

## **A user-friendly method to analyze cost effectiveness of different electric bus systems**

Joakim Nyman<sup>1\*</sup>, Oscar Olsson<sup>\*</sup>, Anders Grauers<sup>2</sup>, Johan Östling<sup>\*</sup>, Gunnar Ohlin<sup>3</sup>, Stefan Pettersson<sup>\*</sup>

<sup>1\*</sup>*RISE Viktoria, Lindholmspiren 3A, SE-417 56 Gothenburg, Sweden, joakim.nyman@ri.se*

<sup>2</sup>*Chalmers University of Technology, Electrical Engineering, SE-412 96 Gothenburg, Sweden, anders.grauers@chalmers.se*

<sup>3</sup>*Lindholmen Science Park, Lindholmspiren 3-5, SE-402 78 Gothenburg, Sweden, gunnar.ohlin@lindholmen.se*

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### **Summary**

This paper is an update on a method to analyze and compare electric bus and charging systems from a total cost perspective. The method is useful for proposing a suitable combination of bus and charger systems depending on the route specifications, timetables and other local conditions. In this update, a user-friendly tool which simplifies the analysis process is presented. The analysis tool enables the user to experimentally investigate and quantify the trade-offs between parameters such as battery size, charging strategies and charging infrastructure, vehicle fleet and operational costs from a total cost perspective.

*Keywords: BEV (battery electric vehicle), bus, cost, public transport, simulation*

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### **1. Introduction**

An all-electric bus system is seen as an opportunity to reduce dependence on fossil fuels but also to reduce local emissions and noise. The energy can be transferred to buses in various ways such as overnight charging, opportunity charging, bus stop charging, in-motion charging or continuously along the route. Various demonstration projects are underway around the world where electric buses are compared from a vehicle perspective. Some cities have even reached the transition phase between demonstration projects and sharp implementations of electric buses.

Traditionally, tools such as Hastus [1] have been used to optimize a bus fleet based on the most efficient utilization of vehicles and drivers. Unlike buses with internal combustion engines and large fuel tanks, providing these vehicles long range and a high degree of flexibility, electric buses may be more or less suitable for a specific route depending on battery capacity and associated charging infrastructure. What type or types of electric buses and charging systems that are the most efficient solution for a local bus network depends on several parameters and potentially complicating local circumstances that might be difficult to foresee. Several different models have addressed this issue in the literature [2-6]. This paper is an update on a method [7] used to analyze and compare a complete system from a total cost perspective, including vehicles, the necessary charging infrastructure and bus schedules. A user-friendly tool which simplifies the analysis process is presented. The analysis tool enables the user to experimentally investigate and quantify the trade-offs between parameters such as battery size, charging strategies and charging infrastructure, vehicle fleet, and operational costs for battery electric buses from a total cost perspective.

## 2. Background

In a deregulated market the planning and operation of a particular bus line using an appropriate number of vehicles is typically the main responsibility of the operator. Planning tools with complicated algorithms are used to calculate in detail the operating costs of a specific line or system of bus lines. The focus has naturally been to optimize the use of buses and staff. Operators have also used the planning tools to make new bus lines and custom timetables. These tools, however, do not traditionally focus on planning and considering effects related to the charging of electric vehicles such as location of charging infrastructure, charging time or consequences of and on a limited grid network.

There are a couple of ongoing research projects with the aim of quantifying the impact from electric buses on a public transport system [8-10]. Given certain assumptions, the total cost for an entire system is estimated depending on the chosen parameters. The focus is rather on clusters of different lines than on the ability to calculate in detail the effects of electrification on a specific line. The aim of this kind of calculation has been to get an overall picture of how a whole city's bus network can be electrified. For example, it may visualize the impact on the grid or total costs, as well as the distribution of the different types of vehicle systems that are most suitable based on desired preferences.

The method described in this paper is a combination of the two methods described above. It is possible to plan and analyze each individual route on a detailed level, including battery cycles, power loads and total cost while also providing the opportunity to plan a complex line network with a combination of different types of vehicles to minimize the total operating cost.

