

Method to analyze cost effectiveness of different electric bus systems

Oscar Olsson¹, Anders Grauers², Stefan Pettersson¹

¹*Viktoria Swedish ICT, Lindholmspiren 3A SE-417 56 Gothenburg Sweden, oscar.olsson@viktoria.se*

²*Chalmers University of Technology, Signals and Systems, SE-412 96 Gothenburg, Sweden,
anders.grauers@chalmers.se*

Summary

This paper presents a method developed to analyze a complete electric bus system including electricity supply infrastructure, charging system, buses' energy system and scheduling. This method can give an understanding of what kind of electric bus system that is the most cost-effective based on local conditions such as transport demand and type of electricity infrastructure available. It is being used as a tool in planning and construction of future public transport systems.

Keywords: public transport, infrastructure, modeling, cost, optimization

1. Introduction

An all-electric bus system not only provides a way to reduce the dependency on fossil fuels but also to remove local emissions, reduce noise and increases energy efficiency. The energy can be transferred to buses at various times such as overnight charging, end stop charging and bus stop charging. A variety of ongoing demonstration projects are testing and comparing electric bus systems, often with a vehicle focus. There are also several projects that are analyzing and optimizing different bus systems [1],[2]. Comparisons of different electric buses without taking into account the infrastructure cost and other operational costs could be misleading since the costs for associated infrastructure and operational costs may vary with the bus technology. However, a method to analyze and compare vehicles and operating costs together with the necessary infrastructure as a complete system, and from that give a suggestion from a total cost perspective, has been missing.

This paper presents a method developed to model an electric bus system including the electricity supply infrastructure, charging system, buses' energy system and operational costs in order to estimate the total operating cost including financial costs. A charger system is a complete set of chargers that shall provide all the energy to the electric buses on one or several bus lines. The method also takes into account the consequences of different local conditions such as transport demand, electricity network capacity, topography and climate.

The method is intended to be a useful tool in discussions during the planning and construction of future public transport. This way of highlighting the most cost-effective system solution is believed to have a positive effect on accelerating the introduction of electric vehicles.

Different types of electric bus systems with varying combinations of battery size and charging system are offered today. The systems have different capabilities, limitations and costs and may or may not be appropriate depending on local conditions. It may not be obviously easy to determine what kind of electric bus system that would imply the lowest cost and solve the public transport needs in a specific city. Nor is it obvious how the charging system will influence costs as a result from different demands related to the bus routes and operating schedule. Investment in electric bus systems on a trial and error basis could be expensive.

The challenge is to develop a method intended for public transport operators and authorities to plan what kind of buses and charging system that is the most appropriate from a lowest operating and financial cost perspective. The results should be based on the prevailing city conditions and transport demand.

The method should be able to analyze new combinations of buses and charging system but also to compare existing combinations of buses and charging system. The method may therefore be useful also for manufacturers to adapt their buses or infrastructure for different types of cities.

2. Technologies compared

Vehicles can be charged at end stations, bus stops, at the depot or at a combination of them. The different charging technologies are on a sliding scale where costs are in simple terms added to either the vehicle or the charging system. There is a tradeoff between frequent high-power charging of small batteries on one end of the scale and slower charging of much bigger batteries on the other end. This division could be illustrated by looking at the charger utilization during the day. This is illustrated in the Figure 1.

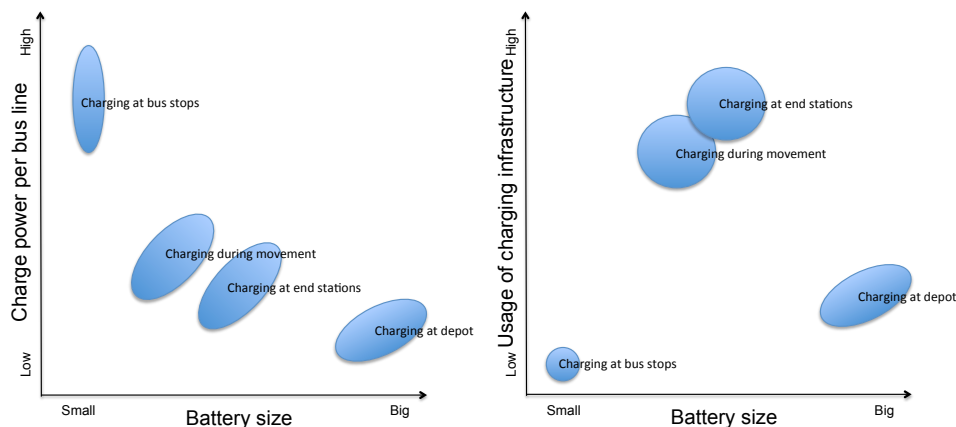


Figure 1. Left: An illustration of total charge power installed for a bus line as a function of vehicles battery size.
Right: The charger utilization per day as a function of battery size.

The different vehicles, infrastructure and charging technologies as well as their prerequisites used in the analysis are described in the following chapters.

2.1 Vehicle and infrastructure prerequisites

The simulations used in the model are all based on the same type of bus. The vehicle parameter data is presented in Table 1. Electrical buses can, perhaps advantageously, be fitted with a small auxiliary power unit (APU) as backup to charge the batteries whenever necessary such as during extreme temperatures or during longer charger downtime. However the APU has not been factored in to the method when optimizing the bus system and batteries since it should only be used as back up.

Table 1. Vehicle parameter data

Weight including passengers	Length	Front surface area	Rolling resistance coefficient	Aerodynamic drag coefficient	Maximum driveline efficiency
16 tonnes	12 m	8.36 m ²	0.008	0.70	93 %

Bus chargers are offered in several sizes and prices depending on the choice of technology and intended application area. Only conductive chargers are considered in this paper although inductive chargers can easily be implemented in the calculation method, but at a different costs and efficiency level. The method will also handle charging anywhere along the bus lines but the focus in this paper is on charging at end stations and in the depot. Standards exist for bus chargers [3],[4] and prices in this paper have therefore been given per kW despite cost fluctuations for local adaptations and special designs.

