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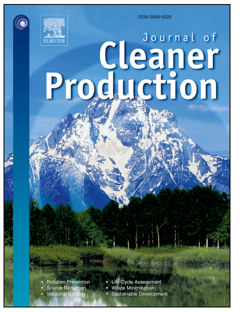

Lifecycle costs and charging requirements of electric buses with different charging methods

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Abstract

Electric city buses and high power charging systems have been rapidly developed in recent years. Battery electric buses are energy efficient and emission free but due to the expensive technology, lifecycle costs can be much higher in comparison to diesel or hybrid buses. This research presents a lifecycle cost analysis for a fleet operation of electric city buses in different operating routes. The objective is to define charging power and battery requirements as well as energy consumption and lifecycle costs. A specific simulation tool was developed to comprehensively evaluate electric buses in different operating conditions. The tool allows to systematically generate and simulate different operating scenarios with a chosen bus configuration, charging method and operating route. Based on the simulation results and predefined cost parameters, lifecycle costs are calculated for each operating scenario. The considered charging methods include overnight, end station and opportunity charging. Simulation results are presented for four operating routes which were measured from existing bus lines in Finland and California, USA. The results show that high energy capacity of the battery system is crucial for the overnight charging buses to achieve adequate daily operation whereas the battery size has a minor impact on the energy consumption and lifecycle costs of the fast charging buses. The lifecycle costs of electric buses are heavily impacted by capital costs including purchase costs of the buses and charging devices. When considering 12 years of service life, the end station charging electric buses can have slightly lower lifecycle costs than diesel buses but on average they have 7% higher lifecycle costs. The overnight charging buses have on average 26% and opportunity charging buses 35% higher lifecycle costs than diesel buses.

Keywords: electric bus; charging power; energy consumption; lifecycle costs; route simulation

1 Introduction

It has been demonstrated by recent research studies (Lajunen, 2014; Lajunen and Lipman, 2016) and development projects (Corazza et al., 2016; Pihlatie et al., 2014) that electric buses are becoming a viable option for sustainable and energy efficient public transportation. Because of the capacity limitations of electrical energy storages, electric buses need to have a large amount of stored energy on-board or the storages are needed to be recharged during operation (Göhlich et al., 2014; Rogge et al., 2015). For defining energy and cost efficient solutions of electric city buses in different operation scenarios, a thorough evaluation needs to be done for understanding the best technical solutions in terms of bus configuration and charging method. Plug-in hybrid buses can be considered as the main competitors for electric buses because they have partly emission free operation and their capital costs are lower in comparison to electric buses (Lajunen, 2015). Traditional hybrid buses can increase energy efficiency (Zeng et al., 2016) and are economically competitive with diesel buses but their environmental impacts are similar to those of diesel buses (Lajunen, 2014).

Research has been increasingly done in this field to define the technical requirements for the bus technology and charging infrastructure. The battery and charging power requirements were recently evaluated in Rothgang et al. (2015), and Rogge et al. (2015). Rothgang et al. (2015) concluded that the local operating situation and requirements have important influence on the battery system design and charging concept choice of electric buses. The analysis by Rogge et al. (2015) pointed out that it is necessary to focus on the entire bus operation schedules instead of individual trips. The operation and charging scheduling of electric buses were evaluated by Paul and Yamada (2014). They developed a specific algorithm to create operating and charging schedule for an electric bus by determining the appropriate charging locations and charging amounts to maximize the travelled distance. Research studies have also been carried out to define the costs of the charging infrastructure e.g. Wang et al. (2014) concluded that the payback period of the charging infrastructure investment for electric buses is still very long and future work is required on the refinement of cost calculation model and cost data updating. Lifecycle costs of a bus fleet operation have been rarely taken into account in scientific studies that focus on the evaluation of electric buses. It can be challenging to integrate all the different technical and economic aspects and to be able to fairly compare different operating methods of electric city buses as it was shown in Wang and González, (2013) and Mahmoud et al. (2016). Both studies concluded that the successful implementation of electric buses is highly sensitive to operational context and energy profile.

During the last decade, the development of lithium-ion battery technology has made electric vehicles as a sustainable solution for transportation (Budde et al., 2013; Jaguemont et al., 2016). A recent study by Sen et al. (2017) indicated that battery electric trucks would significantly improve the life-cycle performance of a truck as well as ambient air quality. Lithium-ion batteries have been widely evaluated and characterized in literature e.g. Saw et al. (2016) and Zackrisson et al. (2010). This battery technology is still in development phase meaning that the quality, reliability and specific energy could be improved (Saw et al., 2016), and their environmental impacts reduced (Zackrisson et al., 2010). The number of electric vehicles in passenger vehicle market has been increasing rapidly in recent years. There are also increasing number of electric city buses commercially available at the moment (Corazza et al., 2016). The main challenges in adopting electric buses are related to charging infrastructure development and high investment costs of buses. The costs and durability concerns of lithium-ion batteries have a significant impact on the lifecycle costs of electric buses (Lajunen 2014; Pihlatie et al., 2014). In a recent study by Newbery and Strbac (2016) cost estimations were presented for electric vehicle battery packs. They estimate that by 2020 a battery pack specific cost would be between $275/kWh and $375/kWh. However, these cost levels may not be valid for electric buses due to the larger battery systems and different chemistries. Another challenge with batteries is hot and cold climate conditions. The battery system needs to have an effective cooling and heating system to avoid power degradation and aging (Jaguemont et al., 2016; Lajunen and Kalttonen, 2015). Extreme weather conditions are also challenging for the cabin thermal management and ensuring adequate operating range. Battery-swap or exchange systems are sometimes proposed as a solution for the charging challenge of electric buses. According to a recent study by Kim et al. (2015), the major advantage of the battery exchange system is the quick re-charging and the possible utilization of the battery exchange station as a mini scale energy storage system for grid system peak power shaving.

There are several demonstration projects underway in which electric buses are deployed around the world e.g. (Corazza et al., 2016; Choi et al., 2012; Festner and Karbowski, 2012; Laurikko et al., 2015). In the most of these projects, the buses are recharged during service operation and different charging methods are being implemented. With the end station and opportunity charging, the on-board battery capacity does not need to be very high in comparison to overnight charging (Lajunen and Tammi, 2016). The opportunity charging refers to charging during the service operation and the charging is usually done on bus stops. In Espoo, Finland, four commercial and one demonstration electric buses were in test operation from 2011 to 2016 (Laurikko et al., 2015). In the “Foothill Transit Ecoliner Electric Bus Program”, Proterra electric buses have been operated since 2010 (Festner and Karbowski, 2012; Prohaska et al., 2016). The battery is recharged at layover by using a fast charging method. The battery can be quick-charged from 10 percent to a 95 percent state of charge in ten minutes. Opportunity charging is being demonstrated in TOSA project in Geneve (Ahmed et al., 2013). The demonstration started in 2013 and includes an articulated bus which is fast-charged in two bus stops during 15 seconds (maximum power of 400 kW) and at the end station during 3-4 minutes (200 kW). Wireless charging is being demonstrated e.g. in United Kingdom where a fleet of eight electric buses operate along a busy route in Milton Keynes (Miles and Potter, 2014). The fleet operates on a route which covers 25 kilometers and the buses are recharged at the start and end of the route as well as during the night. Wireless charging was also demonstrated to increase the operating range of an electric shuttle bus in (Bailey et al., 2012). It is recognized that there could be different types of challenges regarding to the installation of charging stations in inner cities and more research should be done in that area but it is out of the scope of this study. Also, the charging infrastructure can be planned in an optimized way as it was shown in Kunith et al. (2016) and Sebastiani et al. (2016).

