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Cost Savings Potential of Optimized Recharging Infrastructure for Fleets of Electric Buses

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Summary

Installing a separate high-power charger for each bus of an electric bus fleet leads to unnecessarily high investment costs in charging infrastructure. In a simulation study, the sharing and optimized scheduling of chargers resulted in a 78% reduction in investment costs for chargers and their installation, and a 26% reduction in total peak load, limiting grid upgrade costs and reducing electricity bills. Grid upgrade costs to accommodate a 100% electric bus fleet may equal the costs of chargers and their installation and must be taken into account when planning for the transition to clean transportation.

Keywords: bus, fleet, charging, cost, simulation

1 Introduction

The medium- and heavy-duty vehicle segment is a large emitter of greenhouse gas emissions. Buses and trucks cause 30% of transportation emissions in Canada [1]. To realize a net-zero carbon future, these vehicle types will need drastic emission reductions. Most of the Canada's electricity is produced with very low emissions [1]. Battery electric vehicles may therefore be a suitable alternative to diesel vehicles in this transportation segment.

Battery electric buses present unique opportunities and challenges compared to electric light-duty vehicles. Many research studies have been conducted on various aspects of using electric buses. Some example publications are presented here:

- Several studies have examined the economic feasibility and infrastructure planning side of electric buses [2-4]. Different opportunity charging strategies and the impact of battery size on the total cost of ownership were investigated (e.g. [2]). CALSTART researched and analysed the factors electric buses (and trucks) faced, from utility rate structures to demand charges [5].
- A number of studies and models were focused on solving the fast charging location siting problem for transit systems, e.g. [6-8]. In other studies, the deployment of fast charging stations was investigated by considering demand charge reduction [9-10].

- Simulation tools based on a total cost of ownership evaluation method for electric bus systems were developed to optimize bus scheduling and charging infrastructure (including cost-optimized charging locations for opportunity charging). The need for a detailed analysis of the local bus network in order to make an informed procurement decision was emphasized in [11].
- The value of the energy storage system in electric bus fast charging stations had been analysed previously [12].

While the above studies addressed different aspects of electric bus recharging, none of them included the evaluation of the grid upgrade costs in the economic analysis of their studies. The study presented in this paper focussed on both the investigation of the potential to reduce investment costs in charging infrastructure through charging optimization and on creating a deeper understanding of what grid upgrades would be required to ensure that the electricity distribution grid can handle the peak load of the chargers.

1.1 Scenarios

When designing a charging infrastructure for a fleet of electric buses, the simplest approach would be to give each bus its own high-power charger that can fully recharge the bus in just a few hours. This option will come with high investment costs, and will result in a concentrated load peak that may require significant and costly upgrades to the grid connection of the bus depot. However, in an electric bus fleet, there will be many buses with a less demanding duty cycle, which will have much more time than a few hours to get recharged. This presents an opportunity to optimize the charging infrastructure regarding the power level of the chargers and the sharing of chargers between buses through a strategy of staggered charging.

Three scenarios were evaluated in the investigation of the potential to optimize the charging and to reduce the costs of charging infrastructure and of required grid upgrades:

- Scenario 1: Basic charging. Each bus has its own charger.
- Scenario 2: Optimized charging. Chargers are shared between buses and their scheduling is optimized.
- Scenario 3: Further optimization through swapping buses between long and short operation schedules on alternating days.

Additionally, charging optimization may lead to a lower peak load. The impact of this on the electricity bill of the bus depot was assessed.

2 Method

The operational schedule of the total bus system in the city of Ottawa (Ontario, Canada) was used as an example case for investigating the possibilities to optimize the recharging infrastructure for a 100% electric bus fleet.

A simulation model was created to evaluate the required recharging infrastructure to give each bus a full battery before leaving the depot on the next day. The model used 30-minute time slots and was designed to match each bus with the charger with the lowest power level available that would still give it a full battery before its next shift. The charging load of all chargers was aggregated to determine the total load on the grid and evaluate the need for grid upgrades.