Cost estimates have been made from the 10 kV substations up to the charging system. A 400V subscription was judged to be enough given that transformation can be made close to the power load for grid connections with power demands below 1 MW. A 10 kV subscription was considered for power demands above 1 MW.

2.2 Charging at depot

Electric buses designed for charging at the depot have a battery range of up to 300 km on one charge under favorable conditions, which could be enough to complete an entire transport work needed during one day. The bus type has a usage characteristic similar to a combustion engine bus in the sense that charging is only needed a few times per day. No chargers are necessary along the route. It is therefore a very flexible electric bus in terms of capability to adapt to different bus routes and could replace a traditional inner city bus without modifications of the route. One charger with roughly 80 kW is however needed per bus at the depot with enough power to charge the battery during the night, and possibly to top-up during the day depending on the timetable. The high-energy battery chemistry, such as LFP or NMC, is optimized for long-range and low weight. Regardless of the high power-to-weight ratio the battery, typically with a capacity between 250 and 350 kWh [5] but occasionally above 500 kWh [6], occupies volume and adds weight to the bus. The size affects the energy consumption and also the number of passengers allowed.

2.3 Charging at end stations

Charging at the end stations allows the bus to carry a much smaller battery, usually around 50 to 90 kWh [7]. The battery chemistry used for fast charging, often LTO, is optimized for high power and is heavier and more expensive than energy optimized batteries per kWh. The batteries are usually optimized to occasionally last longer than a route back and forth to enable the bus to skip one charging in order to keep the timetable. Charging the battery usually takes between 3 to 6 minutes depending on the size of the battery and power installed in the charger. The charge power installed is usually between 150 and 500 kW [8]. Higher power means shorter stop times but may have an impact on the battery lifetime. The time required to charge also affects the number of buses capable to serve every hour.

Given that the end stations and route distance remains the same the bus is flexible and can adapt to route modifications. Starting a bus line with end stations requires somewhat more planning to identify the most suitable places for the chargers. The timetable may have to be adjusted to allow for longer dwell time at the end stations. Longer routes demand larger batteries and also longer charge times or higher charge power. Chargers can be placed anywhere along the route but it is most beneficial at end stations to avoid passengers on the bus waiting for the charging to complete. High charger utilization can be achieved since several vehicles share the same chargers. The high power and the autonomous charging require an automated connector to connect between the bus and the charging system.

2.4 Charging at bus stops

Charging at several bus stops along the bus line implies using only the time it takes for passengers to get on and off. No additional stop time should be required for charging. With shorter distance between the chargers the batteries can be even smaller, typically between 30 to 40 kWh [9] with LTO chemistry, depending on the distance between the bus stops. However, the battery cannot be made extremely small since it needs to be big enough to handle the many charges that occur every day and the high charging power. It also needs to handle faults, such as a charger taken out of service or route changes. Due to the smaller battery the solution is limited to a particular route with only minor changes.

The concept requires chargers with high power to be installed along the route. To reduce the cost for grid connection the chargers can be fitted with a stationary energy storage, such as a super capacitor. The local storage can be charged at a low power when there is no bus at the stop, and then quickly charge the bus at high power when it arrives. The use of energy storage in the charger is a tradeoff that reduces cost for the grid connection at the expense of the cost for the local energy storage.

The total length of the route does not affect the cost of the bus as it normally only needs to reach to the next stop. The number of charging stations will however increase with the length of the route. The type of bus is likely to be most suitable on routes with very high traffic demand in order to utilize the chargers to a high extent. A bus charged at a bus stop needs to be connected to a charger similar to buses charged at end stations with a special automatic connector. This connector needs to be fast since the charging time is very limited and is therefore more advanced than for end stop charging.

2.5 Charging during movement

Charging while the bus is driving removes the extra dwell time to recharge the battery and can be achieved for example with overhead wires or wireless with inductive energy transfer from the ground. The inductive energy transfer technology can be hidden in the road in contrast to the conductive solution that is most probably similar to trolleybuses with trolley poles and overhead lines.

The size of the battery required depends on the length of the route that is not electrified. The ratio between the electrified distance and the entire route length also determines if the battery should be optimized for high power or high energy. The buses are constrained to stay a certain minimum time of the route in charging mode to get enough energy. Apart from that minimum time, they are free to connect and disconnect automatically and thus able to overtake or make major deviations from the route. If multiple buses share the same route they can be charged simultaneously.

3. The analysis method

The method developed to analyze different charger solutions for electric buses includes:

- Method to find good candidate places to put chargers along the bus line. By analyzing the energy consumption of the bus line different alternative charger systems are designed.
- For each charger the charger power is selected and the bus batteries and timetables are adapted for each different charger system, in order to make the comparison of them as fair as possible. This step also includes sizing the systems to be robust for several expected types of disturbances in the system.
- The economics for the different systems is analyzed, by calculating the cost for investments and operation of the bus lines using the different analyzed charger systems.
- Drawing conclusions on strengths and weaknesses of the compared charging systems.

Below the different steps in this method are explained and discussed, and some results from a case study are shown as illustrations of how the method is used.

Notice that there can be different reasons to analyze the charging system for electric buses, and depending on the purpose the method will partly be changed. This method is designed to analyze how suitable different charging systems will be in the long run, if it is assumed that both buses and chargers as well as the planning of timetables are adapted to the system being proposed. The result of such an analysis is an indication of which direction the development is likely to go. However, when planning for a specific bus line here and now the analysis should rather be made for only the buses and chargers offered on today's market, and then the purpose is to "build the best system with the available components" rather than "Finding the best system and show how the components should be adapted for it".