Complexities of electric bus operation increases the challenges in decision making therefore it is important to investigate in great detail the different technology options and operating models of electric buses. This paper introduces a comprehensive approach to evaluate technical and economic performance of electric city buses in different operating conditions. This is important because electric buses are considered as viable replacements for diesel buses and their implementation has been increasing in recent years. The present literature does not include in-depth evaluation of the lifecycle costs of electric buses especially in relation to different charging methods. Most of the previous studies only focus on a single charging method. The presented results in this paper give a clear presentation about the impacting factors on the lifecycle costs of electric bus operation in which the different charging methods have been taken into account. The lifecycle costs analysis also illustrates the cost breakdown and includes electricity demand charges which are often omitted. Energy consumption, battery dimensioning, charging power and lifecycle costs are evaluated in four different operating routes. Lifecycle cost analysis is carried out on the basis of the recent cost parameters presented in literature and in comparison to traditional diesel buses. Overnight (ON), End station (ST) and Opportunity charging (OP) were the chosen as charging methods. In this case, the opportunity charging refers to the charging at the bus stops along the route. The reference electric bus is based on a full size, lightweight city bus design. The bus corresponds to the prototype bus that was developed in the research project ECV-eBus in Finland (Laurikko et al., 2015) and is presented in Fig. S1. In the sections below, the paper first presents the developed simulation tool for electric bus simulations. Second, the electric bus model and simulation parameters are introduced. Then, the lifecycle cost calculation is presented. After that, the simulation and lifecycle cost results are analyzed with appropriate discussion. Finally, the key findings are summarized in the conclusions.

2 Electric bus simulation tool

2.1 Previous simulation studies

Simulation has often been used as the research method in electric bus operation development because it enables fast evaluation of operating models in different conditions. For example, simulation was used in Rogge et al. (2015) to define the required charging infrastructure and energy storage requirements. The research result showed that the charging power and battery energy capacity is heavily dependent on the operating route. Simulation of an electric transportation system was presented in De Filippo et al. (2014), and simulation based investigation of the charging load characteristics of battery-swap station was carried out in Dai et al. (2014). The commercial simulation tools rarely offers a suitable environment that could be directly used for the evaluation of transit bus operations. A specific spreadsheet tool for a lifecycle cost (LCC) model of transit buses was developed by Golub et al. (2011) to assist transit agencies in forecasting life-cycle operating and capital costs when choosing among various bus technologies. Simulation is also a practical tool for optimization. Different types of optimization studies have been presented for electric buses. In Ding et al. (2015), optimal sizing and control of a fast charging station and energy storage system was carried out by mixed integer nonlinear programming. An optimization strategy that utilizes a bi-objective genetic algorithm was developed by Sebastiani et al. (2016) to minimize both the number of charging stations and the average extra time stopped in the station to recharge electric buses. The construction costs of electric bus implementation were optimized in Ke et al. (2016) based on the number of e-buses, level of battery capacity, number of chargers, and electricity costs.

2.2 Description of the evaluation tool

One of the main objectives of this research was to develop a systematic process to evaluate different solutions for the energy and cost efficient operation of rechargeable electric city buses. Therefore, an analytical simulation tool was developed for the evaluation. The tool allows defining initial parameters as quantitative metrics for the selection of the bus and charging method configurations depending on the operating route and conditions. The tool is based on a mathematical model of a generic electric bus and was developed in MATLAB environment. The graphical user interface (GUI) of the simulation tool is presented in Fig. S2. The basic simulation parameters are defined in the main screen of the GUI. The simulation process takes into account the charging method, operating route, operating schedule, bus configuration, and auxiliary power consumption which depends on ambient weather conditions as described in (Lajunen and Tammi, 2016).

After a simulation is done, the results can be analyzed and lifecycle costs calculated. Simulation results can also be saved for a comparison analysis between simulations e.g. with different operating conditions or bus configuration. By selecting a parametric study, the user can choose different values for certain parameters e.g. for the battery capacity and all the chosen battery options are then simulated. Fig. 1 illustrates the simulation process including the required initial data and data processing during simulation.

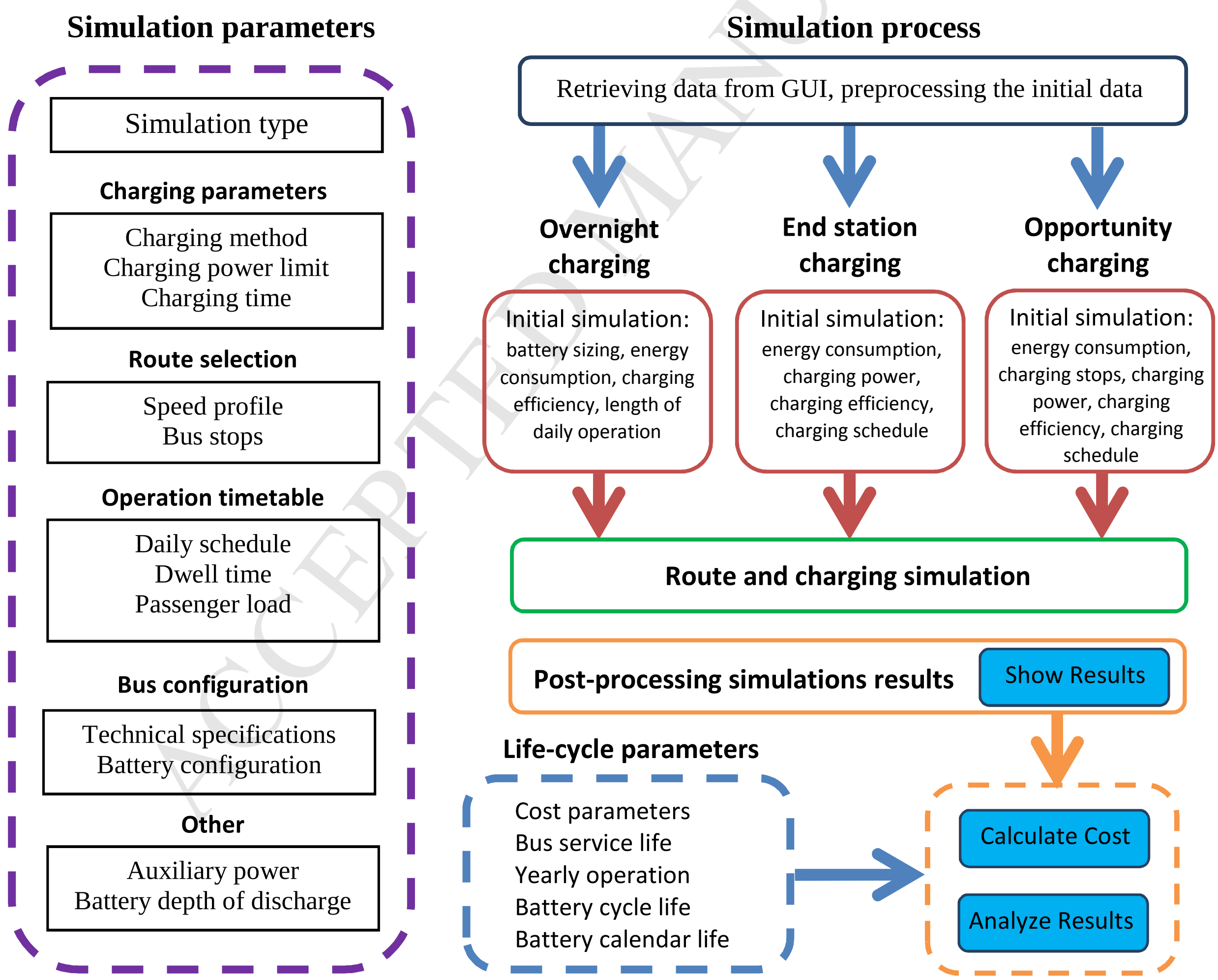

Fig. 1. Flowchart of the simulation process.

The simulation tool include three different charging methods: 1) Overnight (ON), 2) End station (ST), and 3) Opportunity (OP) charging. These different charging methods can also be combined. A maximum charging power limit can be set for each charging method. The battery charging is included in the simulation model and if necessary, the charging power is limited to avoid over voltage of the battery system. The simulations are always done by using a specific operating route or multiple routes which define the driving profile and bus stops along the route. An operating route can be defined as a single route or as a roundtrip which is often the case for transit buses. The reference bus driving speed profiles such as Braunschweig and Manhattan are typically defined as single routes without elevation profile. The operation timetable can be freely chosen from the GUI. The timetable is defined by the starting and ending time of the daily operation, the operation interval and the dwell time at the end station. The passenger load can be defined as percentage of the full payload. The minimum number of buses (fleet size) is calculated based on the operating schedule.