2.1 Bus schedule

The complete bus schedule for the city of Ottawa for a weekday in April 2021 was obtained from the website of the local bus company [13]. The data set consisted of 965 operational 'blocks', each detailing the routes that were driven in sequence by a single bus before returning to the depot. Total block distances ranged from 7 to 404 km (Figure 1, left). The non-driving time per bus varied from 2:47 hours to 23:11 hours (Figure 1, right), when using 15-minute 'gap times' to allow the bus to travel from the depot to the start of its first route and from the end of the last route back to the depot. Because no information was available on how the Ottawa bus company may utilize certain buses for more than one ‘block’ a day, it was assumed that each block required a separate bus. The impact of this assumption on the conclusions of the study was evaluated at the end of the study.

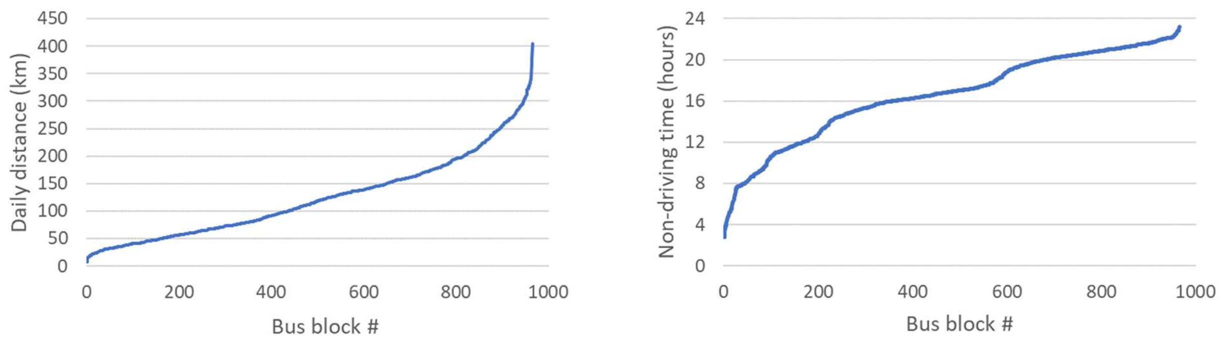

Figure 1: Distribution of daily driving distance per bus block (left) and of non-driving time (right)

2.2 Electric buses

Several manufacturers produce electric buses for the North American market, e.g. [14-17]. The battery sizes of their longest-range versions vary roughly from 450 kWh to 675 kWh. The buses can be recharged from regular DC fast chargers at power levels up to 150 kW, while some buses can also use overhead pantograph recharging with up to 450 kW of power.

The electricity consumption of an electric bus varies through the year. A worst case winter performance of consuming 1.8 kWh/km (estimated from [18]) was used in this study to ensure that the charging infrastructure would be able to provide each bus with a full battery at the beginning of each day of the year.

A 50 km ‘reserve’ range was used to allow the buses to travel from the depot to the start location of their first route, for driving to a new start location when changing routes, to drive back to the depot after their last route, and for when traffic conditions would be unusually heavy.

A hypothetic electric bus (‘CurrentBus’) with a battery size of 562.5 kWh was defined representing the middle of the current range of offerings. Assuming that 95% of the battery capacity is usable, and taking the 50 km reserve range into account, the bus had an effective range of 247 km. This range is not sufficient to cover the blocks with the longest ranges. However, as the focus of this study was on the optimization of the charging infrastructure and not on how to distribute longer distance blocks over different buses, it was decided to use the route blocks without any changes. A ‘FutureBus’ was defined having a 1,000 kWh battery and an effective range of 478 km. The FutureBus was given the same electricity consumption and charging characteristics as the CurrentBus.

2.3 Chargers

Different buses have different charging requirements depending on to the distance they drive and the time they have for recharging. In the simulations, a mix of chargers with different power levels was used to match the charging requirements of the buses. Table 1 presents the cost for the chargers and their installation.

Table 1: Charger costs (based on [19] and discussions with charging station manufacturers)

Charger power (kW)	Charger type	Hardware ($)	Installation ($)	Total ($)	Relative costs ($/kW)
30	DC fast	19,000	12,000	31,000	1,033
60	DC fast	35,000	19,000	54,000	900
100	DC fast	56,000	22,000	78,000	780
150	DC fast	94,000	28,000	122,000	813
450	Pantograph	425,000	225,000	650,000	1,444

* All cost figures in this article are in Canadian dollars

2.4 Grid upgrade costs

The electricity for the charging of the electric buses needs to be supplied by the local electricity distribution grid. While most bus depots have a grid connection, the capacity of this connection may not be large enough to provide the electricity for charging. In this case, upgrades to the distribution grid will be needed. Table 2 presents estimates for the costs of upgrading different components of the electricity distribution grid.

