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Developing a dynamic optimization model for electric bus charging infrastructure

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Abstract

Urban regions account for 64% of global primary energy use and 70% of carbon emissions. For that reason, options to decarbonize urban environments are receiving increasing attention. In this context, public transport shall play a key role in decarbonizing urban road transport. One efficient way to achieve that is shifting towards clean fuels and modern electric buses, an option that is already under implementation in several cities around the world. In this paper, the basis for developing a dynamic optimization model for establishing charging infrastructure for electric buses is presented, using Stockholm, Sweden, as a case study. The model places constraints depending on the bus stop type (end or middle stop) which affects the time available for charging at each particular location. It also identifies the optimal technology type for the buses: conductive or inductive. In addition, the electric buses compete with buses run on biogas or biodiesel. In this paper, we present the results of a cost minimization scenario with constraints placed on the available charging time and power, differentiated between end stops and major public transport hubs. The mean charging time is 7.33 minutes, with a standard deviation of 4.78 minutes for all bus stops. The inner city bus routes require less charging time, which ranges on average at around 3 minutes. The installation of chargers at the locations proposed in the model would require scheduling adjustments and careful planning for the density of charging occasions.

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Keywords: electric bus; charging infrastructure; optimization; Mixed Integer Linear Programming; public transport; Sweden

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1. Introduction

The Conference of the Parties to the UNFCCC (COP 21) held in December 2015 in Paris resulted in a historical agreement among 195 countries to limit global temperature increases to well below 2 degree Celsius (see e.g. European Commission, 2016). In order to turn the Paris agreement into a success, decarbonization is needed in all sectors of the economy. Cities will play an important role in this context, as urban regions accounted for 64% of global primary energy use and 70% of carbon emissions in 2013 (IEA, 2016). One of the major challenges on the way to environmental sustainability of cities is the decarbonisation of transport. The transport sector emissions represented 23% of the global emissions in 2013, with road transport emissions accounting for 75% of the total emissions in the sector (IEA, 2015). By 2013, emissions from road transport had increased by 68% compared to 1990 (IEA, 2015). Electrification of road transport in combination with a modal shift towards public transport can be key to achieving decarbonisation and energy efficiency improvement of the sector. In line with the above, Sweden has been testing solutions for bus transport electrifications in various locations around the country. A target of 80% electric city buses by 2030 and 100% by 2050 is suggested by the Swedish government (Regeringskansliet, 2013)

In this paper, a dynamic optimization model for establishing charging infrastructure for electric buses is presented, using Stockholm, Sweden, as a case study. Our objectives are: (i) to identify the potential spatial distribution for large scale electric bus charging infrastructure, and (ii) to explore the impact of time constraints and charging availability as an effect of the scheduled operation of the bus network. The main questions we aim to answer in this paper are the following: *(i) How do charging time constraints within the bus network affect the potential electrification of certain routes, and the number of chargers to be installed?* and*, (ii) What are the main implications of scheduling constraints when it comes to strategic planning for bus transport electrification?* The model presented here is an updated and enhanced version of the model originally presented in Xylia et al. (2017).

Charging infrastructure requirements is being largely debated in the context of urban energy planning for transport electrification. As electric vehicles are gaining momentum, the issue of locating and securing the availability, efficiency and effectiveness of charging infrastructure becomes a complex question that needs to be answered. The problem of optimizing charging station locations has been addressed previously using different methodologies and approaches by a number of authors. For example, the environmental impacts resulting from a shift to electric buses was investigated by Lajunen (2014) using an LCA perspective, and by Ribau et al. (2014) using a GA approach. Optimization models with application similar to our model, i.e. identifying charging infrastructure requirements for electric bus networks, have been developed by Kunith et al. (2016); Rogge et al. (2015); and Sinhuber et al. (2012). The approach of our model is somehow different from these previous studies - first and foremost because of the much larger scale of the bus network under consideration. The bus network of the wider Stockholm region comprises 526 bus routes and 11,436 bus stops. Such a large network requires higher automatization and adaptability of the tools used to build the model, as well as necessary simplifications and adjustments.