3.1 What is special with this method?

There are several different similar methods described in the literature [10-14]. What is special with this method is its attempt to include a wider system perspective, in order to find what the long term suitable system design is. To achieve this it is not only the charging system that is analyzed, but also how the batteries on the buses and the operation of the buses should be changed to fit different charging systems. This has been found to be vital, since the cost of the batteries and the cost to operate the buses change rather much for different charger systems. The method also includes looking at non-economical factors for where to place the chargers, like building constraints and robustness of the system, see Figure 2.

3.2 Method overview

The analysis method is designed such that it can analyze different charging system for one or several bus lines. The core analysis will answer how big battery is required in the different buses to meet energy demand, power demand and cycle life length.

Due to the many non-economic factors, which are likely to play an important role when comparing different alternatives, a purely economic optimization is not believed to provide a desired solution. Still a mathematical cost minimization can very well be a tool in finding the overall most suitable solution.

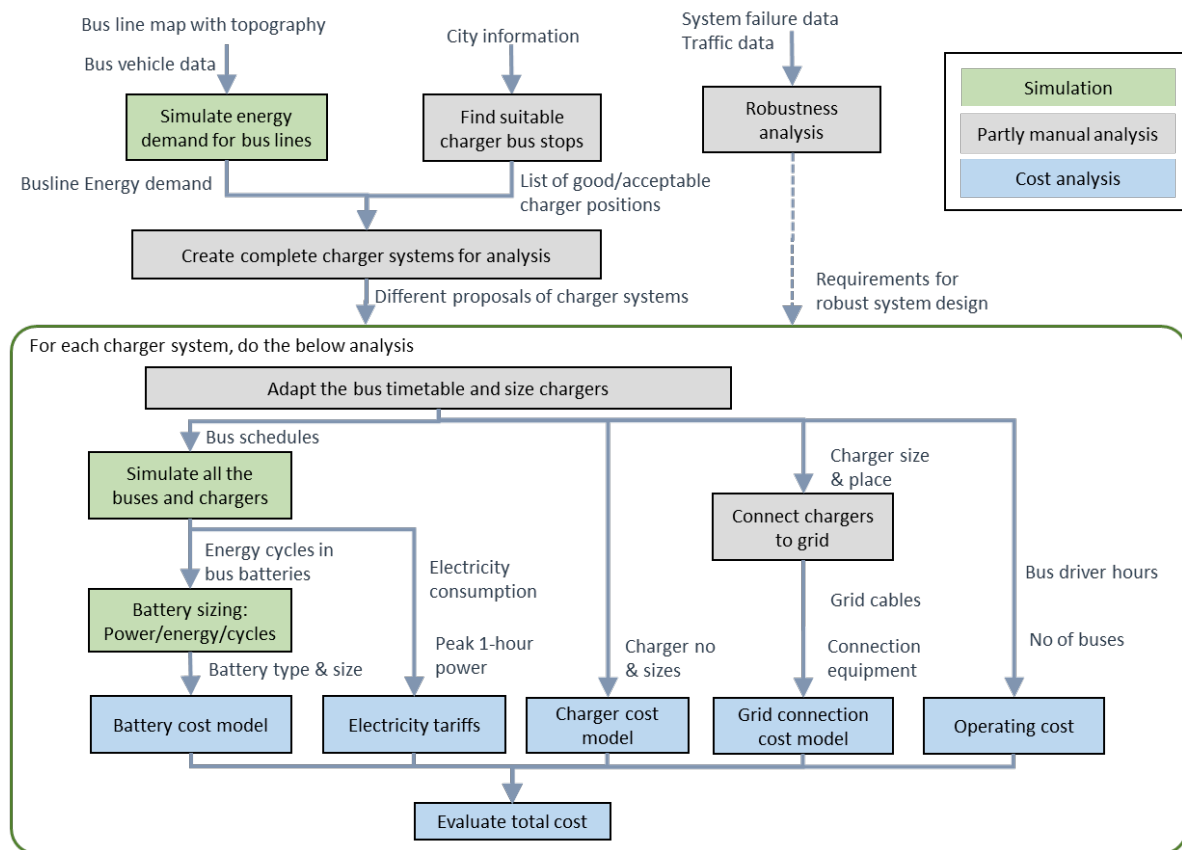


Figure 2. Schematic picture of the analysis method described in this paper

3.3 Find suitable charger bus stops

The first step when creating feasible charger systems is to select which bus stops are good candidates for placing chargers. This involves comparing many different aspects and since they are difficult to measure objectively, the method focuses on a structured analysis, but still relying on the involved experts to weigh the different pro's and con's based on their experience. For this type of method to lead to good results it is important that the involved persons combined expertise cover all the analyzed aspects. The method focuses on analyzing the possible candidate bus stops regarding many different aspects. To simplify the discussion the aspects are divided into three categories: Bus operation, building aspects and charger utilization. A simplified example of how to summarize this analysis is shown in Table 2.

Table 2. A protocol to summarize the analysis of different bus stops as candidates for chargers. The aspects are judged as green = good, yellow = adequate and red = not suitable.

Stop	Bus operation		Building aspects	Charger utilization	Total rating
	No passengers on the bus while charging	Other bus lines using same bus stop			
Bus depot	Green	Green	Green	7	Green
End stop 1	Green	Yellow	Green	72	Yellow
Train station	Red	Green	Green	144	Red
Stop A	Red	Yellow	Green	115	Yellow
Stop B	Red	Yellow	Red	44	Red
End stop 2	Green	Green	Yellow	44	Green

3.4 Simulate energy demand for bus lines

In our example we have analysed two bus lines which are using seven buses in total, and for which the buses regularly switch between one line and the other line. Data to simulate these buses come from a public

database published by Trafiklab [15] with all the public transportation in Sweden published in GTFS format. Plotting that data for the two bus lines an ordinary Wednesday show all the individual trips during that day, see Figure 3.

