**	**74,20**
Other relevant data								
Total number of vehicles [units]	*31*	*31*	*31*	*30*	*30*	*29*	*29*	*29*
Total driver time per yr [hrs]	*183 294*	*181 576*	*178 179*	*175 367*	*173 566*	*169 909*	*167 124*	*163 233*
Total number of charger [units]	*6*	*6*	*5*	*4*	*4*	*4*	*4*	*2*
Total charger effect [kw]	*526*	*585*	*540*	*501*	*584*	*701*	*876*	*585*

Total annual cost: Route 2 for all runs Overnight Charge – Simulation 2

All costs are presented in k€ if nothing else is stated - Overnight Charge

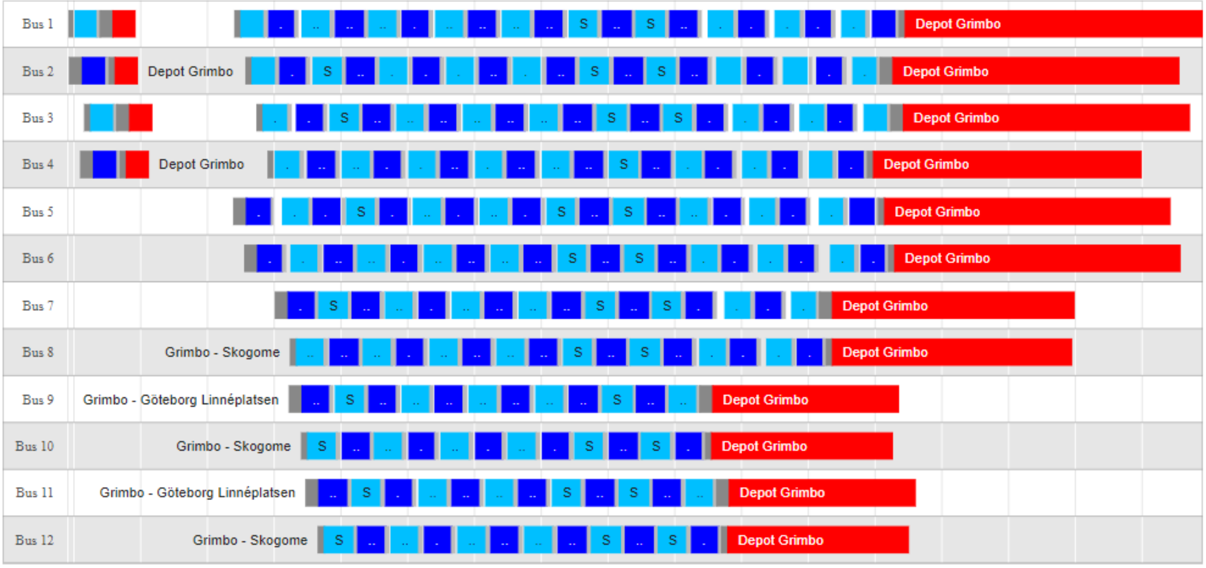
Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment costs								
Vehicle investment	10 135	10 135	10 135	10 135	10 135	10 135	10 135	10 484
Battery investment	8 696	8 434	8 140	7 682	7 421	6 898	6 636	6 594
Infrastructure investment	859	840	817	783	763	724	704	701
Total investment cost	**19 690**	**19 408**	**19 092**	**18 600**	**18 319**	**17 757**	**17 475**	**17 780**
Annual costs								
Depreciation vehicles	1 250	1 250	1 250	1 250	1 250	1 250	1 250	1 293
Depreciation batteries	1 292	1 253	1 209	1 141	1 102	1 024	986	979
Depreciation chargers	77	76	74	70	69	65	63	63
Total annual depreciation cost	**2 618**	**2 578**	**2 532**	**2 461**	**2 420**	**2 339**	**2 299**	**2 335**
Insurance vehicles	113	113	113	113	113	113	113	117
Maintenance vehicles	316	316	316	317	316	318	319	319
Tyres vehicles	26	26	26	27	27	27	27	27
Maintenance chargers	16	16	15	14	14	13	12	12
Total annual insurance and maintenance cost	**472**	**471**	**471**	**471**	**470**	**470**	**472**	**475**
Annual electricity fee	1	1	1	1	1	1	1	1
Electricity subscription fee	0	0	0	0	0	0	0	0
Electriciy power fee	28	27	26	25	24	22	21	21
Electricity variable fee	14	14	14	14	14	14	14	14
Consumption	153	153	153	154	153	154	154	154
HVO for heating	46	46	46	46	46	46	47	47
Total annual energy cost	**242**	**241**	**240**	**239**	**238**	**237**	**237**	**237**
Total annual driver cost	5 737	5 726	5 742	5 752	5 743	5 834	5 789	5 754
					-2,18%			
Total annual cost	**9 069**	**9 016**	**8 985**	**8 924**	**8 872**	**8 881**	**8 796**	**8 802**
Cost per km [€]	**5,99**	**5,96**	**5,94**	**5,90**	**5,86**	**5,87**	**5,81**	**5,82**
Cost per hour [€]	**83,16**	**82,67**	**82,39**	**81,82**	**81,34**	**81,43**	**80,66**	**80,70**
Other relevant data								
Total number of vehicles [units]	*29*	*29*	*29*	*29*	*29*	*29*	*29*	*30*
Total driver time per yr [hrs]	*164 168*	*163 838*	*164 299*	*164 588*	*164 333*	*166 939*	*165 646*	*164 643*