The bus configuration data is defined in a predefined initialization file which includes the general technical parameters of the electric bus and the initialization data for powertrain components: the battery, electric motor and differential gear. The battery configuration is calculated based on the battery type (high-power or high-energy) and energy capacity. The battery capacity can be increased by adding more modules in parallel and/or in series. In the calculation, the battery systems voltage has low and high limits, and the cell capacity (Ah) is fixed. The cycle and calendar life of the battery are required for the lifecycle cost calculation.

2.3 Electric bus model

A simplified model of the electric bus powertrain was developed to simulate the energy consumption in different operating conditions. The original simulation model was developed in the research project ECV-eBus and verified with the measured results acquired from the prototype bus tests (Lajunen and Kalttonen, 2015; Laurikko et al., 2015). The simulation model equations are defined in (1) – (7). The model inputs are driving speed, road grade, and charging power. The target value of the charging power is pre-calculated for the operating route based on the charging method, operating schedule, and energy consumption.

The torque requirement at the wheels (T_w) is calculated based on the speed (v) and road grade (α) as in

$$T_w(t) = \left(0.5\rho_a C_D A_f v(t)^2 + Mgf_r \cos\alpha(t) + Mg\sin\alpha(t) + M\frac{dv}{dt}\right)/r_d + T_{w0}, \quad (1)$$

where ρ_a is the density of air, C_D is the drag coefficient, A_f is the frontal area of the bus, M is the bus total mass, g is the gravitational acceleration, f_r is the rolling resistance coefficient, r_d is the rolling radius of the tire, and T_{w0} is the inertial torque of the powertrain. The required torque at the electric motor can be defined as in

$$T_m(t) = T_w(t)/\left(i_g i_{fd} \eta_g \eta_{fd}\right) + T_{m0}, \tag{2}$$

where i_g is the gearbox gear ratio, i_{fd} is the gear ratio of the final drive (differential gear), η_g is the efficiency of the gearbox, η_{fd} is the efficiency of the final drive, and T_{m0} is the inertial torque of the electric motor. The electric motor rotational speed is defined in (3)

$$\omega_m(t) = \left(v(t) i_g i_{fd}\right)/r_d, \tag{3}$$

The power requirement from the battery can be calculated as in

$$P_{b\_out}(t) = \omega_m(t) T_m(t)/\eta_m(\omega_m(t), T_m(t)) + P_{aux}(t), \tag{4}$$

where η_m is the electric motor efficiency in function of the rotational speed and torque. P_{aux} is the auxiliary power demand. The power consumption of the battery is the sum of the output power (P_{b_out}) and battery internal losses (P_{b_loss}) as described in (5).

$$P_{b\_cons}(t) = P_{b\_out}(t) + P_{b\_loss}(t) = I_b(t) U_b(t) + r_b(q_b(t)) I_b(t)^2, \tag{5}$$

where I_b is the battery current, U_b is the battery voltage, r_b is the battery internal resistance in function of the battery state of charge q_b. The battery current is defined as in

$$I_b(t) = \left(U_{voc}(q_b(t)) - \sqrt{U_{voc}(q_b(t))^2 - 4 r_b(q_b(t)) P_{b\_out}(t)}\right)/2 r_b(q_b(t)), \tag{6}$$

where U_{voc} is the battery open circuit voltage in function of the state of charge, which is calculated based on the battery current and battery capacity (C_b) as in

$$\frac{dq_b}{dt} = I_b(t)/(3600 C_b). \tag{7}$$

3 Simulation parameters

3.1 Vehicle and powertrain

The simulation model parameters consist of the general technical specifications of the bus and powertrain component data. The electric bus model correspond to the lightweight transit bus which was developed in the research project ECV-eBus (Pihlatie et al., 2014). The general specifications of the reference bus are presented in Table 1. The powertrain components include battery, electric motor, and final drive (differential gear). The simulation model also allows to use a reduction gear for the electric motor to adjust the motor speed range to the driving speed. In this case, the electric motor maximum speed is quite low so that there was no need for a gear reduction.

The specifications for the high-energy and high-power battery are shown in Table 2. High-energy batteries have high specific energy ratio (kWh/kg) among the lithium based batteries and high-power batteries have high specific power (kW/kg). High-power batteries, such as lithium titanium oxide cells, can also accept very high currents which is required for fast charging applications. The high-energy battery was used for the overnight charging buses and high-power battery for the end station and opportunity charging buses. The required energy capacity of the battery for overnight charging buses was calculated by the simulation software. The required capacity depends on the energy consumption, operation schedule and charging power. The calculation was done by iteration because the weight of the bus is dependent on the battery capacity and the weight impacts on the energy consumption. Also, the battery capacity can be increased or decreased only by a certain amount of energy because the battery system consists of modules and it has predefined low and high limits for the system voltage. The battery weight was calculated based on the cell weight and packing factor, which refers to the weight factor from battery cell to pack level.

Table 1: Technical specifications of the reference electric bus.

	Abbrv.	**Value**
Curb weight without battery (kg)	M_c	8500
Gross weight (kg)	M_g	15000
Vehicle frontal area (m^2)	A_f	6.20
Drag coefficient	C_D	0.70
Rolling resistance coefficient	f_r	0.008
Rolling radius (m)	r_d	0.412
Wheel inertia (kgm^2)	J_w	7.23
Final drive ratio	i_{fd}	4.88
Final drive efficiency	η_{fd}	0.97
Gear reduction ratio	i_g	1.00
Gear efficiency	η_g	1.00
Electric motor nominal power (kW)	P_{mot}	207
Electric motor nominal torque (Nm)	T_{mot}	1100@1500rpm

A parametric study was carried out for the end station and opportunity charging buses. Four different configurations (battery energy capacity of 60, 80 100 and 120 kWh) were defined for the high-power type battery. In all simulations the passengers load was 50 passenger which correspond to about 3750 kg. The reference auxiliary power was 6 kW which can be considered as operation in mild weather conditions (Lajunen and Kalttonen, 2015).

Table 2: Battery technical specifications.

	High-energy battery	**High-power battery**
Cell chemistry	Graphite/NMC	Titanium Oxide
Cell capacity (Ah)	100	30
Cell nominal voltage (V)	3.7	2.1
Cell weight (kg)	2.2	0.9
Packing factor	1.4	1.25
Module configuration	7 cells in series	10 cells in series

3.2 Operating routes

The simulated operating routes were generated on the basis of four measured driving cycles which are described in Table S1 and Fig. S3. Espoo line 11 (E11) and H550 are existing bus lines from Helsinki region in Finland. Line 18 and Line 51B are measured from Berkeley, California. These bus lines are exceptionally interesting because in Espoo, there have been battery electric buses in test operation (Laurikko et al., 2015), and in Berkeley, there have been fuel cell hybrid buses in operation for several years (Eudy and Post, 2014). It can be seen in Fig. S3 that the Berkeley operating routes have much more elevation changes than in the routes from Finland. The aggressiveness is calculated based on the level of acceleration and it is usually higher in city center type cycles due to frequent acceleration-deceleration phases (Lajunen and Kalttonen, 2015). All the simulated operating routes were defined as roundtrips.

3.3 Description of the simulation runs

All simulations were carried out with the same operating schedule and charging parameters. The simulation of the overnight charging buses differs from the other simulations because the required battery energy capacity was calculated before the simulation by the software. The maximum battery capacity was defined to be 400 kWh and the maximum overnight charging power 50 kW. Simulations were carried out with three different auxiliary power consumptions which corresponded to mild weather conditions (6 kW), cold or hot conditions

(14 kW), and extreme cold conditions (22 kW). Table 3 describes the general simulations parameters for the electric bus operation.

Table 3: Description of simulation parameters.