Following the present introduction, Section 2 presents the structure of the dynamic optimization model. Section 3 includes the results of the model, showing the location of chargers in Stockholm's bus network under a reference cost optimization scenario. We then discuss the charging times and where the main scheduling bottlenecks exist. Finally, conclusions on the study as well as planning recommendations are given in Section 4.

Nomenclature

GA	Genetic Algorithm
GAMS	General Algebraic Modeling System
LCA	Life Cycle Analysis
O&M	Operation and Maintenance
SEK	Swedish Krona

2. Methodology

The basic methodology used here follows the one originally developed in Xylia et al. (2017). The structure of the model can be split in four main components: (i) the *data processing component* where information on the characteristics and costs of the bus and charging station technologies as well as schedules is collected and managed; (ii) the *geospatial component* where bus routes are matched to their respective bus stops and a distance matrix between the stops of each route is created in ArcGIS from the bus network map input ; (iii) the *optimization component* where either the total costs or the total energy consumption is minimized in GAMS; and (iv) *the scenario analysis component*, where the selected charging stations from the optimization component are located and the impact of various parameters on the results is discussed. More information on the structure and main assumptions behind the model can be found in Xylia et al. (2017). The parameters used in the present model can be found in the Appendix Table A.1of this paper.

We enhance the model in this study, focusing on dynamic aspects such as the charging availability constraints caused by the practical limitations of the time a bus can spend at each stop. This available time for charging is assumed to differ here, depending on whether the bus stop is at an end stop (i.e., start or end of the route) or a major hub along the route (i.e., mid-route). In the optimization algorithm, S is the number of bus stops, L the number of routes for the buses, *Tech* the number of technologies that can be implemented for the buses, i.e. biodiesel, biogas, and electric. The corresponding sets are: $\tilde{S} = \{1,..,S\}$, $\tilde{L} = \{1,..,L\}$ and $\widetilde{TECH} = \{1,..,TECH\}$. Besides, the number of stops at the start (S^{start}), middle (S^{middle}) and end (S^{end}) of each route are considered. The corresponding sets are $\widetilde{S^{start}} = \{1,..,S^{start}\}$, $\widetilde{S^{middle}} = \{1,..,S^{middle}\}$, and $\widetilde{S^{end}} = \{1,..,S^{end}\}$ respectively. The new components added to the optimization algorithm first presented in Xylia et al. (2017) are shown in detail in Appendix Table A.2. The energy provided for charging a bus with technology (*tech*) on the line (*l*) at a station (*s*), $P^{charging}_{l,s,tech}$, is related to the time available for charging, the capacity of the charging station, and is calculated for each stop as shown in Eq. (1). The energy provided should not exceed the total time that the bus can stop at each occasion in relation to the maximum charging capacity (see Eq. (2)).

$$P^{charging}_{l,s,tech} = T^{load}_{l,s,tech} * Cap^{charging}_{tech}\ , l \in \tilde{L}, s \in \tilde{S}\ , tech \in \widetilde{TECH} \tag{1}$$

$$P^{charging}_{l,s,tech} \leq T^{station}_{l,s,tech} * Cap^{charging}_{tech}, l \in \tilde{L}, s \in \tilde{S}\ , tech \in \widetilde{TECH} \tag{2}$$

The time spent at each bus stop of each route ($T^{station}_{l,s,tech}$) is the sum of the time needed for charging ($T^{load}_{l,s,tech}$) and the time needed in order to satisfy the exact time constraint set for the stop ($T^{wait}_{l,s,tech}$) (see Eq. (3)).

$$T^{station}_{l,s,tech} = T^{load}_{l,s,tech} + T^{wait}_{l,s,tech}, l \in \tilde{L}, s \in \tilde{S}\ , tech \in \widetilde{TECH} \tag{3}$$