Appendix C – Findings for Route 3

Appendix C includes:

- Example of bus schedule for Route 3 from the EAEB-tool for Overnight Charge
- Total annual cost: Route 3 all runs for Opportunity Charge – Simulation 1
- Total annual cost: Route 3 all runs for Overnight Charge – Simulation 2

Example of bus schedule for Route 3 from the EAEB-tool for Overnight Charge



Total annual cost: Route 3 for all runs Opportunity Charge – Simulation 1

All costs are presented in k€ if nothing else is stated - Opportunity Charge

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment costs								
Vehicle investment	4 893	4 893	4 893	4 893	4 893	4 543	4 194	4 194
Battery investment	1 139	1 139	1 139	1 139	1 139	1 057	976	976
Infrastructure investment	1 001	1 045	855	889	936	988	1 073	1 236
Total investment cost	**7 033**	**7 077**	**6 886**	**6 921**	**6 968**	**6 589**	**6 243**	**6 406**
Annual costs								
Depreciation vehicles	603	603	603	603	603	560	517	517
Depreciation batteries	169	169	169	169	169	157	145	145
Depreciation chargers	90	94	77	80	84	89	97	111
Total annual depreciation cost	**862**	**866**	**849**	**852**	**857**	**806**	**759**	**773**
Insurance vehicles	55	55	55	55	55	51	47	47
Maintenance vehicles	199	199	199	200	199	197	197	197
Tyres vehicles	17	17	17	17	17	16	17	17
Maintenance chargers	15	16	11	12	13	14	16	20
Total annual insurance and maintenance cost	**285**	**286**	**281**	**283**	**283**	**278**	**277**	**281**
Annual electricity fee	2	2	2	2	2	2	2	2
Electricity subscription fee	0	0	0	0	0	0	0	0
Electriciy power fee	25	26	20	21	23	24	26	31
Electricity variable fee	9	9	9	9	9	8	8	8
Consumption	92	92	92	92	92	91	91	91
HVO for heating	29	29	29	29	29	29	29	29
Total annual energy cost	**156**	**157**	**151**	**153**	**154**	**154**	**156**	**161**
Total annual driver cost	3 379	3 325	3 310	3 226	3 152	3 013	2 935	2 931
Total annual cost	**4 683**	**4 634**	**4 591**	**4 514**	**4 446**	**4 251**	**4 126**	**4 146**
Cost per km [€]	**4,96**	**4,91**	**4,86**	**4,78**	**4,71**	**4,50**	**4,37**	**4,39**
Cost per hour [€]	**85,85**	**84,95**	**84,17**	**82,76**	**81,50**	**77,92**	**75,64**	**76,01**
Other relevant data								
Total number of vehicles [units]	*14*	*14*	*14*	*14*	*14*	*13*	*12*	*12*
Total driver time per yr [hrs]	*96 697*	*95 143*	*94 717*	*92 321*	*90 193*	*86 206*	*83 971*	*83 861*
Total number of charger [units]	*4*	*4*	*2*	*2*	*2*	*2*	*2*	*2*
Total charger effect [kw]	*436*	*485*	*273*	*311*	*363*	*436*	*546*	*727*