Parameter description	**Value**
Daily operation	6:00 – 22:00, 16 hours
Operating timetable	interval of 10 minutes
Dwell time at the end station	5 minutes
Maximum time for opportunity charging	30 seconds
Battery depth of discharge for fast charging buses	75%
Battery depth of discharge for overnight charging buses	95%

The required charging power for the end station and opportunity charging was calculated in simulations based on the battery capacity, operating route, energy consumption, and chosen charging method. The maximum power for the end station and opportunity charging was 400 kW. There is a charging station at both ends of the roundtrip routes for the end station charging. The charging stations of the opportunity charging are located at bus stops.

4 Lifecycle costs

4.1 Cost calculation

The lifecycle cost model is based on the model that the author has presented in his previous research (Lajunen and Lipman, 2016). Three main cost areas were considered in the lifecycle costs of electric city buses; capital costs (C_{CAP}), operation costs (C_{OP}), and technology replacement costs (C_{REP}). Technology replacement costs refers to the battery system replacements, which is not considered as a maintenance cost. The calculation of annualized lifecycle costs for a bus fleet is described in (8)

$$C_{LC} = C_{CAP} + C_{OP} + C_{REP}. \tag{8}$$

The capital costs consists of the purchase costs of a bus (C_{bus}), the initial costs of the charging devices (C_{chg}), and the salvage value of the buses and charging devices (C_{SV}). N_{bus} is the number of buses in a fleet. The calculation of the capital costs can be defined as:

$$C_{CAP} = N_{bus}C_{bus} + C_{chg} - C_{SV}. \tag{9}$$

The operation costs include energy, maintenance and carbon dioxide (CO_2) emission costs. The calculation of annualized operation costs is given by:

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

where D_j is the yearly driven distance, C_{nrj_j} is the energy cost, C_{m_j} is the maintenance cost, C_{co2_j} is the CO_2 emission costs, m_{chg} is the charging device maintenance cost factor as percentage, d_{rate} is the discount rate, and T is the time period for the lifecycle analysis. The CO_2 emission cost were not included to the lifecycle cost analysis but the effect of CO_2 emission costs was evaluated. The technology replacement costs refer to the necessary replacement of batteries. The calculation of annualized technology replacement costs is given by:

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

where C_{tech_j} is the yearly technology replacement costs which is calculated as in

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

where C_{batt} is the battery specific cost (€/kWh), E_{batt} is the energy capacity of the battery (kWh), and F_R is the replacement function which have output of 0 or 1 indicating battery replacement. D_{cum_j} is the cumulative driven distance and L_{BATT} is the useful life of the battery in kilometers. The useful life for the batteries was defined based on the estimations presented in literature. The useful life was calculated on the basis of the total energy throughput:

$$L_{BATT} = \frac{N_{cycle} E_{batt}}{E_{km}}, \tag{13}$$

where N_{cycle} is the battery life as amount of deep discharge-charge cycles, and E_{km} is the energy throughput of the battery (kWh/km). The useful life of the high-energy type batteries was assumed to be 5000 cycles and 10000 cycles for the high-power type batteries. The maximum calendar life was defined as 10 years.

4.2 Cost parameters

The cost parameters were defined based on the values presented in recent literature. Table 4 shows the chosen cost parameters for this evaluation. The purchase costs of battery electric buses can vary significantly depending on the battery energy capacity and battery chemistry.

Therefore, the purchase cost of the reference bus was defined without a battery. The operating costs include electricity consumption, component replacement costs, and regular maintenance costs. In the electricity costs, besides the energy specific costs (€/kWh), also the demand charges (€/kW) were taken into account. The costs of the demand charges are calculated on monthly basis by using the maximum charging power used in that period. The component replacement costs include the periodic replacement of batteries and maintenance costs include general repairs and spare parts as well as the maintenance of the charging devices.

Table 4: Default cost parameters.

Parameter description	Value
Purchase cost of electric bus (without battery) (€)	350000
Purchase cost of diesel bus (€)	225000
High-energy battery cost (€/kWh)	500
High-power battery cost (€/kWh)	800
Maintenance cost (€/km)	0.20
Fast charging device cost (P > 200 kW) (€)	250000
Overnight charging device cost (P <= 50 kW) (€)	20000
Yearly charging device maintenance (%)	3
Electricity cost (€/kWh)	0.10
Electricity demand charges (€/kW)	10.00
Reference service life of buses (years)	12
Discount rate (%)	3
Yearly operation (h)	4000
Service life of charging devices (years)	20

The following assumptions were made related to the estimates of lifecycle costs:

- All costs are considered in current prices in euros (year 2016);
- Labor costs are assumed equal and are not included to the calculation;
- A yearly discount rate of 3% (real) is assumed in all calculations;
- As a reference, service life of 12 years is assumed for electric and diesel buses but lifecycle costs were also calculated for 16 years of service;
- The service life of the charging devices was assumed to be 20 years. The residual value of the charging devices was taken into account in the lifecycle costs calculations.
- The salvage value of all buses is considered to be zero at the end of their service life;
- Other than periodic component replacement, additional unscheduled maintenance is not included;

- The charging device costs include the equipment and installation costs. The yearly maintenance of the charging devices was assumed to be 3% of the initial costs
- Charging stations are route specific, thus they are not shared with other operating routes; and
- Same cost parameters were used for all driving cycles. Therefore, the California cycles (Line 18 and 51B) are considered as different operating cycles in Finnish context.

5 Results and analysis

5.1 Energy consumption and charging power

The energy consumption was calculated from the simulation results for the different bus configurations and operating routes. Fig. 2a presents the energy consumption of the electric buses in different operating routes with 6 kW of auxiliary power consumption. The fast charging buses have battery capacity of 80 kWh. For overnight charging buses the battery energy capacity varies between the operating routes. The results show in Fig. 2a that the consumption variation between cycles is almost 30% and the overnight charging buses have on average 10% higher energy consumption than the fast charging buses. The average driving speed is also shown in Fig. 2a for each cycle. It can be seen that the lower average speed increases the energy consumption but the higher energy consumption in the route Line 51B is partly caused by the more aggressive driving (Table S1). Fig. 2b presents the energy consumption increase due to the higher battery capacity of the fast charging buses and higher auxiliary power consumption. According to the results, an increase of 10 kWh in the energy capacity increases the energy consumption only about 0.5% and there were practically no differences between the operating routes. The constant 14 kW auxiliary power corresponds to the consumption in hot or cold ambient conditions (Lajunen and Tammi, 2016). The higher auxiliary power increases significantly the total energy consumption as presented in Fig. 2b. The energy consumption of a typical diesel city bus is between 4-6 kWh/km which means that electric buses have almost 80% higher energy efficiency than diesel buses (Lajunen and Lipman, 2016).

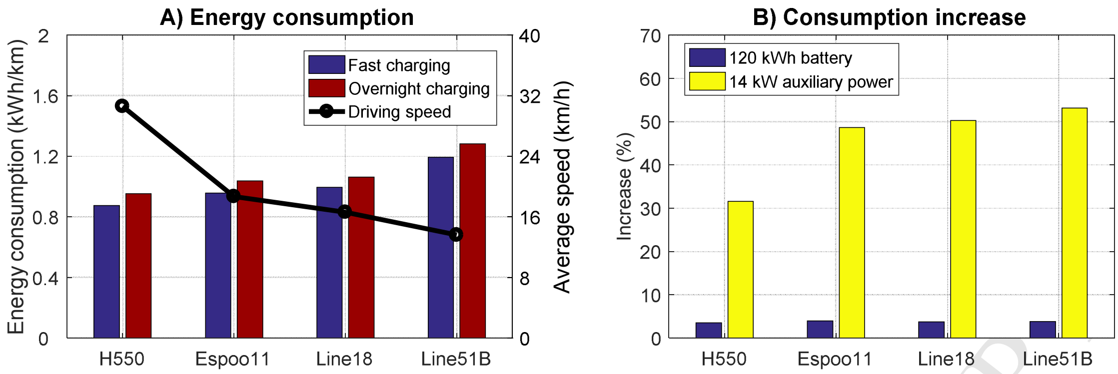

Fig. 2. Energy consumption of the electric buses.

