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Comprehensive Economic Assessment of Charging Options for Long-Haul Trucks along Highways

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Executive Summary

Decarbonizing the Canadian long-haul trucking sector using battery electric trucks will require a nation-wide charging infrastructure covering all major highways. In a simulation study, different charging options were evaluated by comparing requirements for overnight charging to those for megawatt charging during lunch breaks or at the end of the day. A comprehensive economic analysis was conducted, including not only the costs for chargers, their installation and for electricity (energy) and demand charges (power), but also often ignored costs for grid upgrades and grid expansion, new truck stops, battery degradation, and work time lost while charging. Results show that grid upgrade/expansion costs and lost productivity are important factors that significantly impact overall costs and thus must be included when evaluating charging options. While megawatt charging scenarios have the lowest 'cost at the charger', the overnight charging scenario leads to the lowest overall costs for the trucking sector.

Keywords: Heavy Duty Electric Vehicles & Buses, Fast and Megawatt Charging Infrastructure, Modelling and Simulation, Electric Vehicles, AC & DC Charging Technology

1 Introduction

The Canadian long-haul trucking sector is a large emitter of Greenhouse Gas (GHG) emissions. Decarbonization of this sector using battery electric trucks (BETs) seems well possible given Canada's clean electricity and generally low electricity prices. However, this transition will require a nation-wide charging infrastructure along major highways to provide the BETs with the energy they need during their multi-day trips all over the country.

Although the electrification of the long-haul trucking sector is still in its infancy, the enormous amount of energy consumed by this sector, in combination with the long lead times for grid expansion projects, requires forward looking planning activities to ensure the required grid capacity will be available when the majority of trucks will be electric.

Several studies have analyzed technical aspects of BET charging infrastructure, focusing on power demand, hub distribution, and grid integration. A trip chain model estimated the number of overnight and megawatt chargers required in Europe by 2030, considering long-haul truck movements and charging needs [1].

In Germany, a simulation-based approach using MATsim evaluated charging infrastructure requirements, incorporating a trip-based analysis to account for trucking logistics, daily route variations, mandatory rest periods, and State-of-Charge (SoC)-based recharging strategies during trips [2][3]. Another study examined the electrical infrastructure needed to support heavy- and light-duty electric vehicles, proposing methods for upgrading conductors and substation sizing to ensure voltage regulation compliance [4]. This study also included a case analysis of a real highway in Norway, assessing traffic demand and the capacity of medium-voltage substations to support BET charging.

While many studies focus on the technical aspects of BET charging infrastructure, fewer have explored its economic feasibility. For instance, the financial impact of transitioning a haulage company's fleet from diesel to battery electric trucks was investigated in [5]. This study compared the costs of relying solely on public charging infrastructure versus supplementing depot charging with public chargers. Additionally, the effects of the BET charging demand on power distribution systems were examined in [6], which provided cost estimates for upgrading distribution networks to accommodate increased depot charging loads.

These studies provide partial answers regarding charging infrastructure for BETs, but a comprehensive investigation into the economic factors determining BET charging along highways is lacking. This paper therefore presents the results of a broad economic analysis of different BET charging strategies, including not only the costs for chargers, their installation and electricity (energy and power components), but also costs for grid upgrades and grid expansion, new truck stops, battery degradation and time lost for charging, which are often ignored in other studies.

2 Method

2.1 Charging Strategies for Electrified Long-Haul Trucks

In this study, the hypothetical scenario of a full transition of the trucking fleet to BETs was taken for the evaluation of the economics of different options for the required nation-wide charging infrastructure. As the consensus is that the large majority of trucks are cubed out (i.e. limited by the volume they can transport) rather than weighted out (limited by the weight of the payload), the simplification was made that battery weight would not hinder a total conversion to BETs.

The study considered the use case in which long-haul trucks drove 600 km per day, 300 days per year. The trucks were given a battery size large enough for a full day of driving, thus only needing one charge per day. A battery size of 1,200 kWh was selected, which included a buffer for battery degradation.

Provincial truck traffic counts on major highways were used to determine the required number of charging stations and total grid capacity per highway section. It was assumed that each highway section must provide all energy for trucks driving that section.

Different charging strategies were investigated through four scenarios (see Table 1). Utilizing the mandatory 8-hour overnight break for the driver, a 200 kW charger would be sufficient to fully charge the battery. For faster recharge during either lunch break or at the end of the driving day, chargers with a power level of 2 MW were used.