Table 2: Ballpark numbers for grid upgrade costs

Component	Capacity (MW)	Typical costs (million $)	Relative costs ($/kW)
Transformer	2.5	< 0.1	< 40
Feeder line (5 km)	5 – 20	2.8	560 – 140
Feeder line (10 km)	5 – 20	5.6	1,120 – 280
Feeder line (15 km)	5 – 20	8.4	1,680 – 420
Substation (expansion)	20	5	250
Substation (new)	20	10	500

It should be noted that grid upgrades can be very expensive and that their relative costs (see last column of Table 2) could equal or exceed those costs of the charging infrastructure (last column of Table 1).

While Table 2 presents general estimates for grid upgrade costs, the actual costs can vary significantly per location, because the electricity distribution grid has a large variety in the amount of spare capacity on feeder lines.

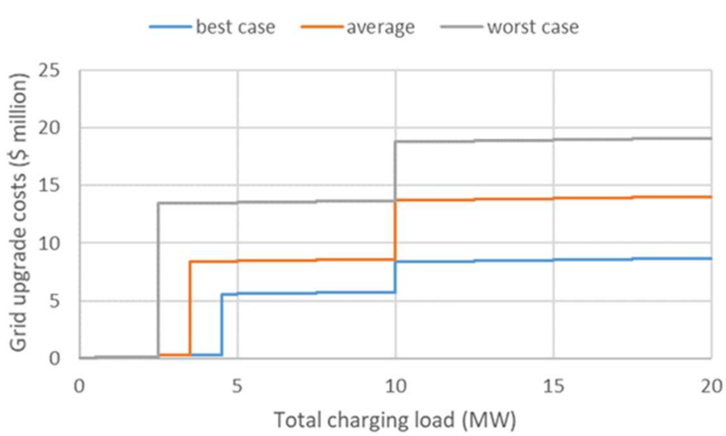

Figure 2: Order of magnitude estimation of grid upgrade costs to expand the capacity of the transformer, feeder line, and substation

Most feeder lines in Ottawa have 2 – 4 MW of spare capacity, but every location is different and will require a separate evaluation. It will therefore not be possible to give more than a general indication of the order of magnitude of grid upgrade costs to accommodate the charging of fleets of electric buses. Figure 2 shows the potential grid upgrade costs for a best case, average, and worst case scenario, assuming that the expansion of substations is done in blocks of 10 MW.

2.5 Electricity bills

The charging of electric buses will increase the electricity bill of the bus company. Electric distribution utilities generally charge companies for the amount of electricity used (i.e. the number of kWh consumed) and they apply fees ('capacity charges' or 'demand charges') based upon the peak load (the highest amount of power drawn). While different recharging scenarios will require the same number of kWh to be recharged to the fleet of electric buses, charging optimization can reduce the peak load of the charging system and of the associated demand charges applied to the electricity bill of the company.

Commercial electricity rates for Ottawa (see Table 3) were used to calculate the impact of charging optimization on the hydro bill of the bus company.

Table 3: Commercial electricity rates for Hydro Ottawa for January 2022 [20]

Rate class		1,500 – 5,000 kW
Energy charge	$/kWh	0.1315
Capacity charge	$/kW	10.3092
Fixed charge	$/billing period	4,193.93

3 Results

3.1 Scenario 1 – Basic charging: Each bus its own charger

When transitioning to electric driving, bus fleet operators tend to install a separate charger for each bus to ensure a full recharge overnight. In this study, a charger with a 60 kW power level was used, which would need close to 8 hours to recharge 250 km of winter driving. Additional higher power chargers were needed for buses with longer daily distances and/or shorter downtime periods.

Table 4 presents the required charging infrastructure for the basic scenario for different gap times, which reflect the impact of shorter charging periods on days with adverse weather and/or traffic conditions. The results show that a small increase in the number of high-power chargers is already sufficient to enable the charging infrastructure to meet the charging need on days with longer gap times.