Fig. 3 shows the number of required charging stations for the opportunity charging with different charging power levels and charging times at the bus stop. The number of charging stations is the minimum number of stations for a roundtrip to ensure charge sustaining operation of the bus. No optimization was used to determine the location of these stations. The number of required charging stations was decided based on the charging power, energy consumption, charging energy losses and charging time. Because the operating routes H550 and Line 18 are much longer than Espoo 11 and Line 51B, the total number of the charging stations is much higher for these routes. The number of charging stations can be decreased by increasing the charging power or the charging time. Increasing charging power over 400 kW could require additional equipment such as an energy buffer at the charging station. There is also limits for the duration of the charging time at the stop. Therefore, in this evaluation the maximum charging power was 400 kW and charging time 30 seconds. These results indicate that there could be a possible optimal solution for each operating route in terms of the charging power, charging time and lifecycle costs. Table 5a presents the required number of charging stations, the number of charging stations per kilometer, and total number of bus stops on the route. The same results are presented in Table 5b with a constant auxiliary power of 14 kW. The number of required charging stations would be much higher due to the increased energy consumption. Even if the total number of charging station is the highest for the route H550, there would be least amount of stations per kilometer.

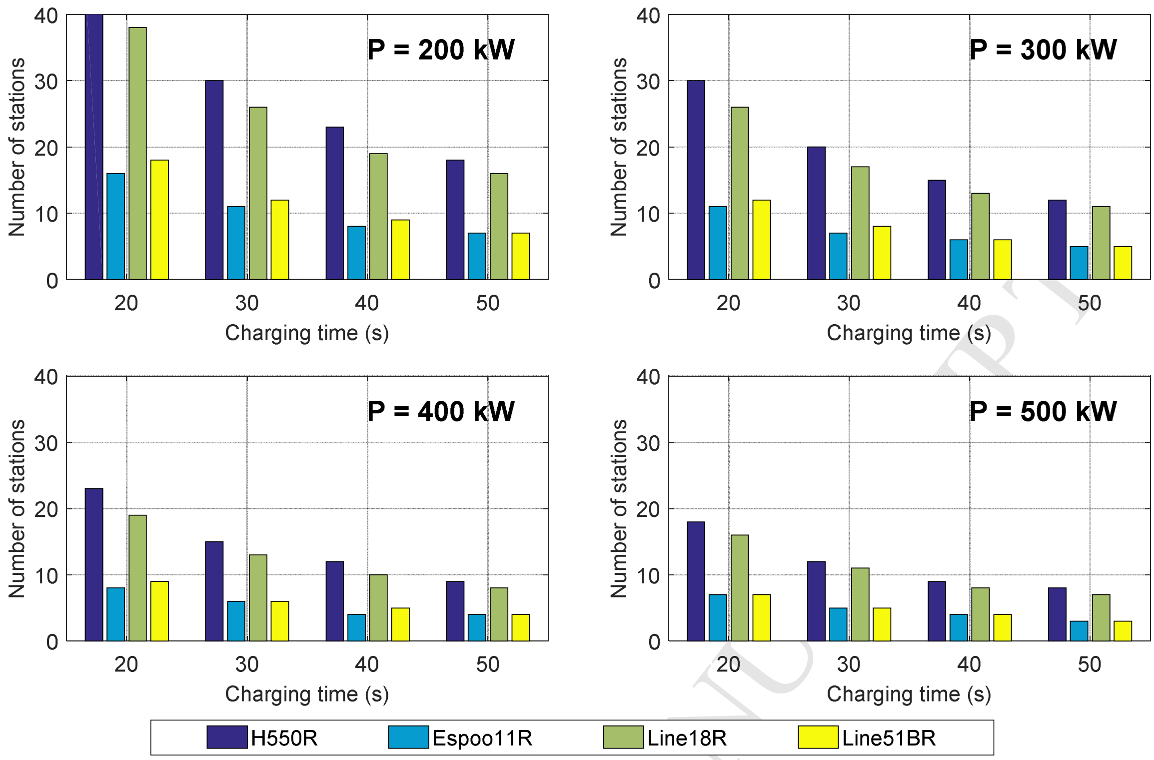

Fig. 3. Number of charging stations for the opportunity charging.

Table 5a. Number of charging stations for opportunity charging with 400 kW of charging power. Number of stations per kilometer (St/km).

Cycle \ Time	t = 20 s		t = 30 s		t = 40 s		t = 50 s		Bus stops
	Nbr	St/km	Nbr	St/km	Nbr	St/km	Nbr	St/km	
H550	23	0.40	15	0.26	12	0.21	9	0.16	78
Espoo 11	8	0.44	6	0.33	4	0.22	4	0.22	52
Line 18	19	0.45	13	0.31	10	0.24	8	0.19	127
Line 51B	9	0.56	6	0.37	5	0.31	4	0.25	57

Table 5b. Number of charging stations for opportunity charging with 400 kW of charging power and auxiliary consumption of 14 kW.

Cycle \ Time	t = 20 s		t = 30 s		t = 40 s		t = 50 s		Bus stops
	Nbr	St/km	Nbr	St/km	Nbr	St/km	Nbr	St/km	
H550	30	0.52	20	0.35	15	0.26	12	0.21	78
Espoo 11	12	0.66	8	0.44	6	0.33	5	0.28	52
Line 18	29	0.68	19	0.45	15	0.35	12	0.28	127
Line 51B	14	0.87	9	0.56	7	0.43	6	0.37	57

The required charging power for the end station charging buses is heavily dependent on the route distance. In the H550 route the charging power was around 310 kW and 260 kW in the Line 18. For the shorter routes, Espoo 11 and Line 51B, the required charging power was on average 106 kW and 118 kW, respectively. The operation in cold and hot conditions would require higher charging power. The simulations with the 14 kW of constant auxiliary power indicated that the charging power would be 30–50% higher. Alternatively, the battery energy capacity had only a minimal influence on the charging power. Fig. S4 shows the battery state of charge (SOC) in the route Line 51B for two different battery options.

Fig. 4 shows the speed of the bus and the state of charge (SOC) signal of the battery for the overnight charging buses for one day of operation. These results show that the overnight charging buses can operate 16-hour daily service in all the other routes except the H550 route in which the operation time is 12 hours per day. The battery energy capacities varies between 292 and 376 kWh, and daily operating distance between 194 and 344 kilometers. Table 6a shows the simulation results for the overnight charging buses with the reference auxiliary consumption of 6 kW. The overnight charging power remains under 50 kW in all operating routes. Higher auxiliary consumption, thus the operation in cold or hot ambient conditions, would increase the energy consumption and decrease the daily operating time as shown in Table 6b.