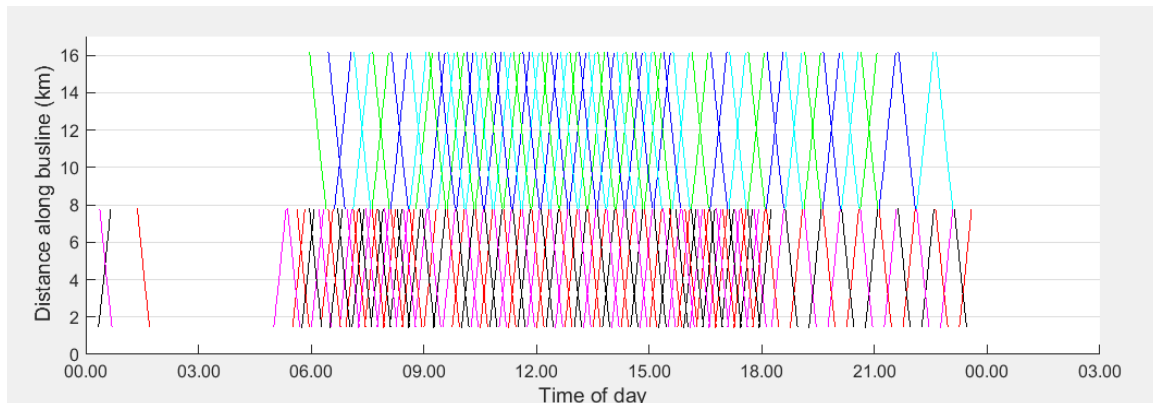


Figure 3. Time table data in GTFS format plotted to illustrate the trips on the two investigate bus lines.

In order to analyze the energy demand and thereafter the sizing of the battery we also need to know how the individual buses are driven. Therefore the bus schedules of the 7 buses were analyzed, and individual driving cycles were generated for them. All these driving cycles are simulated to determine the energy demand. First it is done without any chargers, in order to find the energy required if the buses are only charged during the night. The time it takes to drive to or from the depot is approximately 0.15 h.

3.5 Analysing night charged buses

The energy needed to drive the full day is plotted in Figure 4 for the seven buses used. It can be seen that the total energy demand is at most about 460 kWh for the buses. A battery with an original capacity of at least 600 kWh would be needed in the worst case when adding some margin for battery degradation. This is unrealistic due to the very high weight of the battery, which would severely reduce the maximum number of passengers on the bus.

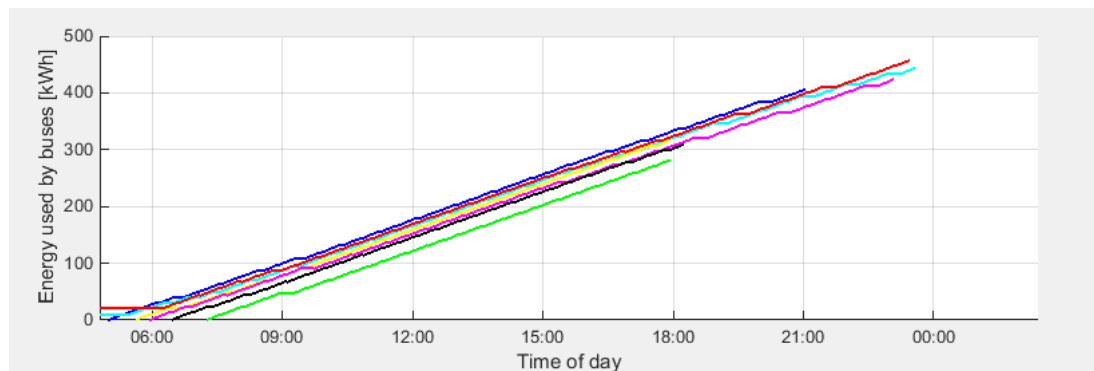


Figure 4. Example of energy consumption for two buses of seven on the analysed bus lines.

One possible solution to extend the range of overnight charged buses is to top up the battery during a period of the day when not all buses are needed in order to meet the timetable. In Sweden this is typically between about 9.00 and 15.00 or after 18.00. For the investigated bus line all buses run also between 9.00 and 15.00, so if there shall be a possibility to charge during this time at least 2 extra buses are required. As that is too expensive, this solution has not been investigated in detail for the two bus lines.

However, to present how this can be used on other bus lines a general example is discussed here for a bus line on which 6 buses are needed during rush hours but only 4 are needed between 9.00 and 15.00. Since two buses can be charging at any time between 9-15 the buses can take turns driving to the depot and top up the battery. An example of how this is done, and what resulting state of charge the six buses have during the day is shown in Figure 5 below. One of the buses also charge during the evening, to allow it to drive until after midnight.