In order to be able to differentiate the available charging time for end stops and stops along the route of the bus, separate charging time constraints were created for the end and start station ($T^{end\ station}$) and middle station ($T^{middle\ station}$) as shown in Eqs. (4) and (5):

$$T^{charging}_{l,s,tech} = T^{end\ station} * US_{l,s,tech}, l \in \tilde{L}, s \in \widetilde{S^{start}}\ or\ \widetilde{S^{end}}, tech \in \widetilde{TECH} \tag{4}$$

$$T^{charging}_{l,s,tech} = T^{middle\ station} * US_{l,s,tech}, l \in \tilde{L}, s \in \widetilde{S^{middle}}, tech \in \widetilde{TECH} \tag{5}$$

If the charging time required at the bus stop as calculated from Eq. (3) complies with the time constraint for the particular bus stop type as identified from Eq. (4) or (5), then the bus is able to charge at this bus stop. In addition, if the charging power provided is adequate for the bus to reach the next potential charger location, the bus stop is selected as a charger location. Once a stop is selected to be a charger, the other bus routes crossing that stop can use the charger, provided that time constraints are satisfied and the bus schedule is not compromised. For the reference case presented here, the maximum time the buses can spend at end stops ($T^{end\ station}$) is set to be 25 minutes, while for stops along the route, the maximum time ($T^{middle\ station}$) available is constrained to 6 minutes.

3. Results and discussion

3.1 Charger location optimization

Applying the model for a cost optimization case using the time and charging power constraints as discussed earlier in Section 2, we observe that electrification is still an option for Stockholm buses, although with differences compared to the optimization results without such constraints, which were presented in Xylia et al. (2017). Fig. 1 maps the optimization model results in a reference, cost-minimization case. The majority of selected locations for installing charging stations can be found in the inner city of Stockholm, but there are several charging stations installed at the end of longer routes connecting the Southern suburbs of the city with the centre. The chargers are of conductive technology, which is assumed to be cheaper at the moment. Therefore, the latter are selected against the inductive technology in the cost optimization case. However, estimating costs of charging infrastructure involves uncertainties, and is subject to change as road transport electrification matures and economies of scale effects are achieved.

Table 1 compares the results of the model with time constraints, as tested here, to the model results without time constraints as tested in Xylia et al. (2017). We observe that a higher number of routes is electrified when constraints are imposed (52 instead of 42 routes) and, not surprisingly, a significantly higher number of chargers are needed for operating these routes (102 chargers instead of 59 chargers). This happens due to the fact that the constraint posed in Eq. (5) limits the number of chargers that can be installed along the routes and, as a result, more charging is required at the end stops to operate the route on electricity. Despite of the higher infrastructure investment costs (29 instead of 17 million SEK/year), the total costs of the system decrease, driven by an overall reduction in fuel consumption (497 instead of 630 million SEK/year). However, although such balances are positive at the system level, it is necessary to take into account and analyse further how infrastructure costs should be shared among involved stakeholders. While the benefits of lower fuel costs can be accrued by specific stakeholders of the system (i.e., the operators), investments to build charger installations are expected to be undertaken by the public transport authorities, municipalities and/or the national government. Alternatively, new business models are needed to attract investors to this sector. It should be noted that the optimization is feasible even in cases when stricter time constraints are imposed for the middle-of-the-route stops serving as major public transport hubs. In our analysis, we have identified that the time constraint in Eq. (5) can be reduced to two minutes without changing the number of electrified routes or chargers installed as shown in Table 1. However, in this case, the time constraint for the end stops (Eq. (4)) needs to be relaxed to at least 28 minutes in order to allow the buses to charge with more power at the end stops.