Total annual cost: Route 3 for all runs Overnight Charge – Simulation 2

All costs are presented in k€ if nothing else is stated - Depot Charge

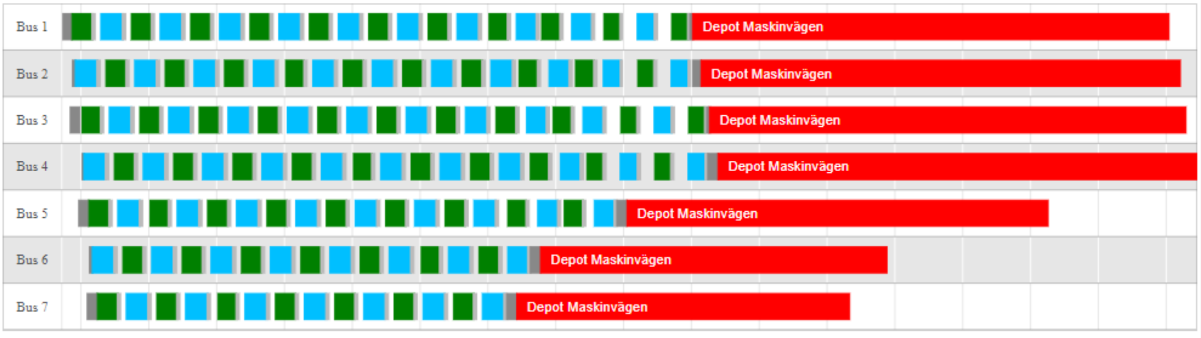
Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment costs								
Vehicle investment	4 194	4 194	4 194	4 194	4 543	4 893	5 592	6 291
Battery investment	4 398	4 232	3 997	3 914	4 076	4 099	4 481	4 668
Infrastructure investment	495	484	468	463	473	475	500	512
Total investment cost	**9 087**	**8 910**	**8 659**	**8 571**	**9 092**	**9 466**	**10 573**	**11 471**
Annual costs								
Depreciation vehicles	517	517	517	517	560	603	689	776
Depreciation batteries	653	629	594	581	605	609	666	693
Depreciation chargers	44	44	42	42	43	43	45	46
Total annual depreciation cost	**1 215**	**1 189**	**1 153**	**1 140**	**1 208**	**1 255**	**1 400**	**1 515**
Insurance vehicles	47	47	47	47	51	55	62	70
Maintenance vehicles	197	197	198	200	199	199	199	201
Tyres vehicles	17	17	17	17	17	17	17	17
Maintenance chargers	7	7	7	6	7	7	7	8
Total annual insurance and maintenance cost	**268**	**267**	**268**	**270**	**274**	**277**	**285**	**295**
Annual electricity fee	1	1	1	1	1	1	1	1
Electricity subscription fee	0	0	0	0	0	0	0	0
Electriciy power fee	12	12	11	11	12	12	13	13
Electricity variable fee	9	9	9	9	9	9	9	9
Consumption	98	97	98	99	99	99	98	99
HVO for heating	29	29	29	29	29	29	29	29
Total annual energy cost	**148**	**148**	**148**	**149**	**149**	**149**	**149**	**151**
Total annual driver cost	2 927	2 948	2 956	2 964	2 965	3 031	3 013	3 055
Total annual cost	**4 558**	**4 553**	**4 524**	**4 523**	**4 596**	**4 712**	**4 848**	**5 016**
Cost per km [€]	**4,83**	**4,82**	**4,79**	**4,79**	**4,87**	**4,99**	**5,13**	**5,31**
Cost per hour [€]	**83,56**	**83,46**	**82,93**	**82,91**	**84,25**	**86,38**	**88,87**	**91,96**
Other relevant data								
Total number of vehicles [units]	*12*	*12*	*12*	*12*	*13*	*14*	*16*	*18*
Total driver time per yr [hrs]	*83 751*	*84 363*	*84 570*	*84 810*	*84 845*	*86 721*	*86 220*	*87 402*