Early analyses have shown that the electrification of certain lines can have relatively big consequences on a schedule where traffic previously has been carried out by vehicles with internal combustion engines. The ability to calculate in more detail, instead of using standard estimated values, has in these cases proved necessary to get results accurate enough to select charging infrastructure and type of buses. This applies especially to lines where buses have very long working hours per day or if the vehicles have several subsequent trips which limit charging opportunities. In addition, there are often local requirements related to a certain line, such as being able to customize a timetable and charging window to match a train timetable, traffic conditions, or limited access to a certain bus stop. The purpose of the method has, therefore, been to enable relatively detailed analysis in a user-friendly manner while not hindering the user from analyzing a complex line network. On the other hand, the functionality to change timetables or create new routes has not yet been implemented.

## 3. What to analyze and for whom?

Expert tools like Hastus will most likely always be needed to enable detailed calculations of most optimal use of vehicles and equally important, drivers, in a bus network. The present tool can be seen as a complement, where electrified bus systems are in focus and where the user-friendliness of the tool and the possibility to grasp the larger picture are more important aspects than to get optimized results. It may also fill in gaps where incentives or necessary knowledge to perform detailed calculations for every route are lacking, or when advanced scheduling tools are not available due to costly licenses. The present analysis tool was born and is shaped primarily from work and studies performed by researchers, but as electrification of bus routes become more and more mainstream it seems likely that more actors could benefit from a user-friendly tool for analysis. A few examples of use cases and areas of application follow below.

Since electric bus operation and related infrastructure involve multiple stakeholders, several actors may have reason to study electrification of a certain route or network of routes. The most obvious use case may be for a bus operator to investigate which type of electric vehicles are best suited for a certain bus route or network. However, if the vehicles require charging infrastructure which may come to be owned by or in other ways involve the city or municipality, there may be reasons also for the public transport authority (PTA) to analyze and compare the suitability or cost effectiveness of different electric bus systems.

Ownership of charging infrastructure could be compared to ownership of bus stops and depots. It may therefore be of interest to study the suitability or cost effectiveness of different charging locations. There may also exist a need for cities to prepare installation of charging infrastructure, for instance in terms of permits and roadworks. Such preparations may be associated with long lead times and could affect the time between when the operator is awarded the contract and the start of the bus operation. The preparation process has traditionally been in the hands of mainly the operator and the vehicle manufacturer.

Present scheduling tools are not designed to take into account the effects of electric vehicles on the electric infrastructure and vice versa. The local grid owner may for instance be interested in understanding the consequences when multiple electric buses are deployed and simultaneously charged at a single bus stop, city hub or in the depot during the night.

To only optimize bus utilization carries a risk of creating local optima and may lead to increased total costs. The above examples show part of the complexity arising when vehicles can not be decoupled from the infrastructure and considered separately. One ambition when developing the present tool is therefore to keep the systems perspective and display the total costs involved.

During development of the tool, it has been applied in studies of bus routes in five Swedish cities. This work has provided useful input regarding which functionality is necessary and desirable and how the results can be presented in an easily understandable way. Input to the development has also come from two workshops involving key actors, such as representatives from the vehicle industry, charger manufacturers, electric grid operators, bus operators, public transport authorities, academia and research institutes.

#### **4. The analysis method and required capabilities**

The type of analysis discussed here usually starts with existing routes and timetables. Timetables can often, and *always* in the case of Sweden, be retrieved from open sources in GTFS (General Transit Feed Specification) format. Various additional information regarding for instance stop locations is also available and can be used to calculate route length and other parameters. Understanding a given timetable requires finding out whether there are timed connections, passing trains or other parameters that need to be considered. Further statistics on the frequency of bus delays at certain stops can be useful for deciding whether existing time that a bus spends standing still at the stop can be used for charging or whether time buffers need to be expanded. A collection of such information is used to make an early estimate of appropriate vehicle and charging solutions to consider. For new routes and/or timetables that are not already in use, this information needs to be estimated by a traffic planner based on transport needs and departure frequency. Vehicles following a timetable with small or no time buffers must be equipped with large batteries that can either be charged rapidly or last long periods without charging. One also needs to consider to what extent a system needs to be oversized in order to handle variations in traffic and weather as well as different faults that might occur.

Next follows an investigation of the conditions along the route. This includes depot location and grid connection possibilities. Depot location is necessary to calculate the energy and time required to drive from/to the depot. At locations where chargers are planned, including the depot, information is needed regarding distance to grid connections, available power at those connections and an understanding of the type of area in which cabling would be installed - costs vary depending on whether cabling is installed in dense urban areas, sparse urban areas or rural areas. Furthermore, if no grid connection is available in the vicinity or if available connection points do not have sufficient power available, additional transformers or an entire new substation might be needed.