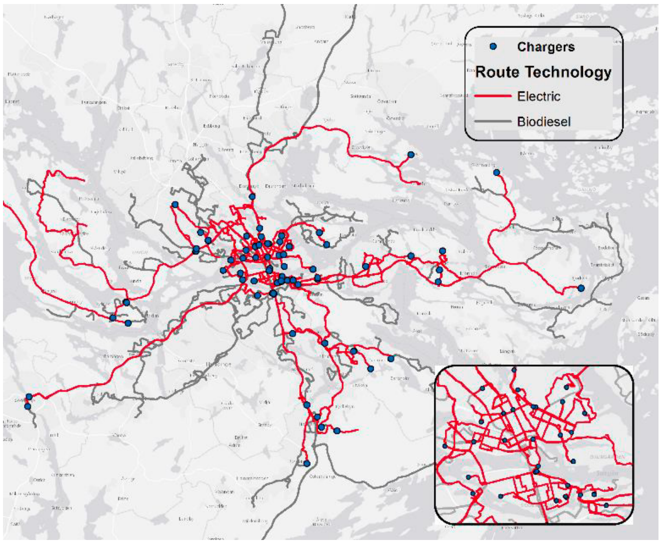


Fig. 1. Bus technology selection and electric bus charging station locations

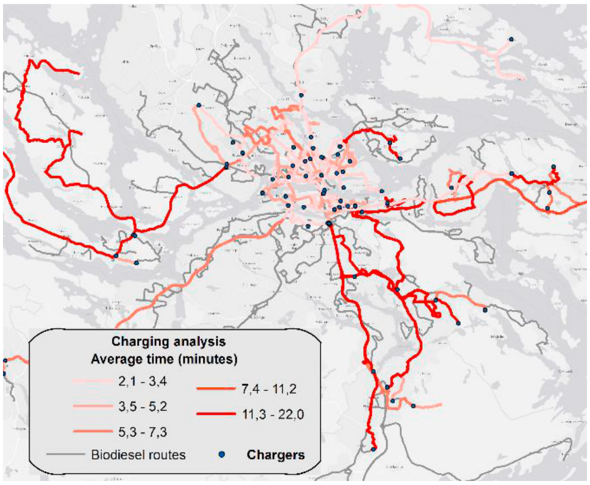
Table 1. Results for cost optimization when time constraints are applied compared to results without time constraints

General	*With time constraint*	*No time constraint*
Total costs (billion SEK/year)	3.69	*3.75*
Total energy use (GWh/year)	392	*473*
Cost breakdown		
Infrastructure (million SEK/year)	29	*17*
Vehicle (million SEK/year)	466	*446*
O&M (million SEK/year)	2,703	*2,663*
Fuel (million SEK/year)	497	*630*
Number of charging stations		
Conductive	102	*59*
Inductive	0	*0*
Number of bus route technology		
Biodiesel	91	*101*
Biogas	0	*0*
Electric	52	*42*

3.2 Charging time analysis

Fig.2 shows the average charging time required for the electrified bus routes of the network. We group the charging time in 5 clusters, ranging from 2 to 22 minutes. As expected, the inner city routes, where the total length and the stop distances are shorter, show lower charging time requirements than the routes that connect the city center with the suburbs of Stockholm. Further investigation is needed to confirm that the specific prerequisites of each route allow such longer time intervals for end-stop charging of suburban routes, (e.g., sufficient space for installing chargers without compromising public transport services and impact on O&M costs from longer driver shifts). The mean charging time is 7.33 minutes, with a standard deviation of 4.78 minutes.

Fig. 3 shows the impact of charging power capacity on the number of bus routes that are electrified. Capacities below 50% of the reference capacity start to have stronger impact. The choice to electrify a bus route in the model is less sensitive to capacities above 50% and up to the reference value. It is worth noting that, in the extreme case of only 10% of the reference charging power capacity being available (30 kW), only 5 bus routes are electrified (see Fig. 3): these are bus routes 2, 4, 59, 61, and 72, which all operate within the limits of the inner city and pass multiple public transport hubs. In this way, despite of the low power capacity of the installed chargers and the time constraints, the buses of these routes are able to charge long enough in multiple locations and still operate on electric mode along the route.