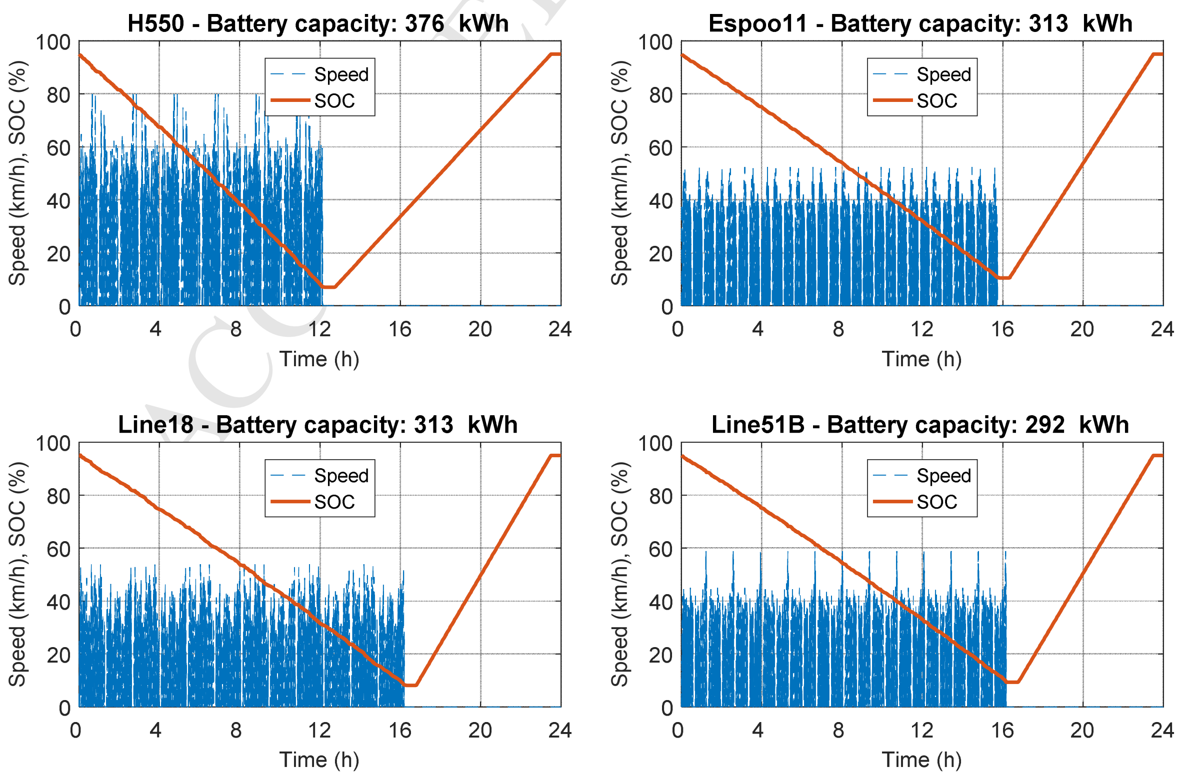

Fig. 4. State of charge signal of the battery for the overnight charging buses.

Table 6a. Simulation results for the overnight charging buses.

	H550	Espoo 11	Line 18	Line 51B
Battery capacity (kWh)	376	313	313	292
Charging power (kW)	34	41	45	42
Daily operation (h)	12.2	15.8	16.3	16.3
Daily distance (km)	344	253	254	194

Table 6b. Simulation results for the overnight charging buses with auxiliary consumption of 14 kW.

	H550	Espoo 11	Line 18	Line 51B
Battery capacity (kWh)	326	391	391	365
Charging power (kW)	21	41	40	38
Daily operation (h)	8.2	13.6	13.6	13.6
Daily distance (km)	229	217	212	161

5.2 Lifecycle costs

Fig. 5 shows the results of the lifecycle cost calculation for the simulated electric buses and for the reference diesel bus. The lifecycle costs are presented as cumulative costs up to 16 years of service life. The energy consumption of the diesel bus was simulated in previous research (Lajunen and Lipman, 2016). The results show the cumulative total costs for a bus fleet in each operating route. In all operating routes, the lifecycle costs of the opportunity charging buses are the highest. The end station charging buses and overnight charging buses have quite similar costs but the battery replacement after 10 years of operation for overnight charging buses increases significantly the total costs. The end station charging buses are then the most cost efficient electric bus option.

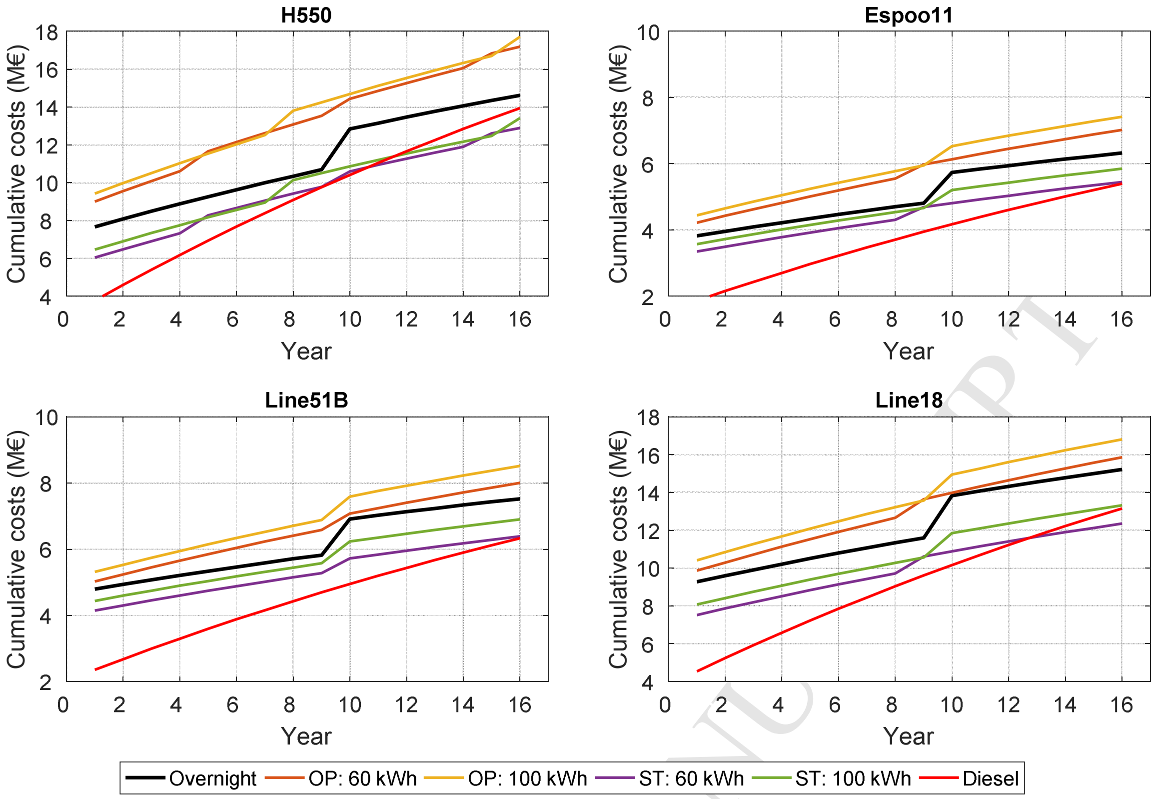

Fig. 5. Lifecycle costs for the simulated electric buses and a reference diesel bus.

Considering a typical 12 years of service life in comparison to diesel buses, end station charging buses have only about 5% higher lifecycle costs in route Line 18, and around 13% higher costs in routes Espoo 11 and Line 18B. In route H550, the end station charging buses have about 5% lower lifecycle costs than diesel buses. The overnight charging buses have 15-30% higher lifecycle costs than diesel buses depending on the operating route. The lifecycle costs of the opportunity charging buses are generally more than 30% higher than the costs of the diesel buses. If considering service life of 16 years, the end station charging buses are more cost effective basically in all operating routes than diesel buses. According to these results, the battery energy capacity has a slight impact on the costs of the fast charging buses, especially in the shorter and less demanding operating routes. In Espoo 11 and Line 51B routes, the electric buses with 100 kWh battery capacity have about 6-9% higher lifecycle costs than the electric buses that have battery energy of 60 kWh.

The impact of auxiliary power consumption on the lifecycle costs is presented in Fig. 6. The results were quite similar in all operating routes therefore results are only presented for the route 550. As expected, higher auxiliary power increases the lifecycle costs up to 10% for end station charging buses and up to 30% for opportunity charging buses.