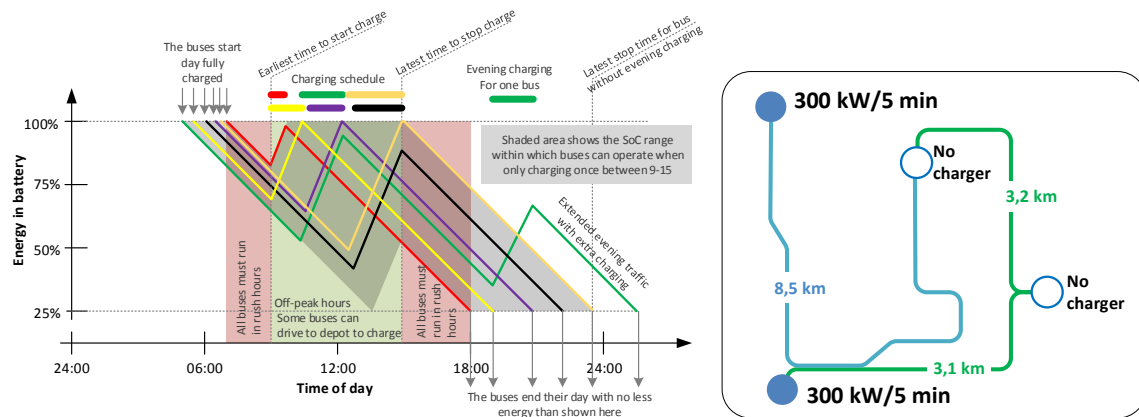


Figure 5. Left: Example of energy consumption for six overnight charged buses which top up their charge between 9 and 15.00. Right: Placement of chargers as result of the investigation.

Figure 5 shows that it is possible to run night charged buses the whole day, but it requires some charging also during the day. For this to work there shall either be lower frequency on the bus line between morning rush hour and afternoon rush hour, or extra buses are required. Note that all buses do not need to charge equally much, rather the charging schedule takes into account how late the bus will drive in the evening. The fact that the afternoon rush hour plus evening traffic can be up to about 10 hours for some buses, it may be necessary that some buses also charge once during the evening. Note that the buses are not at all fully charged when the afternoon rush hours start. In fact it is maximum 2 buses which theoretically can be fully charged by then. However, the charging schedule is very tight, so the average state of charge at 15.00 is not higher than at 9.00. To clarify, there seems not be time enough to charge more than what corresponds to the energy used during the 6 hours from 9-15. To charge more will require rather high power of the chargers, which means that the night chargers perhaps are not large enough.

3.6 Analysing end-stop charged buses

Since overnight charging did not work for the analysed bus line, end stop charging was the next step in the investigation. The investigation of the different bus stops lead to the result that for these two bus lines, there was only two really good bus stops to place the chargers, see the map in Figure 5. Due to the limited power capability of the batteries the chargers were selected to 300 kW and that required a 5 min charging time. Since the buses run with 10 minutes or more between them, a 5 min charging time leads both to rather high utilization of the chargers and a robustness since the charging time in case one charger fails can be doubled at the other charger (assuming some changes to the time table). The battery energy profiles over the day were simulated with the two chargers added. For each of these energy profiles the number of charging cycles of different depths were calculated using a rain-flow-count method [16]. By using a battery cycle life model it could then be determined how big the battery needed to be in order to last the whole planned life, with the simulated number of cycles and their different depth of discharge. A sizing algorithm used a numerical search method to find the smallest battery which met the required life length of 10 years. For the investigated bus lines that lead to a battery size of 72 kWh. The resulting battery cycles over the day, for some of the seven buses are presented in Figure 6. Notice that the cycles typically only use 30 % of the battery capacity. There are two main reason for this. One is that the high number of cycles per day, make it necessary to reduce the cycle depth for the battery to last long enough. A second reason for this is that the bus system must be capable of handling a failure in one of the chargers for some time until it has been repaired. In these cases the cycle depth will be doubled to about 60%. Also notice that the battery at the end of its life will only have about 80% of the capacity remaining.

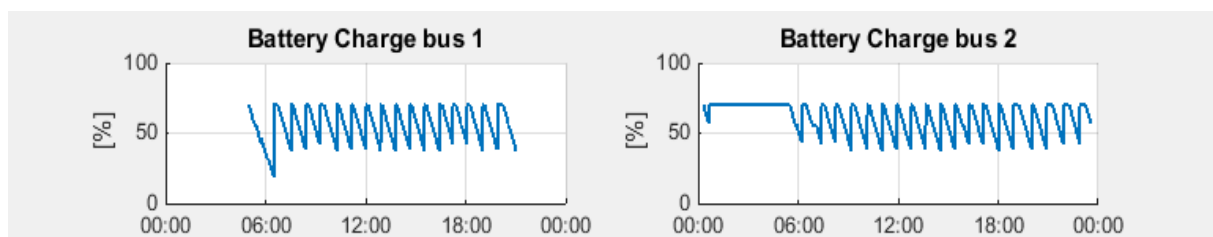


Figure 6. Battery state of charge for some of the seven buses with two 300 kW end stop chargers and 72 kWh batteries.

3.7 Adapting battery size and bus schedule for each charger solution

The sizing of the bus battery and the scheduling of the timetable are both very important in order for a charger system to be used effectively. Therefore, to compare charger systems without adapting the bus batteries and the timetables for each individual charger system will give misleading results. For example, if the battery size is fixed during the analysis of different charger systems, it will look like the most cost effective solution is the one that minimizes the number and size of the chargers for that particular size of batteries. However, it is often a more cost effective solution to increase the number of chargers in order to allow reducing the battery size on the buses, even though that increases the cost of the chargers. In a similar way, the effective use of a charger at a certain bus stop requires that the timetable provide enough time to charge at that bus stop. Thus the time table should, when possible, be adapted for the different charger solutions such that most of the dwell time is at the bus stops with chargers. Of course it must also be analyzed if the changes in the time table are negative from any other perspective before it is decided which time table is best for a given charger solution. So, in order to find the best charger solution for one or several bus lines we must use a method that allows the bus batteries and the time table to be adapted to each individual charger solution being investigated. By adapting those for each charger solution we ensure that we make a fair comparison between different charger systems.