In order to assess charge power requirements, and also battery capacities and charge times, one need estimates of the energy consumption of vehicles driving the routes in question. With geographic and topographic information about the routes, in addition to trip durations and coupled with models of the vehicles, one can

make such estimates. Limitations along the routes, such as maximum vehicle length, weight or height, may impose bounds that must be examined during the analysis. There may for instance also be practical considerations to take into account, such as reasons to limit the variety of different vehicle configurations in the system.

If the analysis is to be relevant, the planner needs to obtain an understanding of the characteristics of the routes in question. Examples of routes with special characteristics are circle routes, routes with varying termini, routes with large distances and high speed, routes with immediate turnaround at the termini, or routes with great variations in traffic intensity. Such characteristics greatly impact charging opportunities and suitable types of vehicles. One final example of special considerations is whether the vehicles will be used specifically on one route or whether they will also be used on other routes which then need to be examined as well.

## 5. The analysis tool

Previously, a combination of Matlab, spreadsheets and various manual steps were used to perform the necessary analysis tasks and calculations. The ambition with the present tool is to collate, streamline and simplify the process in order to make the analysis more efficient and also minimize the dependency on specialty software and certain technical expertise. An online web application was chosen for this purpose. A server is responsible for building and serving databases and performing heavier calculations and other operations, while a web page provides a user interface and performs some lighter operations.

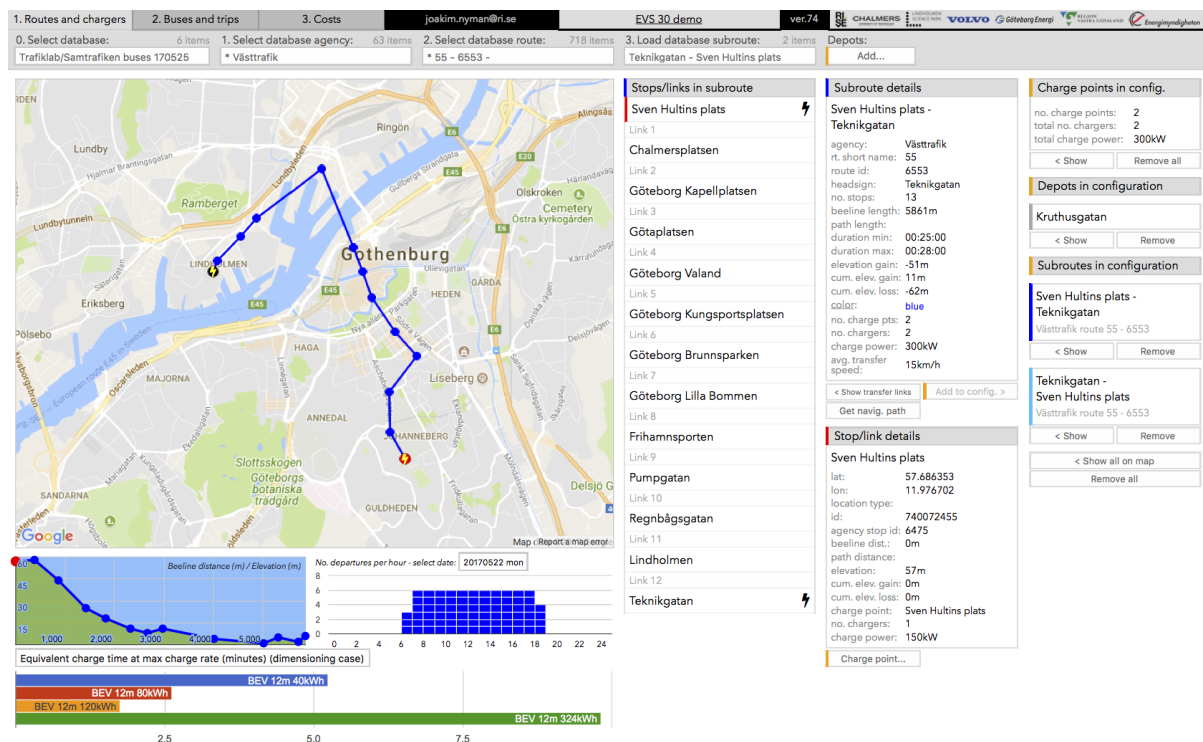
A user can access the analysis tool by logging on to a web site in a normal web browser. The ambition is for this web site to enable the entire analysis process, from configuring the system of bus routes and chargers as well as bus types and driving schedules, to performing necessary simulations and calculations, to finally viewing different resulting properties of the system in terms of for instance costs or energy and power demand. The interface is divided into three tabs, respectively dealing with i) routes, chargers and depots, ii) charging times, buses and trip schedules, and iii) costs. Figures 1-3 show overviews of these three parts of the interface.