For the megawatt charging scenarios, Scenario 2 represents the expected charger utilization associated with the current way trucks are operated, while Scenario 4 reflects a hypothetical scenario of maximum daily charger utilization. Scenario 3 presents a more plausible optimized charging scenario, under which some drivers will adjust their driving/charging behaviour to benefit from incentives to increase charger use during off-peak times.

Table 1: Scenarios evaluated in this study

	Charging period	Charge power	Number of trucks served per charger per day
Scenario 1	Mandated 8-hour break	200 kW	1.5
Scenario 2	Lunch break or end of the day	2 MW	10
Scenario 3	Lunch break or end of the day	2 MW	16
Scenario 4	Lunch break or end of the day	2 MW	24

2.2 Economic model

An economic model was built to calculate the costs for trucking companies of recharging along highways. This model provides separate results for each of the ten Canadian provinces, because certain costs (for instance electricity rates) vary by province. Table 2 presents an overview of the Canadian provinces, and the abbreviations used for them in this study.

Table 2: Abbreviations for Canadian Provinces

Province	Abbreviation
British Columbia	BC
Alberta	AB
Saskatchewan	SK
Manitoba	MB
Ontario	ON
Quebec	QC
New Brunswick	NB
Prince Edward Island	PEI
Nova Scotia	NS
Newfoundland and Labrador	NFL

As the first step in the economic evaluation, the ‘cost at the charger’ was calculated for different charging strategies. The cost at the charger consisted of the following cost components:

<u>Cost at the charger</u>

- Capital costs for chargers and their installation
  Costs figures for the 200 kW overnight charger were based on values from [7], while estimates for the 2 MW charger were made using information from [8] – See table 3.

- Electricity costs (energy component – cost of each kWh consumed)
  Posted electricity rates [9-18] for large commercial/industrial consumers from provincial electric utilities for September 2024 were used, because BET charging locations will need very large grid connections (megawatts or tens of megawatts) – see Table 4 for the provincial electricity costs.

- Electricity costs (power component – fee based on peak load, also called ‘demand charges’)
  Posted electricity rates [9-18] for large commercial/industrial consumers from provincial electric utilities for September 2024 were used – see Table 4.

- Grid upgrades and grid expansion
  In most jurisdictions, grid upgrade and grid expansion costs need to be paid by the client that has made the upgrades/expansions necessary, i.e. the client who’s request for a larger grid connection cannot be accommodated without making these upgrades and grid expansion. It is therefore assumed that the truck charging station operator needs to pay for any dedicated grid upgrades/expansion required to supply power to the charging facility.
  Costs were based on results of an in-house developed calculation model for grid upgrades/expansion,

including costs for new feeder lines, substations and transmission lines. This model was based on data from [19] and additional information from a Canadian electric utility.

- Building new truck stops (only required for Scenario 1)
  Many regions currently have a lack of truck parking spaces, requiring the construction of additional parking spots at existing truck stops or of new trucks stops to enable the charging of a fleet of BETs. To gain an understanding of the relative importance of this cost component, the full costs for building new trucks stops were included in the economic evaluation.
  Costs were based on estimates for building new truck stops [20] and considered land acquisition costs based on provincial values for cultivated land from [21] – see Tables 3 and 4.

No marketing markups were included in the 'cost at the charger'.

For a trucking company, however, the 'cost at the charger' is not the only metric to be considered. Different charging strategies will impact other aspects of the trucking business model in different ways. Therefore, additional cost components were taken into account to compare the overall economics of the different charging strategies:

<u>Other costs</u>

- Battery degradation
  Detailed battery life simulations were conducted for scenarios representing the different charging strategies. The simulations included the thermal effects of varying ambient temperatures and resulted in a 5.2 year battery life for the overnight charging scenario and a 3.9 year battery life under megawatt charging. For these simulations, the battery was assumed to have reached the end of its life when the remaining capacity would be 70% of the original battery capacity.

- Time lost while charging (compared to conventional diesel refueling taking 15 minutes)
  There are costs to a trucking company (e.g. driver salary, missed business opportunity) if a truck is delayed (i.e. has to spend extra time being parked) at a charger. Costs were calculated using a dwell time value from [22] – see Table 3.

Tables 3 and 4 present the values for the seven cost components used in this study. All costs are in Canadian dollars.