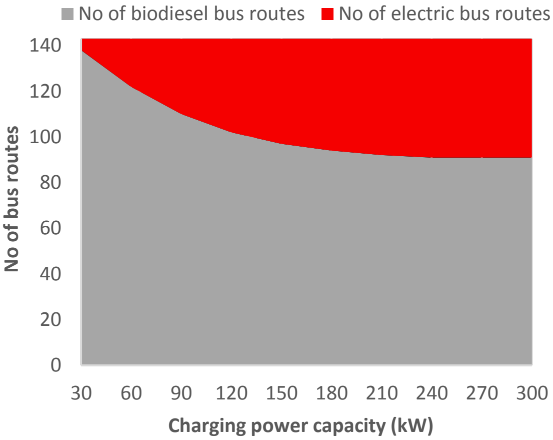


Fig. 2 (left).Spatial analysis charging time distribution.

Fig.3 (right). Sensitivity analysis electrified routes in relation to charging power (in kW).

Analysing the density of charging stations required per bus stop area, the major public transport hubs, such as Slussen and Gullmarsplan, show high concentration of chargers (six and seven respectively – see Fig. 4), with charging times that range between six and nine minutes. The majority of bus stop areas require the installation of one charger, and in a few cases two or three. The charging times vary significantly, from less than three up to more than fifteen minutes.

Fig. 4. Number of chargers per bus stop area mapped in relation to average charging time (in minutes).

The above place a challenge when planning for public bus electrification: in the cases where many charging stations are required, such as the major public transport hubs, the schedule needs to be fitted so that more bus routes share less chargers, something that would increase the use to idle time ratio of the charger and justify the infrastructure investments. On the other hand, there is more available time for charging at end stops, but much less bus routes share the same end stop. As a result, fewer number of chargers required for such stops, as shown in Fig.4. Further research, data collection, and updates to the present model are required in order to investigate the opportunities offered by hub stops that are simultaneously end stops when optimizing the distribution of chargers in the bus network.

4. Conclusions

This paper explores the opportunities given by adding dynamic constraints in a previously developed model for optimization of electric bus charger location. The results show that it is still possible electrify large parts of Stockholm's bus network under various charging time constraints. However, in comparison with the original model in which no time constraints were imposed, we observe that more chargers need to be installed, and their location is mainly at end stops instead of stops along the bus routes. This leads to an increase in the infrastructure costs, which at systems level is balanced by the fuel cost decrease. However, this raises a discussion on who actually bears the costs and who benefits from a scenario of full-scale implementation of electric bus services. The business models that will finance such investments need to be further investigated.

The results indicate a mean charging time of around 7 minutes for most of the stations selected. Still, there are bus routes that require charging times quite above the average (e.g. more than 15 minutes) and the feasibility and benefits of electrifying them should be carefully evaluated. Most of the chargers are concentrated in public transport hubs that serve as end stops. This is positive from the point of view of investments, as a high use to idle time ratio is ensured for chargers in these locations. However, such a solution would require scheduling adjustments and careful planning for the density of charging occasions.

In order to allow a higher concentration of electrified bus routes with minimum number of chargers at these hubs, the design of platform stations needs to be revisited, and the concept of charging where the bus is loading passengers needs to be re-evaluated. For instance, placing the charger at the layover (parking) zone instead of the loading (passenger) zone would allow longer charging without interfering with the operation of bus routes sharing the same loading zone. Such issues could also be addressed by considering opportunity charging, where the buses charge on the go, either conductively or inductively. On the one hand, such solution would be more expensive than stationary charging, but, on the other hand, it would be more beneficial in terms of space and charging time requirements, especially in the case of inductive charging, which does not include any visible or moving parts. The above indicate that technologies for large-scale bus electrification may not be exclusively selected on grounds of their associated costs, but also taking into account other aspects affecting the overall system operation.

Another major issue is the electricity grid capacity needed in order to achieve multiple chargers' being installed across the city. As shown from the sensitivity analysis results, the number of electrified bus routes drastically decreases as the available charging power decreases. Ensuring that the optimal interplay between charging time and power capacity is achieved is of utmost importance for a smooth operation of a fast charging system for electric buses.