Appendix D – Findings for Route 4

Appendix D includes:

- Example of bus schedule for Route 4 from the EAEB-tool for Overnight Charge
- Total annual cost: Route 4 all runs for Opportunity Charge – Simulation 1
- Total annual cost: Route 4 all runs for Overnight Charge – Simulation 2

Example of bus schedule for Route 4 from the EAEB-tool for Overnight Charge



Total annual cost: Route 4 for all runs Opportunity Charge – Simulation 1

All costs are presented in k€ if nothing else is stated - Opportunity Charge

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment costs								
Vehicle investment	2 446	2 446	2 446	2 446	2 446	2 446	2 446	2 446
Battery investment	380	380	380	380	380	380	380	380
Infrastructure investment	623	634	650	669	694	730	784	874
Total investment cost	**3 449**	**3 461**	**3 476**	**3 496**	**3 521**	**3 557**	**3 611**	**3 701**
Annual costs								
Depreciation vehicles	302	302	302	302	302	302	302	302
Depreciation batteries	56	56	56	56	56	56	56	56
Depreciation chargers	56	57	58	60	62	66	70	79
Total annual depreciation cost	**414**	**415**	**417**	**418**	**421**	**424**	**429**	**437**
Insurance vehicles	27	27	27	27	27	27	27	27
Maintenance vehicles	71	71	71	71	71	71	71	71
Tyres vehicles	6	6	6	6	6	6	6	6
Maintenance chargers	5	5	6	6	7	8	9	11
Total annual insurance and maintenance cost	**109**	**109**	**109**	**110**	**111**	**111**	**113**	**115**
Annual electricity fee	2	2	2	2	2	2	2	2
Electricity subscription fee	0	0	0	0	0	0	0	0
Electriciy power fee	10	10	10	11	12	13	15	18
Electricity variable fee	3	3	3	3	3	3	3	3
Consumption	31	31	31	31	31	31	31	31
HVO for heating	10	10	10	10	10	10	10	10
Total annual energy cost	**56**	**56**	**56**	**57**	**58**	**59**	**61**	**64**
Total annual driver cost	1 741	1 739	1 693	1 691	1 690	1 688	1 686	1 685
Total annual cost	**2 319**	**2 319**	**2 275**	**2 277**	**2 279**	**2 282**	**2 288**	**2 300**
Cost per km [€]	**6,87**	**6,87**	**6,74**	**6,74**	**6,75**	**6,76**	**6,78**	**6,81**
Cost per hour [€]	**88,40**	**88,40**	**86,73**	**86,78**	**86,85**	**86,99**	**87,23**	**87,67**
Other relevant data (no costs)								
Total number of vehicles [units]	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*7*
Total driver time per yr [hrs]	*49 803*	*49 754*	*48 441*	*48 393*	*48 344*	*48 297*	*48 249*	*48 201*
Total number of charger [units]	*2*	*2*	*2*	*2*	*2*	*2*	*2*	*2*
Total charger effect [kw]	*119*	*133*	*149*	*171*	*199*	*239*	*299*	*399*