Table 3: Inputs of cost components that are the same for all provinces

	Overnight Charging	Megawatt Charging
Charging station	$600/kW	$400/kW
Installation	$40,000	$175,000
Truck stop (excl. land)	$6,000,000	
Battery	$200/kWh	$200/kWh
Time lost while charging	$100/h	$100/h

Table 4: Cost inputs for electricity and land for the different Canadian provinces

	BC	AB	SK	MB	ON	QC	NB	PEI	NS	NFL
Electricity costs										
Energy ($/kWh)	0.0653	0.1336	0.0703	0.0377	0.1102	0.0403	0.0685	0.0862	0.1171	0.1029
Power ($/kW)	13.30	55.00	11.59	7.72	26.33	15.43	17.50	14.50	13.85	6.14
Reference	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]
Land costs (k$/hectare)	277.3	12.4	7.2	13.1	47.4	36.6	11.1	16.1	10.4	4.9

3 Results

3.1 Charging Costs in Different Provinces

The results for the different cost components that make up the total 'cost at the charger' are presented in Tables 5-8. Depending on the specific cost component, the results are given per scenario (if they are independent of the province), by province (if they are equal for all scenarios), or per scenario and by province. To allow a comparison between the different cost components, all costs have been converted to costs per kWh supplied by the charger to a BET. In Table 9, the total 'at the charger cost' is given for the different scenarios and provinces.

The results from Tables 5-9 indicate that the demand charges (the power component of the electricity costs) are the most important cost component, representing 33% of the total cost at the charger (on average over the four scenarios), closely followed by the grid upgrade and expansion costs with 30% of the total at the charger costs. The energy component of the electricity costs amounted on average to 22% of the total cost at the charger, while lower percentages were for the average costs of the chargers and their installation (on average 13%) and the costs for new truck stops (5%, only needed in Scenario 1).

Table 5: Cost in $ per kWh supplied for charging stations and their installation

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Charging stations and Installation	0.077	0.071	0.044	0.029

Table 6: Cost in $ per kWh supplied for electricity (energy) and new truck stops

	BC	AB	SK	MB	ON	QC	NB	PEI	NS	NFL
Electricity costs										
Energy	0.069	0.141	0.074	0.040	0.116	0.042	0.072	0.091	0.123	0.108
New truck stops	0.032	0.021	0.021	0.021	0.023	0.022	0.021	0.022	0.021	0.021

Table 7: Demand charges (power component of electricity costs) per province in $ per kWh supplied

	BC	AB	SK	MB	ON	QC	NB	PEI	NS	NFL
Scenario 1	0.100	0.412	0.087	0.058	0.197	0.115	0.131	0.109	0.104	0.046
Scenario 2	0.149	0.618	0.130	0.087	0.296	0.173	0.196	0.163	0.155	0.069
Scenario 3	0.093	0.386	0.081	0.054	0.185	0.108	0.123	0.102	0.097	0.043
Scenario 4	0.062	0.257	0.054	0.036	0.123	0.072	0.082	0.068	0.065	0.029

Table 8: Grid upgrade and expansion costs per province in $ per kWh supplied

	BC	AB	SK	MB	ON	QC	NB	PEI	NS	NFL
Scenario 1	0.109	0.109	0.109	0.109	0.059	0.059	0.109	0.209	0.084	0.209
Scenario 2	0.145	0.145	0.145	0.145	0.071	0.071	0.145	0.272	0.102	0.272
Scenario 3	0.109	0.109	0.109	0.109	0.056	0.056	0.109	0.240	0.081	0.240
Scenario 4	0.078	0.078	0.078	0.078	0.043	0.043	0.078	0.209	0.064	0.209

Table 9: 'At the charger' cost in $ per kWh supplied

	BC	AB	SK	MB	ON	QC	NB	PEI	NS	NFL
Scenario 1	0.386	0.760	0.368	0.305	0.472	0.317	0.410	0.507	0.409	0.462
Scenario 2	0.434	0.974	0.420	0.342	0.553	0.357	0.484	0.596	0.451	0.519
Scenario 3	0.315	0.679	0.308	0.247	0.401	0.251	0.348	0.477	0.346	0.436
Scenario 4	0.238	0.505	0.235	0.183	0.311	0.187	0.261	0.397	0.281	0.375

From Table 9 it can be deduced that the costs for grid upgrades and grid expansion and the costs for new truck stops together add up to more than one third of the total cost at the charger, or result in on average a 56% increase in the cost at the charger in comparison to a simplified scenario that ignores these costs.

The results also show that the utilization factor of the megawatt chargers has a large impact on the charging costs, with the hypothetical Scenario 4 (one charger serving 24 trucks per day) having 42% lower cost at the charger than Scenario 2 (one charger serving ten trucks daily), and Scenario 3 (one charging station serving 16 trucks per day) achieving a 26% reduction in cost at the charger.