3.8 Cost evaluation

Once we have defined charger solutions with suitable battery size and time tables, we need to evaluate their cost in order to say which solution is the most cost effective. To do that, the economic comparison of the systems must include all significant costs, which may differ between the charger systems, while costs that are exactly the same for all the compared systems are in this case not modeled. At a first glance the costs, which are different between the systems, are mainly costs for building and operating the chargers and costs for buying the batteries. However, since a change in the charger placement influence also the time table, and thus the bus and driver utilization, it turns out that also the cost for the drivers, the number of buses and maintenance may be different between the systems. Also, changes in when during the day the battery is charged and how high power is used in different places of the electric grid will also differ between the different charger solutions. Since the electricity tariffs vary during the day and different parts of the grid have their peak load on different times of the day, these differences will make the cost of the used electricity to differ between the systems even if they typically use roughly the same amount of electric energy.

3.9 Economic calculation

The following cost parameters are examples of basic costs needed to use the method. The costs are specific for the case study but averaged to hide traceable information to suppliers. Costs that are technology independent have been excluded. Costs compiled below in Table 3 are based on interviews and information from suppliers of charging system, bus companies, electricity companies and public transport planners.

Table 3. Fixed costs

Fixed costs	
Bus charger	1 €/W
Electricity substation	0,8 €/kW
Cabling in low/medium/dense parts of cities	100/200/300 €/m
12m electric bus excluding battery	400000 €
12m HVO bus	260000 €
Power optimized batteries	1130 €/kWh
Energy optimized batteries	540 €/kWh

The investment costs needed to start traffic on the two bus route are shown in Figure 7, in which they are separated into cost for the vehicle without energy storage, charging system and the battery. A bus with similar cost characteristics as a diesel bus but runs on hydrogenated vegetable oils (HVO) is hereon used as a reference cost. As can be seen, the investment cost for the battery electric buses are estimated to be at least twice the cost for the comparative combustion engine bus system. The investment cost is an important factor to take into account since it might be what transport operators initially look at when comparing the alternative bus systems. Difficulties finding the necessary budget might also be a hinder when deciding what bus system to invest in. High investment costs could of course also be seen as a risk. Interesting to note is that the added cost for charging system is a minor part of the total investment compared to the added cost for the combined bus and energy storage regardless of bus system.

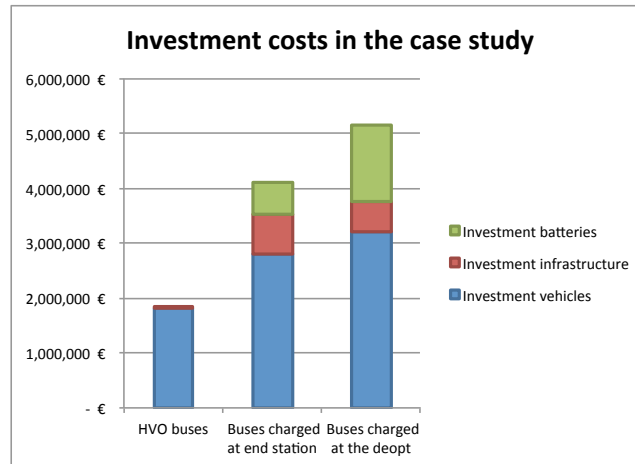


Figure 7. Investment cost for the investigated bus system.

Electric buses have a high investment cost and lower running costs compared to a combustion engine bus whereby the investment costs alone could give a misleading impression of the investment. Henceforth the fixed cost are divided equal between the years in the depreciation period and are independent of when they occur. Examining the annuity as costs for annual depreciation and interest according to the formula below gives a better image of the actual cost to operate bus services on the two bus routes.

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

A = Annuity, NPV = Net present value, p = Interest rate and n = Depreciation time

The variable annual operating costs for drivers, energy, and maintenance according to Table 4 are added on top of the annuity. Driver cost is sometimes overlooked in the belief that it does not differ between the various electric bus systems. As it turns out it may instead in contrary be decisive between the alternatives. For the electric bus charged at end stations that does not have enough energy to skip a charge opportunity there are added costs for drivers and possibly also for an additional bus to maintain the same time table as a regular combustion engine bus. The added stop time at each end station could be described as:

$$T_{added \text{ stop time at end stations}} = T_{recharge} + 2T_{coupling} - T_{dwell} \quad (2)$$

Buses charged at the depot over night might not have enough energy for the entire days driving and might need to return to the depot during low traffic to charge. Therefore the time it takes to drive back and forth to the depot for each bus should be calculated as added driver cost as seen in below formula. If it is not possible for all buses to recharge during off-peak hours, additional buses might be required with additional bus and driver costs as a result. The driver of the bus charged at the depot does not have to wait in the bus while it is being charged in contrast to drivers of buses charged at the end stations. This reasoning apply in theory but in actual operation there is a risk of a hidden cost due to the increased complexity that might arise when several buses share the time available for charging.

$$T_{switch \text{ bus}} = 2T_{driving \text{ to depot}} + T_{start \text{ charging}} + T_{prepare \text{ new bus}} \quad (3)$$

Table 4. Variable costs, depreciation time and rates

Variable costs		Depreciation time	
Driver cost including dwell time and downtime	35 €/h	Electric bus	10 years
Electricity subscription fee per year 400V/10kV	520 €/year / 930 €/year	HVO bus	10 years
Power tariff, highest entry per month 400V/10kV	4,12 €/kW/month / 3,42€/kW/month	Charging system	20 years
Variable energy fee 400V/10kV	0,0068 €/kWh / 0,0031 €/kWh	Batteries	10 years
Energy costs	0,075 €/kWh		
HVO costs	0,995 €/l	Rates	
Maintenance cost per electric bus	0,183 €/km/year	Interest rate	5 %
Maintenance cost per HVO bus	0,292 €/km/year		
Maintenance cost per bus charger	2 % of bus charger cost/year		