Total annual cost: Route 4 for all runs Overnight Charge – Simulation 2

All costs are presented in k€ if nothing else is stated - Overnight Charge

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Investment costs								
Vehicle investment	2 446	2 796	2 796	3 145	3 844	3 844	4 194	4 194
Battery investment	1 301	1 443	1 347	1 476	1 672	1 612	1 614	1 561
Infrastructure investment	291	300	294	302	315	311	312	308
Total investment cost	**4 038**	**4 539**	**4 437**	**4 924**	**5 831**	**5 767**	**6 119**	**6 063**
Annual costs								
Depreciation vehicles	302	345	345	388	474	474	517	517
Depreciation batteries	193	214	200	219	248	239	240	232
Depreciation chargers	26	27	26	27	28	28	28	28
Total annual depreciation cost	**521**	**586**	**571**	**634**	**751**	**741**	**785**	**777**
Insurance vehicles	27	31	31	35	43	43	47	47
Maintenance vehicles	71	71	70	71	72	71	72	72
Tyres vehicles	6	6	6	6	6	6	6	6
Maintenance chargers	2	2	2	2	3	3	3	3
Total annual insurance and maintenance cost	**106**	**111**	**110**	**115**	**123**	**123**	**127**	**127**
Annual electricity fee	1	1	1	1	1	1	1	1
Electricity subscription fee	0	0	0	0	0	0	0	0
Electriciy power fee	4	4	4	4	5	5	5	4
Electricity variable fee	3	3	3	3	3	3	3	3
Consumption	33	33	33	33	34	33	34	34
HVO for heating	10	10	10	10	10	10	10	10
Total annual energy cost	**51**	**51**	**51**	**52**	**52**	**52**	**52**	**52**
Total annual driver cost	1 685	1 695	1 663	1 668	1 702	1 703	1 691	1 684
Total annual cost	**2 362**	**2 444**	**2 394**	**2 468**	**2 628**	**2 619**	**2 655**	**2 640**
Cost per km [€]	**6,99**	**7,23**	**7,09**	**7,31**	**7,78**	**7,75**	**7,86**	**7,82**
Cost per hour [€]	**90,04**	**93,14**	**91,27**	**94,09**	**100,17**	**99,83**	**101,19**	**100,63**
Other relevant data								
Total number of vehicles [units]	*7*	*8*	*8*	*9*	*11*	*11*	*12*	*12*
Total driver time per yr [hrs]	*48 201*	*48 510*	*47 582*	*47 727*	*48 689*	*48 717*	*48 373*	*48 187*

Appendix E – EAEB tool

This appendix presents the tool that was developed in the EAEB project and used in this master's thesis, as presented in chapter 3. Figure E.1 presents the start page, where the routes are chosen, and charger points added.