Normal use of the tool entails configuring the system of interest by visiting the three tabs of the interface one by one. The user starts on tab 1 with selecting the route or routes that are part of the traffic system in question. Every direction or routing variant of each route is separately selected and added to the configuration as sub routes and given a specific colour, which helps in the subsequent interpretation of schedules. After that, chargers are configured at the stops of interest and relevant depot or depots are added.

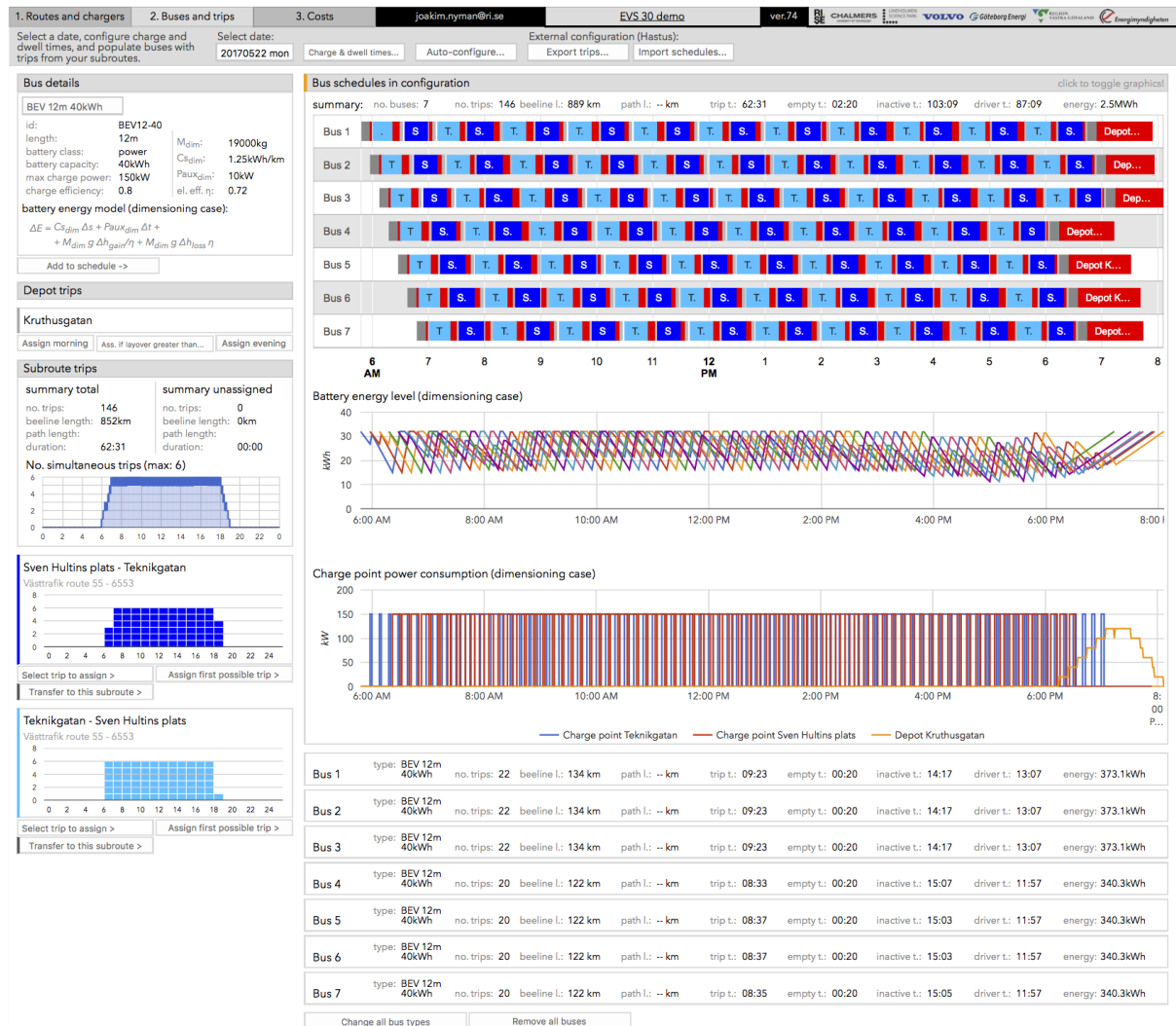
Next, on tab 2, a vehicle schedule is created by selecting bus types from a list stored on the server and assigning the trips that are made on each route according to the time table on a chosen traffic day. Simple schedules can be made directly in the interface and for more complex cases data can be exported to Hastus and the resulting schedule then imported. When a schedule is created or imported, the energy consumption of the buses over the day is simulated and the resulting variation in energy level of each bus battery is shown in a graph. The power consumed at the charge points and the depot is also calculated and plotted. Time for charging between the trips can be reserved ahead of creating the schedule or modified afterwards (then within the constraints of time available between trips in the schedule). Similarly, time not allowed for charging may be configured. The user may also in retrospect change bus types, including battery sizes, or go back to tab 1 and change the charger configuration (location and/or power). This may be iterated to find viable electrification alternatives. Tab 2 thus allows for studying the effects of different electrification strategies on battery state of charge and charger power. Various traffic parameters which also depend on the schedule, such as driving distances and time spent driving trips or empty are also calculated and displayed on this tab.