On average, the optimized megawatt charging scenario (Scenario 3) has a 13% ($0.059/kWh) lower cost at the charger than the overnight charging scenario.

Table 9 also shows that there are large differences in the 'costs at the charger' between neighbouring provinces. This may influence where drivers decide to recharge their trucks and may require a larger number of chargers to be installed at charging facilities located on the cheaper side of provincial borders.

Table 10 displays the results for the 'other costs' for the scenarios evaluated in this study. While these costs do not directly impact the price at the charger, they do influence the economics of the trucking operation. The use of megawatt chargers results in a faster battery degradation and therefore in higher battery degradation costs, although the effect of this is limited. More important is the time lost while waiting for the truck to be recharged. In Scenario 1, the time that the truck is parked overnight is used for recharging, which does not require the driver to spend any additional time parked at a charger. On the contrary, the driver gains time in comparison to operating a diesel truck for not having to spend time filling the diesel tank. In the megawatt charging scenarios, the charging of the truck battery is expected to take about 45 minutes, reflecting the fact that for battery lifetime reasons the charge power will be reduced when the battery is filling up. The monetary value of the difference in time lost between overnight and megawatt charging scenarios is significant and amounts to $0.100/kWh recharged.

The summation of all seven cost components is presented in Table 11. These results show that it is important to include battery degradation costs and especially the value of time lost while charging when comparing different charging strategies for the trucking sector. Although Scenario 3 (optimized megawatt charging) had the lowest cost at the charger, the inclusion of these other costs results in the overnight charging scenario (Scenario 1) clearly having the lowest overall cost for the trucking sector. The overnight charging scenario has on average $0.077/kWh (14%) lower costs than the optimized megawatt charging scenario.

Table 10: Cost per kWh recharged for battery degradation and lost work time

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Battery degradation	0.146	0.181	0.181	0.181
Time lost for charging	-0.033	0.067	0.067	0.067

Table 11: Overall costs expressed in $ per kWh supplied

	BC	AB	SK	MB	ON	QC	NB	PEI	NS	NFL
Scenario 1	0.498	0.872	0.480	0.417	0.584	0.429	0.523	0.619	0.522	0.574
Scenario 2	0.681	1.222	0.667	0.590	0.801	0.605	0.732	0.843	0.698	0.767
Scenario 3	0.563	0.927	0.556	0.494	0.648	0.498	0.595	0.725	0.594	0.683
Scenario 4	0.486	0.753	0.483	0.430	0.559	0.434	0.509	0.645	0.529	0.623

3.2 Impact of Truck Traffic Flow on Grid Upgrade and Expansion Costs

This study showed that grid upgrade and expansion costs are an important factor in evaluating the cost of BET charging along highways. However, the grid upgrade/expansion costs vary greatly for highways with different levels of truck traffic, see Table 11. Busy highways benefit from transmission lines with higher power and voltage levels, which are more cost effective.

Table 11: Grid upgrade and expansion costs in $ per kWh supplied for highways with different truck traffic flows

	Trucks per day*	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Very quiet highway	500	0.209	0.272	0.240	0.209
Quiet highway	1,500	0.142	0.187	0.153	0.121
Moderately busy highway	4,000	0.084	0.102	0.081	0.064
Busy highway	8,000	0.059	0.071	0.056	0.043
Very busy highway	17,000	0.037	0.051	0.035	0.029

* The total of truck traffic flow in both directions

4 Conclusions

The economics of different charging strategies for BETs along highways were compared in a simulation study. It was found that for an accurate view on recharging economics, it is very important to not only consider the costs for chargers and electricity, but also to include costs for grid upgrades and grid expansion, for work time lost while charging, and, though less important, for new truck stops and battery degradation.

While megawatt charging scenarios had the lowest cost per kWh at the charger, after including costs for lost productivity and battery degradation, the overnight charging scenario had the lowest overall costs for trucking companies.

Grid upgrade and grid expansion costs can substantially increase the charging costs, especially on highways used by less than 1,000 trucks per day.

A dynamic pricing scheme to increase charger utilization by incentivizing recharging during quiet hours can significantly reduce overall charging costs.

Large differences in electricity costs between neighbouring provinces are expected to impact the size of charging facilities on either side of provincial borders.

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Presenter Biography

Hajo Ribberink has a M.A.Sc. degree in Applied Physics from Delft University in the Netherlands. He has over 30 years of experience in using modelling and simulation to assess new and innovative technologies in the energy field. At Natural Resources Canada, he leads CanmetENERGY's research on transportation electrification and advanced transportation technologies.