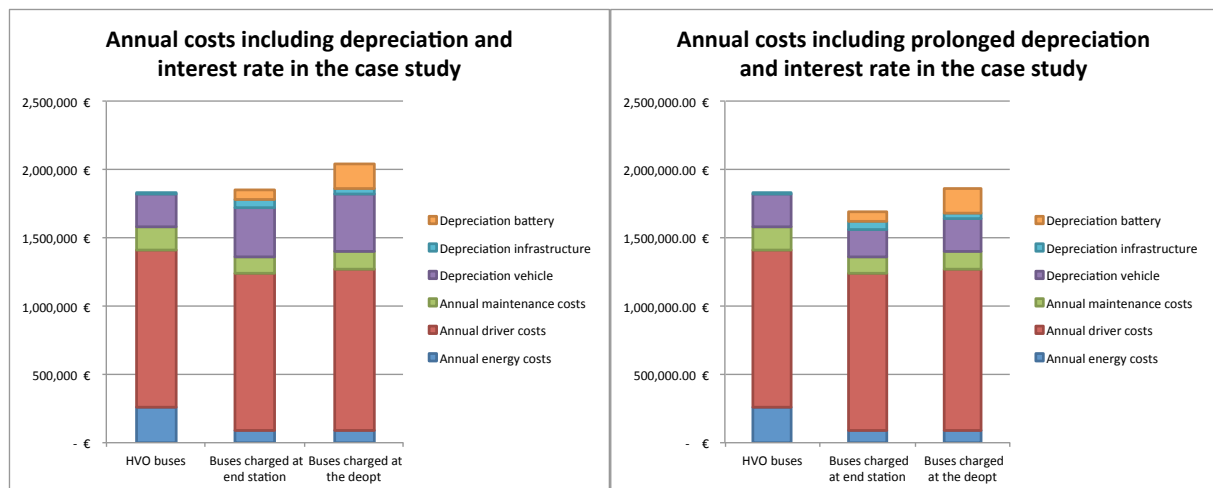


Figure 8 Annual operating costs in the case study. Left: 10 years depreciation time for electric buses and 10 years for HVO buses. Right: 15 years depreciation time for electric buses and the same bus price as for a HVO bus.

Total annual cost for the HVO bus, as seen to the left in Figure 8, for the particular case study is 3.17€ per km. Corresponding cost for the buses charged at the end station is 3.23€ / km and € 3.56€ / km for the buses charged at the depot.

The costs that differ between the options are the fixed costs of infrastructure, the number of buses needed for the operation and the added driver cost occurring when the bus is charged or when the bus runs without passengers to the depot for charging. Additional added costs are linked to the battery with size sufficient to withstand the high charge power and long service life and also energy costs depending on the number of buses and how well they can be adjusted to the route. The maintenance cost does also reflect the number of vehicles in traffic.

Note that the total distance driven does not increase linearly with the possibly increased need for buses to compensate for the charge time. Mileage per bus will be reduced with approximately the same percentage as additional time spent charging per day. As long as procurement periods are defined in years any additional buses operating a bus line should make the bus fleet last longer and have a higher residual value. The annual costs for analyzed electric buses shown to the right in Figure 8 are therefore displayed with 15 years depreciation time and with the same price, excluding the battery, as the corresponding HVO bus to indicate a possible future cost scenario once electric buses have become a more mature bus type.

The depreciation cost of electrical installation and chargers, also shown in Figure 8, is a very small part of the total annual cost of electric buses. Furthermore, the cycle life for charging system may outlive several procurement periods. It can therefore be considered reasonable that the chargers are owned by the city to avoid replacement of functional infrastructure when changing bus operator. Existing standards [3],[4] facilitate the discussion that only the buses and bus operation should be procured. Similar comparisons could be made with bus stops and also the road that is not a part of the procurement of bus operation.

It is important to note that costs may vary greatly between cities and also routes. Hence the above example with distribution of costs should not be considered a general fact. Cities with a greater bus system could for example get a better price from large scale procurements. Meanwhile a route with low traffic intensity and few buses may benefit from minimizing the cost for the installed charging system. The opposite reasoning could be true for routes with high traffic intensity where it could be more important to optimize the usage of the increased number of vehicles.

4. Results and discussion

Analyzing electric bus traffic on two city bus lines and calculating the annual cost of operation the results indicate the importance of reducing battery costs and ultimately to optimize the use of the buses and the drivers. The analysis indicates that it is less important to reduce infrastructure costs or optimize usage of the chargers.

Results indicate that the cost for charging system and electricity connection have a low impact on the total annual operating costs for electric buses in general and especially when comparing electric bus system

alternatives. Solely comparing investment costs might thus give a wrong indication of what type of electric bus system result in the lowest total cost for operating the bus lines. Investments in infrastructure tend to have a long depreciation time and may therefore be relatively small total cost in relation to the operating costs. This is visualized by comparing the annual costs for the different bus systems.

The method also highlights the importance of looking at the total cost for the bus operation instead for an optimum of isolated problems such as in the tradeoff between battery capacity and charger power. Reducing the size of chargers and batteries to a minimum could increase the charge time and require an additional bus to operate the bus line to keep up bus frequency. Operator costs stand out clearly as a significant cost item. High utilization of vehicles and drivers are therefore important. However, when the timetable is fixed and without dwell time for charging neither at depots or at end stations during the day, a relevant tradeoff could be to add an extra bus as an option to increase the battery capacity on all buses.

The method suggests that a planning tool will be required that supports various types of electric buses. Today's bus operation and dwell times are often adapted for combustion engine buses. Timetables for electric buses need special attention to synchronize buses into slots at common charge points and also to add dwell time at end stations. Batteries and chargers could be unnecessary large if adequate time for charging is not accounted for. The analysis does not however take into account how the cost is shared between different actors, which could play an important role for which charger technology to be bought.