Finally, the cost of the system is automatically calculated and can be examined on tab 3. The costs are displayed as investment costs and annual costs and divided into different categories. The amounts of the various items are calculated or estimated based on the configuration performed on tabs 1 and 2, and prices are suggested based on a list stored on the server, but can easily be edited by the user. A table and a column graph summarize the

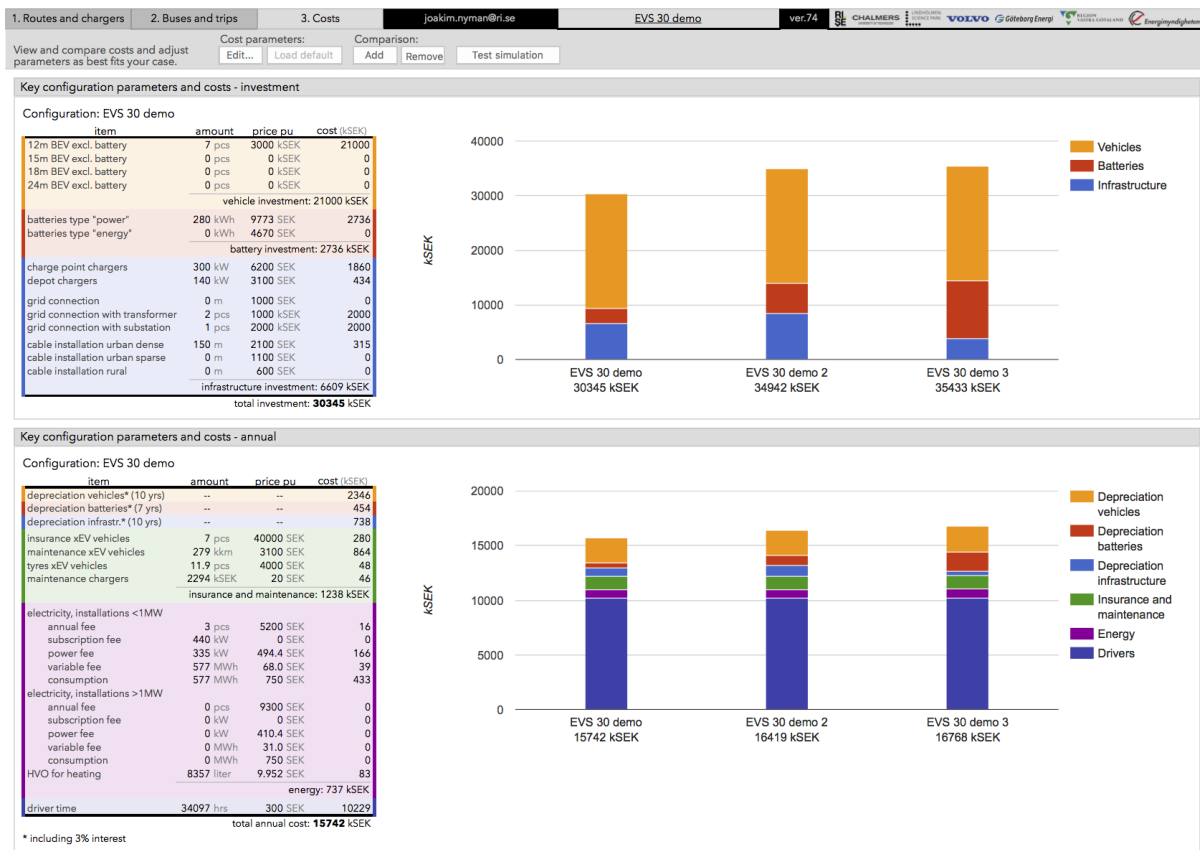
different types of costs. Costs for previously analyzed systems may also be displayed in parallel with the investigated system for easy comparison of different configurations. The cost models and suggested prices are largely a direct implementation of models and prices previously reported [7].