Table 4: Charging infrastructure composition and costs for different gap times

		Number of chargers					
Case	Gap time (min)	60 kW	100 kW	150 kW	450 kW	Total	Total costs (million $)
Basic 1	15	923	33	7	2	965	54.5
Basic 2	30	917	35	7	6	965	56.7
Basic 3	45	910	37	11	7	965	57.6
Basic 4	60	906	39	12	8	965	58.2

For added flexibility, bus fleet operators may choose to install higher power chargers for more buses than strictly necessary. This greatly increases the costs of the charging infrastructure (see Table 5). However, costs savings are also possible through using 30 kW chargers instead of 60 kWh chargers for the large majority of the buses.

Table 5: Charging infrastructure composition and costs for different charger mixes (15-minute gap time)

Case	Number of chargers						
	30 kW	60 kW	100 kW	150 kW	450 kW	Total	Total costs (million $)
Basic 1	0	923	33	7	2	965	54.5
Basic 5	0	0	956	7	2	965	76.6
Basic 6	0	0	0	963	2	965	118.7
Basic 7	806	0	150	7	2	965	38.7

3.2 Scenario 2 – Optimized charging: Shared chargers and optimized scheduling

When chargers are shared between buses and their scheduling is optimized, large cost savings are possible compared to the basic charging scenario of giving each bus its own charger. Tables 6 presents the charging infrastructure costs for the optimized scenario for different gap times. Compared to the base charger mix (case Basic 1), optimization (case Optimized 1) can reduce investment costs in charging infrastructure by 78%.

Table 6: Charging infrastructure composition and costs for different gap times

Case	Number of chargers						
	Gap time (min)	60 kW	100 kW	150 kW	450 kW	Total	Total costs (million $)
Optimized 1	15	147	31	7	1	186	11.9
Optimized 2	30	146	33	7	3	189	13.1
Optimized 3	45	143	31	11	4	189	13.9
Optimized 4	60	142	34	12	5	193	14.8

The costs of the optimized charging system can further be reduced by installing more chargers with higher power levels (see Table 7). However, the lowest cost scenarios may not be practical, as will be explained in section 3.3. Under the optimized charging scenario, the use of 30 kW chargers instead of 60 kWh will increase the overall costs of the charging system.

Table 7: Charging infrastructure composition and costs for different charger mixes (15-minute gap time)

Case	Number of chargers						
	30 kW	60 kW	100 kW	150 kW	450 kW	Total	Total costs (million $)
Optimized 1	0	147	31	7	1	186	11.9
Optimized 5	0	0	100	7	1	108	9.3
Optimized 6	0	0	0	71	1	78	9.3
Optimized 7	215	0	65	7	1	288	13.2

3.3 Charger utilization

Figure 3 presents the temporal profile of the average charger utilization rates for the total charging infrastructure for various charger mixes under the scenarios of basic charging and optimized charging. The approach of giving each bus its own charger results in low utilization rates, while the sharing of chargers in combination with the optimization of their scheduling allows for (very) high utilization rates of the chargers.

When designing a bus fleet recharging infrastructure, the overall charger utilization rate will have to be balanced with the need for flexibility to address unexpected events (e.g. above average traffic congestion, power outages, charger maintenance). The cases Optimized 5 and especially Optimized 6 have average utilization rates that are close to the theoretical maximum of 100%. These scenarios may not be realistic, because their charging systems may have insufficient spare capacity for days with an above average charging demand.