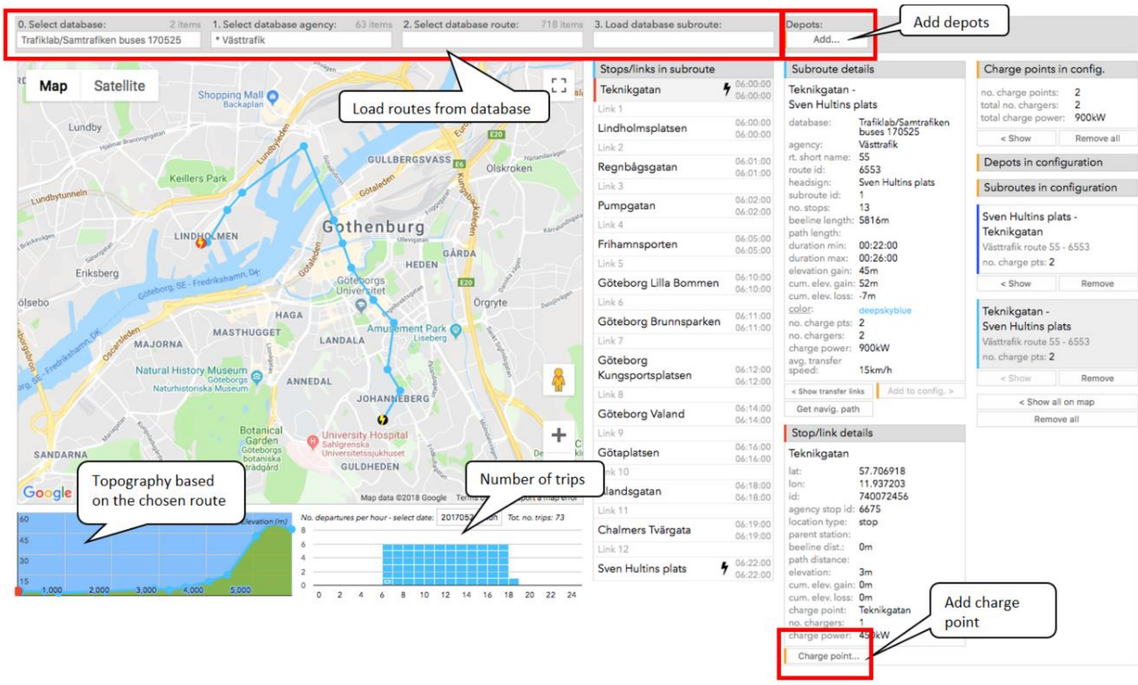


Figure E.1 - The graphical interface of the start page

Figure E.2 presents the graphical interface for the second page, where buses are added, and the schedule optimized. Furthermore, charge and dwell time is adjusted.