This model serves as a tool for simulating real-operation conditions including dynamic aspects for electric bus networks. Further improvements to the model include the addition of a spatiotemporal grid capacity analysis component, as well as the development of the dynamic aspect with the full incorporation of the bus schedules. The latter would require synchronization between the spatial component (bus network maps and bus stop lists) with the dynamic component (detailed bus schedule per route and stop). At the moment, there are discrepancies between the two that need to be alleviated for further improvement of the tool.

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Appendix

Table A.1. Model parameters (reference scenario). Source: (Xylia et al., 2017)

Parameter	Value	Source
Energy consumption bus (kWh/km)		
Biodiesel bus	4.50	adjusted from Mahmoud et al., 2016
Biogas bus	6	adjusted from Hagberg et al., 2016
Electric bus	1.50	adjusted from Hagberg et al., 2016; Lindgren, 2015
Maximum battery capacity (kWh)		
Electric bus	60	Lajunen and Lipman, 2016
Minimum state-of-charge (SOC) for the battery (%)		
Electric bus (opportunity charging)	30	Kunith et al., 2016
Power capacity charging station (kW)		
Electric-Conductive	300	Siemens, 2016
Electric-Inductive	200	Bombardier, 2016
Infrastructure costs (SEK[1])		
	Charging station costs (SEK)	
Electric-Conductive	1,500,000	Lindgren, 2015
Electric-Inductive	2,000,000	Lindgren, 2015
	Pickup for charging station (SEK)	
Electric-Conductive	0	Lindgren, 2015
Electric-Inductive	1,000,000	Lindgren, 2015
	Battery (SEK/Wh)	
Electric-Conductive	10	Lindgren, 2015
Electric-Inductive	4	Lindgren, 2015
	Fixed installation costs (SEK)	
Grid connection	175,000	Lindgren, 2015
Grid connection annual fee	40,000	Lindgren, 2015
Building costs and permits	400,000	authors' assumption
	Vehicle costs (SEK)	
Biodiesel bus	2,500,000	Lajunen and Lipman, 2016
Biogas bus	3,000,000	SLL, 2015
Electric bus	4,500,000	SLL, 2015
Operation & Maintenance (O&M) costs (SEK/km)		
	Driver cost	
Salary costs, insurance etc.	16.40	Hagberg et al., 2016
	Maintenance	
Biodiesel bus	1.50	Lajunen and Lipman, 2016
Biogas bus	3	Hagberg et al., 2016
Electric bus	3	SLL, 2015
Fuel costs (SEK/km)		
Biodiesel bus	6.40	SLL, 2015
Biogas bus	7.10	SLL, 2015
Electric bus	1.40	SLL, 2015

[1] SEK is the Swedish currency (Swedish Krona). The average exchange rate for 2016 is 1SEK = 0.10€ (Oanda, 2016).

Table A.2. Indices, variables, and parameters used in the equations (see Section 2) and optimization algorithm

Indices					
l	bus route	s	bus stop	$tech$	bus technology (biodiesel, biogas, or electricity)
Binary Variables					
$US_{l,s,tech}$					binary variable indicating if charging station is installed at bus stop {0,1}
Positive Variables					
$\mathrm{P}_{\mathrm{l,s,tech}}^{\mathrm{charging}}$	power needed for charging at station (s)			$T^{middle\ station}$	maximum time the buses can spend at middle stops
$T_{l,s,tech}^{load}$	time needed for charging			$T_{l,s,tech}^{station}$	time that the bus stays at the stop for charging
$T^{end\ station}$	maximum time the buses can spend at end (start or end of route) stops			$T_{l,s,tech}^{wait}$	time waiting for charging
Parameters					
$Cap_{tech}^{charging}$	maximum charging power capacity			S^{end}	number of end stops
L	number of routes			$\widetilde{S^{end}}$	subset of stops at the end of the routes
$\tilde{L}$	set of all bus routes			S^{middle}	number of middle stops
S	number of bus stop			$S^{\widetilde{middle}}$	subset of stops in the middle of the routes
$\tilde{S}$	set of all bus stops			$TECH$	

S^{start}	number of start stops	$\widetilde{TECH}$	
$\widetilde{S^{start}}$	subset of stops beginning of the routes		

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