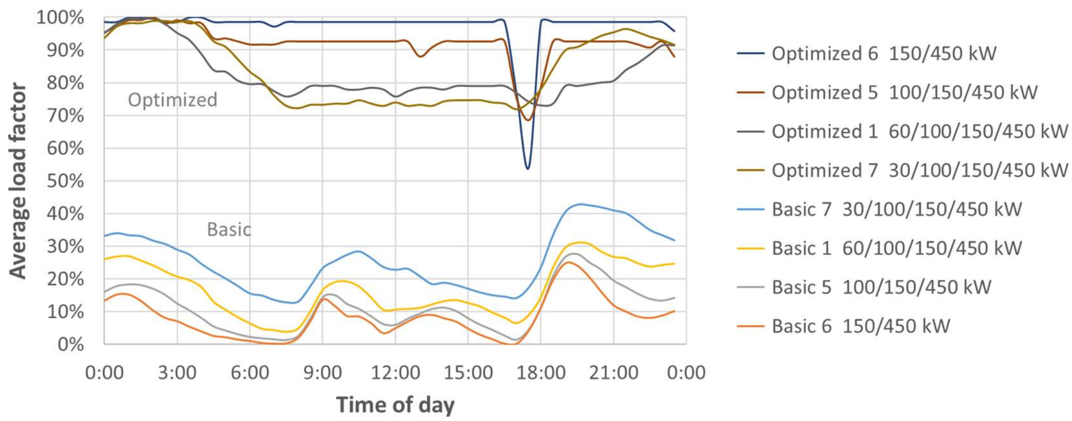

Figure 3: Average load factor of the total recharging infrastructure for different recharging scenarios and charger mixes

3.4 Maximum grid load

Grid upgrade costs strongly depend on the peak power demand of the charging infrastructure. Figure 4 shows the maximum grid load for various scenarios of basic and optimized charging, assuming that all buses are charged at one location and using a 92% efficiency for all chargers. Charging optimization results in a reduction in grid load of 26% for the practical mix of 60/100/150/450 kW chargers, as used in scenarios Basic 1 and Optimized 1.

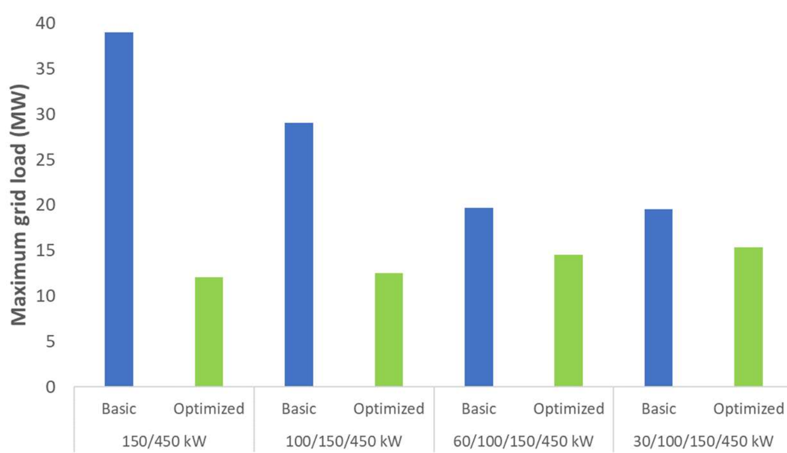

Figure 4: Maximum grid load of the total recharging infrastructure for different scenarios

3.5 Scenario 3 – Further optimization through bus swapping

The possibility to further optimize the charging infrastructure by 'swapping' buses between long and short route blocks on alternating days was investigated. This scenario increases the amount of time available for recharging the buses with the longest duty cycle and reduces the power level needed for a full battery before the next shift.

Nine FutureBuses requiring the highest charging power levels ('Group 1') were paired up with nine different FutureBuses with lower recharge power needs ('Group 2'). Table 8 presents the characteristics of the bus route blocks that were used, and the changes in the average time available for recharging when swapping buses on alternating days. The 'Required charge power' in the last column of Table 8 is the theoretical power level needed to obtain a full battery using the total time available for recharging. Bus swapping reduces the charge power level and allows for the elimination of chargers with power levels above 100 kW.

Table 8: Characteristics of bus schedules and required charge power used in the bus-swapping scenario (for a 15-minute gap time)

Scenario	Schedule	Daily km	Average time available for charging (hh:mm)	Required charge power (kW)
No swapping	Group 1	261 – 404	4:09	109 – 221
No swapping	Group 2	261 – 331	10:40	36 – 77
Swapping	Group 1	261 – 404	6:35	74 – 95
Swapping	Group 2	261 – 331	8:14	43 - 93

Table 9 shows the impact of the bus swapping on the composition and costs of the total charging infrastructure. Bus swapping results in costs savings of $1.3 million and $0.8 million for the basic charging and optimized charging scenarios, respectively.