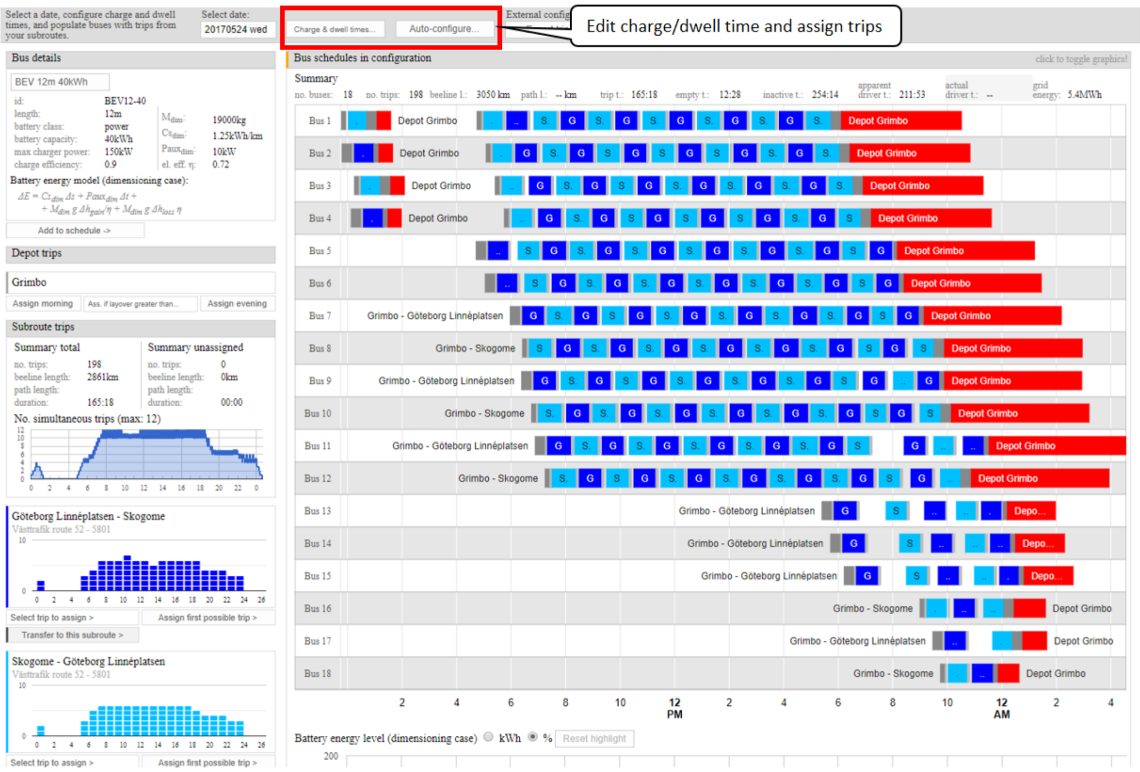


Figure E.2 - The graphical interface for the second page

Figure E.3 presents the third page, where costs are adjusted, and the results are presented for investment costs and annual costs. The output from this page, together with the output from page 2 was used as input for the Excel-tool developed in this master's thesis.

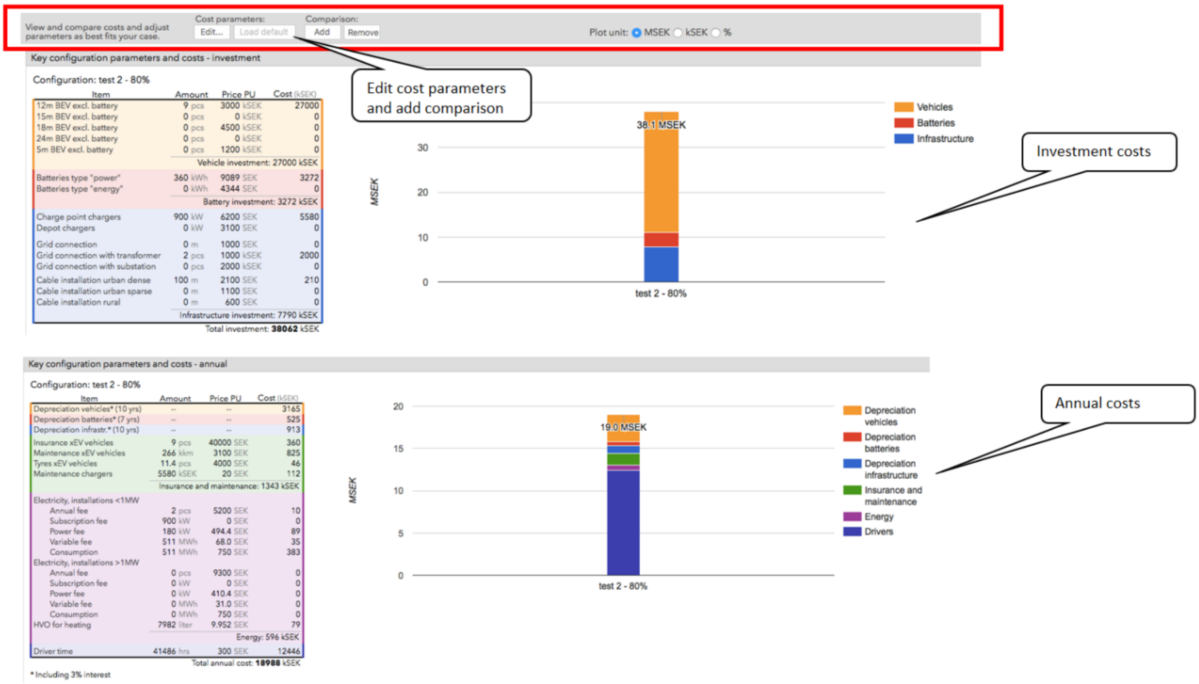


Figure E.3 - The graphical interface for the third page

The project report from the EAEB project can be found at:
http://www.energimyndigheten.se/forskning-och-innovation/projektdatabas/sokresultat/?projectid=22684

While more information about the tool, and five videos regarding the tool can be found at:
https://www.viktoria.se/projects/eaeb-energiforsorjningsalternativ-for-elektrifierade-bussystem-energy-transfer-solutions