**Figure 1.** Overview of tab 1 of the interface to the analysis tool. The user can upload their own GTFS data to the server and then browse and view all bus agencies and routes available in it or in previously uploaded data. Desired route directions/variants (here denoted ‘subroutes’) are then selected and added to the system configuration. Elevation and distance information is automatically added using Google’s API:s [11], based on stop coordinates present in the GTFS data. Google’s API:s are also used for mapping functions and for all plots seen in the interface. Most graphical elements are interactive and show additional information when hovered over, or perform some action when clicked. Energy consumption for bus types stored on the server is automatically calculated for each subroute. On this page, the user can study and analyze the various route and stop information, add chargers to desired locations and also add depots. Transfer links and links to and from depots are automatically created and energy consumption as well as drive time is calculated. When creating charge locations and depots, the user can enter information regarding connection to the electricity grid, for cost calculation purposes. The route and trip information seen in the figure stems from openly available data for all public transport in Sweden, collected by Samtrafiken [12] and published by Trafiklab [13].



**Figure 2.** Overview of tab 2 of the interface to the analysis tool. Here the user selects which date to consider and creates a bus schedule by assigning the trips made on each route that day to desired bus types. Desired bus types are selected from a list stored on the server. Details of the different bus types, including battery capacity, maximum charge power and energy consumption parameters may be viewed on this tab. The battery energy model is also visible and is a linear function of distance driven, time driven, cumulative elevation gain and cumulative elevation loss (results in regen). Simple ‘back-and-forth’ schedules like shown can be auto-configured directly with the tool, and for more complex schedules data can be exchanged with Hastus<sup>1</sup>. Maximum battery state-of-charge and time for charging before and/or after trips, as well as time buffers without charging can be easily configured, with the possibility for different settings during different times of the day. These times are taken into account when creating the schedule but can also be modified afterwards, within the confines of the scheduled trips. The schedule shows both regular trips (here dark and light blue), depot trips (medium gray) and transfer trips (not shown here) as well as blocks indicating charging (red) and non-charging (light gray) time buffers in between trips. The battery energy level throughout the day is simulated and plotted for each bus, as is the power consumption of each charger location in the system. Below the large summary box with the three plots shown here, there are boxes with information for each individual bus. The boxes can be clicked to show the schedule and battery energy variation of that particular bus.



**Figure 3.** Overview of tab 3 of the interface to the analysis tool. When selecting this tab, the user is greeted with a summary of the automatically calculated cost of the configured system. Investment costs are at the top and annual costs including depreciation below that. For each group, a column chart is shown to the right and a more detailed table to the left. In the figure, two other configurations are loaded for comparison, making it three columns to the right. The tables show details of just one configuration at a time; hovering over a different column in the chart switches to showing the details corresponding to that configuration. Default prices for the various items are stored on the server and automatically suggested, but may be edited by the user. Changes in the configuration or prices are immediately reflected on the cost tab.

## 6. Discussion and outlook

In this first phase of developing a tool to simplify the analysis process, we deliberately started as simple as possible in all parts of the tool and were strict in our priorities regarding functionality and features. As a result, the tool is currently complete in the sense that it supports the entire process from gathering route and timetable data and configuring the electrification, to analyzing the energy characteristics and obtaining the costs of the configured system. It is indeed also simple to complete these steps for small systems with a few routes. It is also quick and takes on the order of a few minutes although properly examining the results from the tool and drawing conclusions on the systems viability will take much longer than that. At the same time the tool is incomplete in the sense that in most parts one may point out examples of functionality or features that could or should be added. In the short term our focus continues to be on expanding the capabilities of the tool, continuing with our prioritizations of which features and functionalities are most useful in the analysis process. Let us however discuss a few items that are on our shortlist.