Table 9: Impact of bus swapping on charging infrastructure composition and costs

Case	Gap time (min)	Number of chargers					Total costs (million $)
		60 kW	100 kW	150 kW	450 kW	Total	
Basic 1	15	923	33	7	2	965	54.5
Basic 1-swapping	15	921	44	0	0	965	53.2
Optimized 1	15	147	31	7	1	186	11.9
Optim 1-swapping	15	147	41	0	0	188	11.1

3.6 Grid upgrade costs

If all 965 buses would be charged at a single location, the peak load of the total charging system for case Basic 1 would be close to 20 MW, while for the Optimized 1 scenario the maximum demand would be around 15 MW (see Figure 4). Bus depots with a peak load of 15 – 20 MW require significant upgrades to the distribution grid for the necessary increase in capacity for transformers, feeder lines, and substations. The costs for these upgrades are expected to be in the range of $10 – 20 million (see Figure 2). For the optimized charging scenarios, grid upgrade costs may actually be higher than the costs of chargers and their installation.

The bus company in Ottawa has 5 depots. If the charging load would be divided evenly over those 5 depots, the basic charging scenario would have a peak load of close to 4 MW per location, while the optimized scenario would have a maximum demand of around 3 MW per depot. These peak loads are in the same range as the 2 – 4 MW of spare capacity per feeder. Detailed investigations would be necessary to understand what grid upgrades would be necessary at which location, and at what costs.

3.7 Electricity bills

Charging optimization resulted in a 26% reduction in peak load and in associated demand charges on the electricity bill for the bus company. The combined annual electricity bill for charging the 965 buses at 5 depots reduced by almost $0.6 million (see Table 10).

Although the $0.6 million is a sizable amount, the savings correspond to only 4.3% of the annual bill, because under the specific rate class, only a small portion of the annual bill is impacted by the level of the peak load. Savings could be more substantial for other jurisdictions or rate classes that more heavily penalize peak demand.

Table 10: Annual electricity bill (in $ million) for the electric bus fleet

	Basic 1	Optimized 1
Energy charge	11.238	11.238
Capacity charge	2.281	1.686
Fixed charge	0.252	0.252
Total	13.771	13.176

3.8 Impact of bus allocation assumption on study results

This study assumed that each of the 965 route blocks of the Ottawa bus schedule required a separate bus. Some route blocks cover very short distances, and it is likely that the local bus company would utilize certain buses for more than one route block on a day. Although no scenarios were evaluated in which route blocks were combined, the results of the current study can still give a good impression of what to expected for those scenarios.

Charging optimization reduced the number of chargers from 965 for the Basic 1 case to 186 for the Optimized 1 scenario, a reduction of 81%. The investment costs for charging infrastructure similarly decreased by 78% from $54.5 million to $11.9 million. If only 800 buses would be needed because some buses would do multiple route blocks on a day, charging optimization would still reduce the number of chargers by 77% (from 800 to 186 chargers). If this scenario would eliminate 165 chargers of 60 kW without the need for more high-power chargers, the total investment costs for the basic charging case would reduce to $45.6 million. Charging optimization would then reduce investment costs by 74%

Although the assumption that every route block needs a separate bus is uncertain, the above analysis indicates that it only has a minor impact on the overall results of the study, and does not change the overall conclusions on the potential of charging optimization.

4 Conclusions

A great opportunity exists to optimize the charging infrastructure for fleets of electric buses by sharing chargers between buses and optimizing their scheduling. In the case study for the city of Ottawa, charging optimization resulted in a 78% reduction in the costs of chargers and their installation, and in a 26% lower peak demand, which lowered grid upgrade requirements and electricity bills.

Swapping buses on alternating days between duty cycles with shorter and longer downtime periods can bring additional cost savings by the elimination of chargers with the highest power levels.

Study results indicate that the optimized recharging solution is robust and that effects of extreme weather or increased congestion can easily be managed by installing only a few extra high-power chargers.

Grid upgrade costs to accommodate a 100% electric bus fleet may equal or exceed the costs of purchasing and installing chargers and must be taken into account when planning for the transition to clean transportation.

Acknowledgments

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