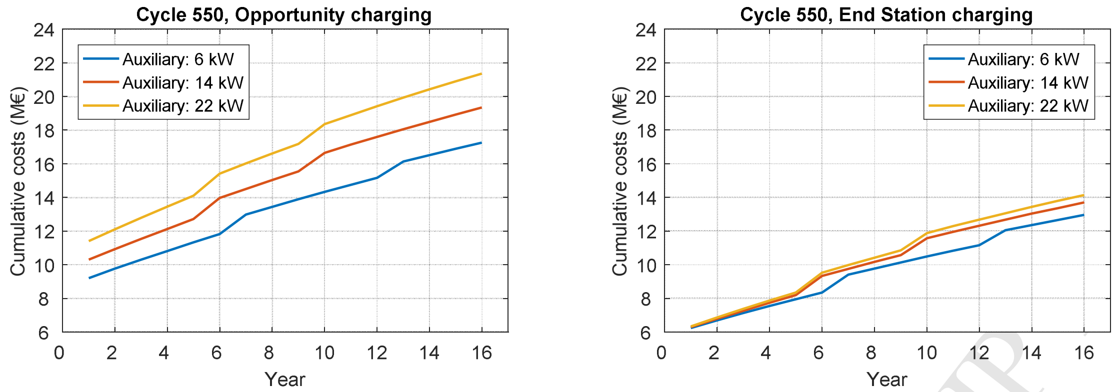

Fig. 6. Impact of auxiliary power on the lifecycle costs.

The breakdown of the distance specific costs (€/km) for one bus are presented in Fig. 7. The fast charging buses have battery energy capacity of 80 kWh and the service life was 12 years. Because the operating routes are quite different, there are major differences in the costs between the routes. The variation can be more than 50% and it is the same for the electric and diesel buses. The energy costs of the electric buses are 60-75% lower than the fuel costs of the diesel buses. It should be noted that the overnight charging bus operation in H550 route is not entirely comparable to other cases because of the shorter daily operation which was only 12 hours.

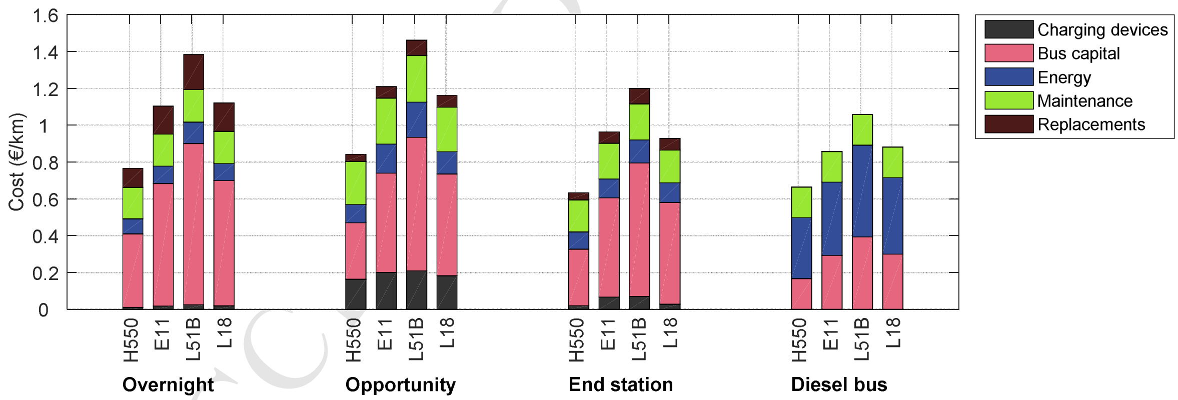

Fig. 7. Distance specific lifecycle cost breakdown and comparison.

Because the distance specific costs may not present well the lifecycle costs of city buses, the operating time specific costs (€/h) are presented in Fig. 8. It can be seen that the variation in costs between the operating routes is lower, but still up to 40%. It is important to notice that the distance specific lifecycle costs for the Line 51B were the highest but the costs based on the operating time are the lowest among these operating routes.

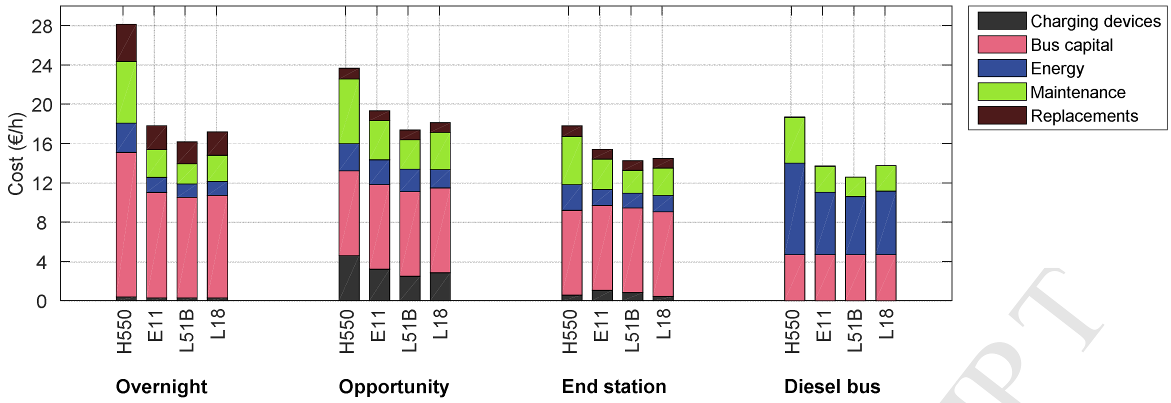

Fig. 8. Operating time specific lifecycle cost breakdown and comparison.

Fig. S5 shows the detail cost breakdown for the Espoo 11 operating route. The bus capital costs represent the major share of the costs for the electric buses. In the case of the overnight charging buses the bus capital costs are around 60% of the total costs. The charging device costs have important impact only on the lifecycle costs of the opportunity charging buses representing about 20% of the lifecycle costs. There are certain amount of uncertainties especially in lifecycle costs of developing technologies. A sensitivity study was carried out to define the most sensitive cost components for electric buses. Fig. 9 shows the results of the sensitivity study. Each of the six cost components were individually decreased by 10% from the reference cost value. The results show that the bus capital cost reduction has naturally a significant effect on the lifecycle costs. The battery costs are much more important for overnight charging buses than for the fast charging buses. A 10 percent decrease in maintenance costs decreases the lifecycle cost almost 2 percent which can be considered quite significant especially when comparing to the other cost components. Opportunity charging buses obviously would benefit from the less expensive charging devices.

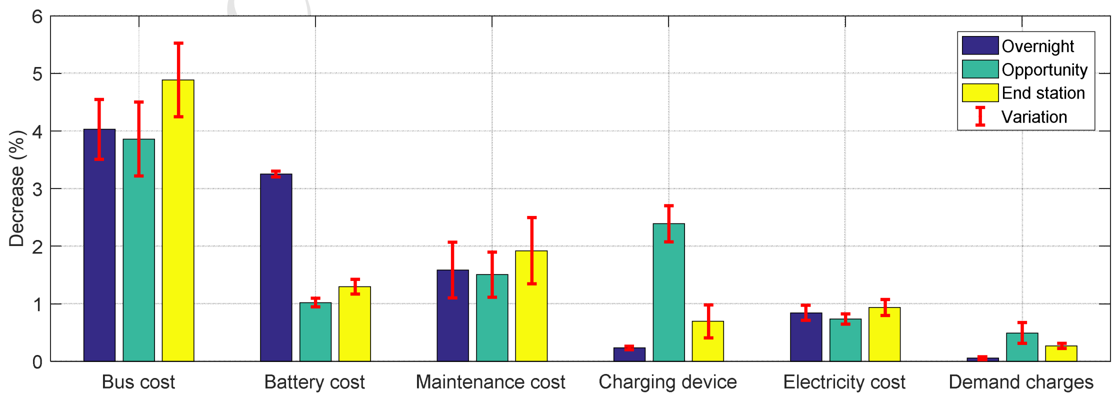

Fig. 9. Sensitivity of certain cost components to the lifecycle costs.

Because there is no fixed prices for CO_2 emissions, the effect of CO_2 emissions costs was analyzed by using different cost scenarios from 0 to 100 €/ton. The bus specific CO_2 emission coefficients were acquired from author's previous research (Lajunen and Lipman, 2016). The combustion CO_2 coefficient for the diesel engine was 73 g/MJ and for the diesel production 15.5 g/MJ. For the electric buses, the CO_2 coefficient for the electricity production was 42 g/MJ. The analysis results show (Fig. 10) that the effect on the lifecycle costs of electric buses is quite small whereas the lifecycle costs of diesel buses would increase significantly. Taking into account CO_2 emission costs could dramatically increase the cost effectiveness of electric buses but it also depends on the operating route.