The two overarching tasks for which the tool is used are the evaluation and analysis of the energetic profile of the electric bus operation, and estimates and calculations of its costs. Starting with the energy considerations, it is important to have sufficient detail and accuracy in the geographic and topographic data of the bus routes in order to make sufficiently accurate energy calculations. Due to that the GTFS data currently used in our

analyses does not include detailed driving paths (which is supported by the GTFS specification but not mandatory), we started by modelling all routes as straight lines between the stops and elevation is collected only at the stops. This causes all driving distances to be underestimated and might hide some topographical features along the routes. Ability to get or create more detailed driving paths is therefore considered.

Driving distances are related to battery wear, which we return to below, and other performance indicators than discussed here, so accurate estimates are relevant for several reasons. ‘Sufficient’ is nevertheless an important keyword; we must remember the overarching tasks. In evaluation and analysis of the energetic profile of the bus system it is primarily important to not grossly underestimate energy consumption so as to not underestimate battery sizes or charging capacity in terms of power and time. In fact, we attempt to model energy consumption parameters of the buses to represent a tough ‘dimensioning’ case, with high energy consumption close but not quite equal to a ‘worst’ case. Similarly, it is wise to consider a schedule representing a tough traffic day.

Energy consumption affects costs as well, and here it must be remembered that we wish to calculate annual costs. We are therefore interested in annual energy consumption, for which highly detailed and accurate simulations are unnecessary and quickly become complex with a large number of days with different traffic intensity and energy consumption, and for systems with many vehicles. Currently the annual energy consumption is calculated from a schedule for just one traffic day and a single energy consumption case (the tough dimensioning cases mentioned above) and a year is approximated by scaling down both the number of traffic days in a year and the energy consumption of one such day. This approach remains to be validated and may turn out to be overly simplistic. More elaborate approximations of annual traffic and energy consumptions will be considered.

In addition to considering tough cases in order not to underestimate the energy requirements of the system, it is also pertinent to remember disturbances and faults such as traffic redirections or charger outages. It is left to the user the tool to manually analyze the system and make allowances for such situations. It might make sense to have the ability to simulate disturbances and faults, or at least to remind the user of the possibility for them and simplify the analysis and allowance-making.

On the topic of designing a system with sufficient margins to handle extreme cases, one of our top priorities is to implement a battery wear model in order to enable estimates of the life-time of the batteries given a certain battery size and chemistry or, vice versa, necessary capacity margin to achieve a desired life-time. Similarly, as for allowances related to disturbances and faults, it is currently up to the user to estimate whether there is sufficient capacity margin for the batteries to last throughout the depreciation period (which is explicitly assigned). We are also planning support for residual values and for situations where batteries need to be replaced within the contract period. The battery wear model is already used in our analysis method, but is not yet integrated in the analysis tool.

While certain manual tasks or estimates should be automated, there is a balancing-act to consider, between simplifying for the user on the one hand and having flexibility for the user to do as desired on the other hand. In other words, we do not wish to automate everything at the expense of excluding the possibility to do things differently. Some concerns have also been voiced that making things too simple might cause users to not consider all necessary aspects and jump to conclusions. In an attempt to prevent such pitfalls, we are in this first iteration consistently and deliberately avoiding making the tool too ‘smart’, leaving the responsibility for being smart to the user. In other words, we try to design the tool to help the user do what he/she wants and show the consequences of that, but not to tell whether what being done is good or what would be the best to do. More smartness might however be added in future iterations as we learn more about usage patterns and what is most helpful during the analysis.

One final example of developments that are considered in the short- to medium terms is expanding the capabilities to supporting more vehicle types and charging solutions. On the vehicle side, we currently support only battery-electric buses. We will most probably at some point expand the scope of the tool to include also

buses with internal combustion engines, to enable easy in-tool comparisons between different powertrain options. Hybrid variants and fuel cell options are also on the table. In a longer perspective, application to entirely different classes of vehicles like trucks or boats might become relevant. For charging/energy transfer, we have not yet in our work encountered analysis cases requiring support for inductive charging or for in-motion charging, but primarily the latter is likely to be considered in the near future.