HVO combustion engine buses was found to be the most competitive financial solution on the two bus lines analyzed despite that the timetables were adapted for electric vehicles. In the calculation the price for the electric buses, excluding battery, was significantly higher than for the corresponding HVO bus. Comparing a very mature market with a technology that is under development could be seen as unfair. With a price for the electric bus, excluding battery, equal to the HVO bus and a depreciation time corresponding to the buses life cycle indicates economic feasibility of bus operation with battery electric buses.

5. Conclusion

A method has been developed primarily for public transport authorities and operators to be able to analyze what kind of electric bus and charging system has lowest total cost depending on the route or city specific requirements. The method is transparent in the sense that the parameters used can be observed and are intended to be adjusted to reflect the circumstances prevailing in a city. Companies developing electric buses and infrastructure can also use the method.

Unique to the method is the wider system perspective and optimization of the total costs of operating an entire bus line. The analysis visualizes that apart from the driver cost, the purchasing cost of vehicles and batteries account for an important part of the total cost. Furthermore it highlights that increased costs as a result from added time needed to recharge the vehicles is an essential cost factor. Additionally, the cost of charging system and energy is shown to have a lower annual cost impact.

Acknowledgments

The project is funded by VINNOVA/FIFFI and Region Västra Götaland.

Project partners: AB Volvo, Chalmers University of Technology, Göteborg Energi, Lindholmen Science Park, Viktoria Swedish ICT and Region Västra Götaland.

References

- [1] M. Pihlatie, Fully electric city buses – the viable option. In proceedings of ECV national seminar, Tampere, Finland, 10 Mars 2015
- [2] D. Göhlich, A. Kunith, T. Ly, *Technology assessment of an electric urban bus system for Berlin*, WIT transactions on the built environment, ISSN: 1743-3509, (2014), vol.138, 137-149
- [3] IEC 61851-23:2014, Electric vehicle conductive charging system - Part 23: DC electric vehicle charging station, ed.1.0, published 2014-03-11
- [4] IEC 62196-1:2014, Plugs, socket-outlets, vehicle connectors and vehicle inlets - conductive charging of electric vehicles - Part 1: General requirements, ed.3.0, published 2014-06-19

- [5] BYD, BYD All-Electric Bus Series -12 m Electric Transit Bus, <http://www.byd.com/ap/images/ebus/download/k9%20brochure.pdf>, accessed on 2016-03-24
- [6] NOW-gmbh, Projektübersicht 2015 /16 Hybrid- und Elektrobus-Projekte in Deutschland, https://www.now-gmbh.de/content/5-service/4-publikationen/1-begleitforschung/now_projektuebersicht_bus_web.pdf, accessed on 2016-03-24
- [7] Volvo 7900 Electric, http://www.buildersbuses.net/public/7900%20Electric%20EN%202015_00688.pdf, accessed 2016-03-24
- [8] Heliox, Opportunity charging, <http://heliox.nl/opportunity-charging>, accessed 2016-03-24
- [9] Olivier Augé, Project TOSA 2013, In proceedings of UITP Geneva, Switzerland, 26-30 may, 2013
- [10] Ebusplan, solutions for clean transportation - LCC calculator, <http://ebuslcc.ebusplan.com/en/calculator/>, accessed on 2016-03-23
- [11] M. Rogge, S. Wollny, D. U. Sauer, *Fast charging battery buses for the electrification of urban public transport – a feasibility study focusing on charging infrastructure and energy storage requirements*, Energies, (2015), vol.8(5), 4587-4606
- [12] L. Lindgren, *Full electrification of Lund city buss traffic – a simulation study*, Department of industrial electrical engineering and automation, Lund institute of technology, report (2015)
- [13] Mediacom, TOSA buses power up for less, <http://actu.epfl.ch/news/tosa-buses-power-up-for-less/>, accessed on 2014-06-16
- [14] L. Nurhadi, S. Borén, H. Ny, *A sensitivity analysis of total cost of ownership for electric public bus transport systems in Swedish medium sized cities*, Transportation Research Procedia 3, (2014), 818 – 827
- [15] Trafiklab, GTFS Sverige, <https://www.trafiklab.se/api/gtfs-sverige>, Accessed on 2015-10-15
- [16] M. Valentin, et al. "A Multi-Factor Battery Cycle Life Prediction Methodology for Optimal Battery Management." Proceedings of the 2015 ACM Sixth International Conference on Future Energy Systems. ACM, (2015).

Authors

Oscar Olsson has been working as a researcher within electromobility field at Viktoria Swedish ICT since 2011. He holds a M.Sc. in Industrial Engineering and Management from Chalmers University of technology. His primary research area includes system requirements and technical solutions for charging infrastructure for heavy-duty electric vehicles. He has been involved in several projects demonstrating different charging infrastructure such as electric highways and fast chargers for electric buses.



Anders Grauers is working at the Swedish Electric and Hybrid Vehicle Centre and he is also an associate professor in Hybrid and Electric Vehicle Systems at Chalmers - Department of Signals and Systems. Anders is presently working with system oriented research on electric and hybrid powertrains and their charging infrastructure. The research includes driving forces for development, system requirements, different technical solutions and analysis of complete systems.



Stefan Pettersson has a background from Chalmers University of Technology, where he received a M.Sc. in Automation Engineering and a Ph.D. in Control Engineering in 1993 and 1999 respectively. He became an associate Professor in Control Engineering in 2004. In the years 2006-2009, Stefan conducted applied research in the automotive industry at Volvo Technology, with a special focus on hybrid vehicles and energy management control. Currently, Stefan is the Research Manager of the Electromobility application area at Viktoria Swedish ICT.