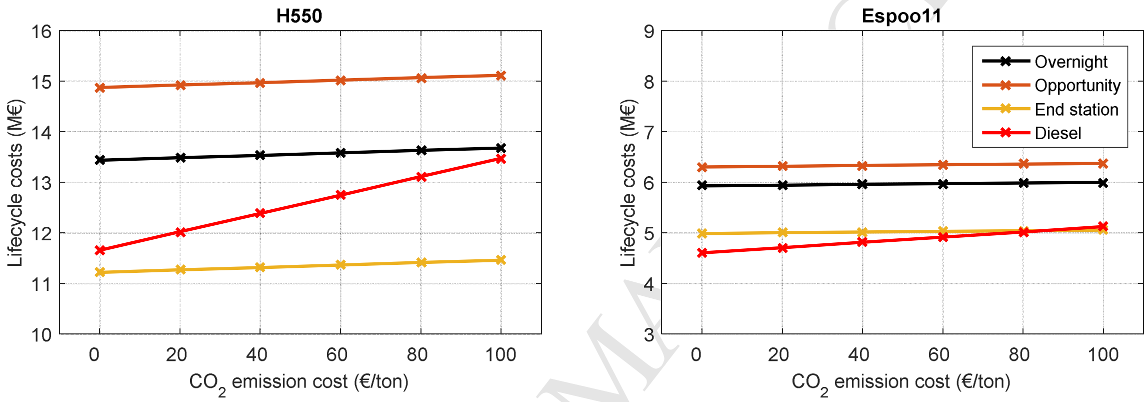

Fig. 10. The effect of CO_2 emission costs on lifecycle cost.

6 Discussion

The results of this research clearly show that the electric buses can be much more energy efficient than conventional diesel buses. It was shown that the energy consumption depends on the weight of the bus, weather conditions and the operating route. Because the energy consumption of the electric buses is much lower than with diesel buses, the variation in the energy consumption can be considered less important especially in relation to the lifecycle costs. Operating in cold climate conditions could increase the energy consumption significantly if the bus heating power is drawn from the battery. However, it was shown in a recent research study that the average increase of the energy consumption due to the weather conditions over a year of operation was only 10% (Lajunen and Tammi, 2016). Therefore, the influence of the weather conditions can be managed with the correct charging power and battery dimensioning for the end station and opportunity charging. It could be more problematic for the overnight charging buses because their operating range is limited by the on-board battery energy capacity.

There have been a great deal of focus on the battery choice and dimensioning for electric buses among researchers and in the industry. Obviously, there is no single solution that could be the best suitable for any kind of operation. The lifecycle cost results strongly indicate that the battery energy capacity is not a major cost component. Although, the battery system can be optimized because there are several characteristics that contribute to the total performance of the bus e.g. battery life, cost, charging performance and energy capacity. Higher battery capacity allows flexibility for using different charging strategies e.g. minimizing charge demands by lowering charging power. The simulation results show that the required charging power is significantly influenced by the chosen charging method and operating route. In an ideal case, the battery capacity would be optimized for the given operation but this could be quite impractical because transit buses are often used for multiple routes.

Lifecycle costs of the electric bus operation are decreasing every year as there are more competition on the bus and charging device markets. The experience from several demonstration projects have indicated that the initial purchase and installation costs of the charging stations can be quite high. The purchase costs of the electric buses, especially overnight charging buses, are much higher than the costs of diesel or hybrid buses. But then, the operating costs are lower, especially the energy costs are much lower when comparing to diesel buses. Electricity demand charges varies a lot depending on the operating route. Among the routes considered in this research, the cost share of the demand charges were between 35-80% from the energy costs.

Planning and implementation of electric city bus operation is a complex task and several different factors and actors need to be taken into account. This research shows a practical approach to better understand the challenges and opportunities of electrified bus operation. The developed simulation tool can provide valuable information about the charging and bus technology requirements in a given route. The tool can be further developed by adding the possibility to simulate multiple routes at the same time which would provide results about the charging infrastructure needs for a bus network and possible limitations in bus scheduling.

7 Conclusions

There are several factors that needs to be addressed when evaluating the operation of electric city buses. Unlike conventional diesel buses and hybrid buses, electric buses require a dedicated charging infrastructure, and the bus configuration has to be suitable for a given operation route and schedule. This research demonstrated that with a specific simulation approach, the different factors can be systematically taken into account and different operation scenarios can be fairly evaluated. The research results indicate that the charging method has a central role in the implementation of electric city bus operation. The overnight charging may not be suitable for all types of operating routes due to the limitations of battery energy capacity. The initial costs of the charging stations for opportunity charging are much higher than for the other charging methods. It is possible that these stations are shared with multiple routes as often the same bus stops are shared with different operating routes. However, taking into account the charging station use in different operating routes would require a specific analysis of the electric bus operation in multiple routes. Usually in the first phases of the implementation of electric buses only dedicated operating routes are considered therefore the choice of the charging method can be different than for a larger amount of routes. According to the lifecycle costs calculations, the end station charging buses have the lowest costs among electric buses.

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Supplementary material

Additional figures and tables as described in the text.

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List of symbols

A_f	Frontal area of the bus (m^2)
C_b	Battery capacity (Ah)
C_{batt}	Battery specific cost (€/kWh)
C_{bus}	Purchase cost of a bus (€)
C_{CAP}	Capital costs (€)
C_{chg}	Costs of charging devices (€)
C_{co2_j}	Annual CO_2 emission costs (€)
C_D	Drag coefficient
C_{LC}	Lifecycle costs (€)
C_{m_j}	Annual maintenance costs (€)
C_{nrj_j}	Annual energy costs (€)

C_{OP}	Operating costs (€)
C_{REP}	Technology replacement costs (€)
C_{SV}	Salvage costs (€)
C_{tech_j}	Annual technology replacement costs (€)
D_j	Yearly driven distance (km)
D_{cum_j}	Cumulative distance (km)
d_{rate}	Discount rate (%)
E_{batt}	Energy capacity (kWh)
E_{km}	Energy throughput (kWh/km)
f_r	Coefficient of rolling resistance
g	Gravitational acceleration (m/s^2)
I_b	Battery current (A)
i_{fd}	Final drive gear ratio
i_g	Gearbox gear ratio
J_w	Wheel inertia (kgm^2)
L_{BATT}	Useful life of batteries (a)
M	Total mass of the bus (kg)
M_c	Curb weight of the bus (kg)
m_{chg}	Cost factor for charging device maintenance
M_g	Gross weight of the bus (kg)
N_{bus}	Number of buses
N_{cycle}	Battery life as cycles
P_{aux}	Auxiliary power (W)
P_{b_cons}	Battery power consumption (W)
P_{b_loss}	Battery internal losses (W)
P_{b_out}	Battery output power (W)
P_{mot}	Electric motor nominal power (kW)
q_b	Battery state of charge
r_b	Battery internal resistance (Ω)
r_d	Rolling radius of the tire (m)
t	Time (s)
T_m	Electric motor torque (Nm)
T_{m0}	Inertial torque of the electric motor (Nm)
T_{mot}	Electric motor nominal torque (Nm)
T_w	Torque at wheels (Nm)
T_{w0}	Inertial torque of the powertrain (Nm)
U_b	Battery voltage (V)

U_{voc}	Battery open circuit voltage (V)
v	Driving speed (m/s)
α	Road slope in degrees
η_{fd}	Efficiency of the final drive
η_g	Efficiency of the gearbox
η_m	Efficiency of the electric motor
ρ_a	Density of air (kg/m^3)
ω_m	Electric motor speed (rad/s)

Highlights

- A specific simulation tool was developed to comprehensively evaluate electric buses
- Electric buses were simulated with different driving conditions and charging methods
- High energy capacity of the on-board battery is crucial for overnight charging buses
- The lifecycle costs of electric buses are heavily impacted by capital costs
- End station charging electric buses have the lower lifecycle costs