## 7. Conclusion

A method to analyze and compare electric bus and charging systems from a total cost perspective has been updated with a tool which simplifies the analysis process. The analysis tool enables the user to experimentally investigate and quantify the trade-offs between parameters such as battery size, charging strategies and charging infrastructure, vehicle fleet and operational costs from a total cost perspective. This is useful for several actors in the public transport space to analyze or propose combinations of bus and charger systems depending on the route specifications, timetables and other local conditions. Unique to the tool is that it retains the comprehensive approach of the underlying method while providing a user-friendly and graphically rich interface which opens up for efficient and simple application of the method. A tool like this is very important to be able to effectively deal with the complexity of planning a cost effective electric bus system, and its graphical user interface helps the user to more easily see the system effects of different choices in the system design and planning of the bus operation.

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## 9. References

- [1] Hastus, <http://www.giro.ca/en/solutions/bus-metro-tram>, accessed 13-01-2017
- [2] *Ebusplan, solutions for clean transportation - LCC calculator*, <http://ebuslcc.ebusplan.com/en/calculator/>, accessed on 2016-03-23
- [3] 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
- [4] Mediacom, *TOSA buses power up for less*, <http://actu.epfl.ch/news/tosa-buses-power-up-for-less/>, accessed on 2014-06-16
- [5] C., Villante, *A tool for Well-to-Wheel evaluation of alternative public transport means*, (2015), EVS28.
- [6] S., Krawiec, et al., *Economic conditions to introduce the battery drive to busses in the urban public transport*, Transportation Research Procedia 14 (2016) 2630 – 2639
- [7] O., Olsson, A., Grauers, S., Pettersson, *Method to analyze cost effectiveness of different electric bus systems*, (2016), EVS29
- [8] L., Lindgren, *Full electrification of Lund city bus traffic – a simulation study*, Department of industrial electrical engineering and automation, Lund institute of technology, report (2015)
- [9] M., Xylia, et.al. *Locating charging infrastructure for electric buses in Stockholm*, Transportation Research Part C, Elsevier, (2017), 183-200
- [10] 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
- [11] *Google API*, <https://developers.google.com>, accessed on 20-01-2017
- [12] *Samtrafiken*, <https://samtrafiken.se>, accessed on 20-01-2017
- [13] *Trafiklab*, <https://www.trafiklab.se>, accessed on 20-01-2017

## 10. Authors



Joakim Nyman began his professional career in automation and then went to Chalmers University of Technology, where he received a M.Sc. in Engineering Physics 2006 and a Ph.D. in Physics 2012. Since 2013 he works as a senior researcher within the Electromobility application area at RISE Viktoria. His main research activities revolve around computational methods, modelling and physical and technical aspects of electromobility.



Oscar Olsson has been working as a researcher within the Electromobility application area at RISE Viktoria since 2011. He holds a M.Sc. in Industrial Engineering and Management from Chalmers University of Technology. His research focuses on reducing barriers for electric vehicle usage for both fleets and private consumers. His primary research area includes system requirements and technical solutions for charging infrastructure for heavy-duty electric vehicles.



Anders Grauers is working at the Swedish Electromobility Centre and he is also an associate professor in Hybrid and Electric Vehicle Systems at Chalmers University of Technology - Department of Electrical Engineering. 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.



Johan Östling is working as a Senior Project Manager at RISE Viktoria since 2015. He is educated at the Military Academy in Stockholm and has the rank of Major in the Swedish Armed Forces. After the Military career he has practised the leadership in the industry at international companies for about 20 years in different positions such as Manager, CEO and Project Manager.



Gunnar Ohlin holds a M.Sc. in Industrial Engineering and Management from Chalmers University of Technology. Gunnar is working at Lindholmen Science Park AB since 2013. As project manager at Lindholmen he has managed and participated in several collaborative projects in electromobility and digitalization. His focus at present is within public transport and how it is affected and transformed by digitalization, automation and electrification.



Stefan Pettersson has a M.Sc. in Automation Engineering and a Ph.D. in Control Engineering and became an Associate Professor in Control Engineering at Chalmers University in 2004. During 2006-2009 Stefan worked in the automotive industry at Volvo Technology. Currently, he is the Research Manager in Electromobility at RISE Viktoria, being responsible for all projects in this area.