Chair in Energy Sector Management
HEC MONTRÉAL

PROJECT COLLABORATOR
cpcs solutions for growing economies

DECARBONIZING LONG-HAUL TRUCKING IN EASTERN CANADA

PART 2 | A techno-economic assessment of net zero technologies on the A20-H401 Corridor between Québec City and Windsor

PREPARED FOR

Québec

MODELLING LEAD

Nicholas Roberts, CPCS

PROJECT MANAGER (MODELLING)

Mathieu Cyr, CPCS

RESEARCH LEADS

Johanne Whitmore, HEC Montréal
Dr Pierre-Olivier Pineau, HEC Montréal

REVIEWERS

Dr Matteo Craglia, International Transportation Forum (OECD)
Dr Simon Langlois-Bertand, Institut énergie Trottier
Joe Lynch, Ontario Ministry of Transportation
Hajo Ribberink, CanmetENERGY, Natural Resources Canada
Dr Arthur Yip, US National Renewable Energy Laboratory

ACKNOWLEDGEMENTS

CPCS's analysis is reliant on publicly available data sources, academic papers, data and insights shared from government, university and industry experts. CPCS acknowledges and is thankful for the input and guidance from HEC Montréal as well as members of industry and academia who have provided feedback on modeling methodology and input parameters throughout the course of this study, most notable during the workshop sessions between April 25 and 27, 2023.

NOTE

This analysis is framed in the context of an academic exercise for assessing the economic costs under theoretical modelling scenarios. As such, there are several assumptions and limitations of the analysis noted in this report. The scope of net zero propulsion types under assessment include: battery electric, catenary electric (with battery), hydrogen fuel cell and renewable natural gas trucks. The observations and conclusions put forward are responsibility of the authors and do not necessarily reflect the opinions of the Government of Québec.

CPCS Canada
Bureau 620, 999 De Maisonneuve Boulevard W.
Montréal, QC H3A 3L4 CANADA
cpcs.ca

Chair in Energy Sector Management | HEC Montréal
3000 Côte-Sainte-Catherine Road
Montréal, QC H3T 2A7 Canada
energie.hec.ca

To cite this report: Roberts, N., Cyr, M., Whitmore, J., Pineau, P.-O., 2023. *Decarbonizing Long-Haul Trucking in Eastern Canada: Part 2 - A cost comparison analysis of net zero technologies on the A20-H401 Corridor Between Québec City and Windsor*, prepared by CPCS and the Chair in Energy Sector Management - HEC Montréal for the Government of Québec.

Deposit: September 2023
ISBN: 978-2-925295-01-3
©2023 Chair in Energy Sector Management – HEC Montréal. All rights reserved.
This report is solely the responsibility of the authors.

Graphic design: Brigitte Ayotte (Ayograph)

Cover images: DepositPhotos

Executive summary

To achieve Canada's net zero commitments by 2050 there is a strong need to decarbonize the transportation sector, which accounts for over 20% of national greenhouse gas (GHG) emissions.[1] Within the transportation sector there is a notable challenge of decarbonizing heavy-duty Class 8 trucks used for long-haul freight as they make up around 24% of the transportation sector's overall emissions and their emissions have been growing since 1990.[2]

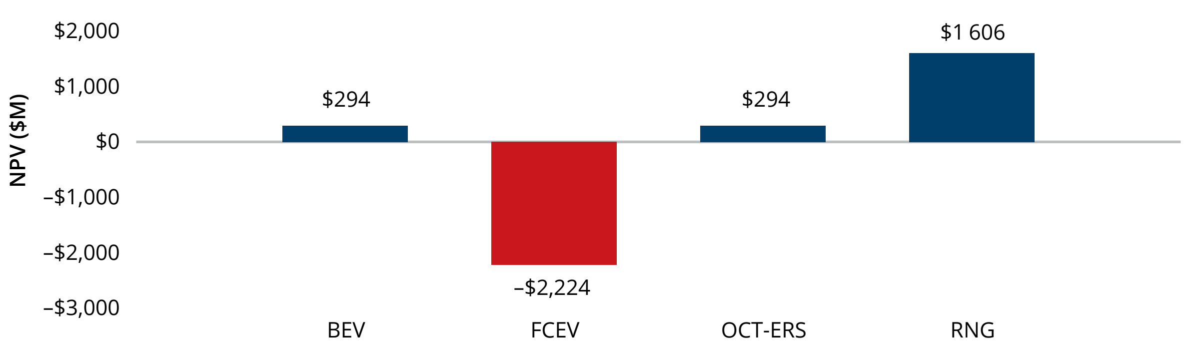
To contribute to the debate on net zero technologies for long haul trucking, a simulation of phased adoption pathways for four net zero technologies is carried out on the Autoroute 20 (A20) – Highway 401 (H401) corridor between Québec City and Windsor. 1) Battery electric, 2) green hydrogen fuel cell, 3) electric catenary and 4) renewable natural gas (RNG) are compared based on their vehicle costs (capital and operating) and infrastructure costs (e.g., charging and fueling stations), as well as mitigated GHG emissions. The comparison is made against a business-as-usual (BAU) scenario of continued operation of diesel trucks on the corridor.

Each technology was assessed under two perspectives: A) *Corridor perspective* – comparing a phased adoption path for all Class 8 long-haul trucks operating on the corridor transitioning to the respective net zero technology by 2050, and B) *Vehicle perspective* – assessing the total lifecycle costs of a single Class 8 long-haul truck over its typical 10-year life.[3] A sensitivity analysis was also included to account for uncertainty and variability in key modelling parameters (e.g., vehicle purchase prices, fuel and electricity prices and infrastructure cost) and to test the robustness of the economic results (e.g., net present value [NPV] and Economic Internal Rate of Return [EIRR]).

Corridor perspective

Overall, **RNG, battery electric and catenary trucks all have potential for negative GHG abatement costs**, meaning that cost savings can be achieved from implementing these technologies relative to diesel trucks. However, each technology faces high upfront costs for vehicles and infrastructure before operational cost savings in fuel, maintenance and mitigated GHG emissions (carbon prices) can materialize to offset the initial investment.

FIGURE 1. CORRIDOR PERSPECTIVE - SUMMARY NPV (2022 CA$ IN MILLIONS) COMPARISON BY TECHNOLOGY



Source: CPCS, 2023.

[1] Government of Canada, 2022. *Canadian Net-Zero Emissions Accountability Act*, web page accessed on August 1, 2023, www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050/canadian-net-zero-emissions-accountability-act.html

[2] Ibid

[3] Estimate from Ontario and Québec provincial trucking associations

On a strictly economic evaluation, RNG trucks tended to perform the best with the highest net present value (NPV) of $1,606 million and a benefit-cost ratio (BCR) of 2.4 under base assumptions. However, RNG trucks still have tailpipe emissions and face criticism of fugitive upstream emissions associated with the storage and transportation of RNG fuel. Furthermore, there is concern over widespread availability and supply limitations of sustainable RNG, particularly if demand continues to grow from the transportation sector and other competing sectors (e.g., buildings, maritime, aviation and industry).[4,5]

BEV trucks (in a tie with catenary trucks) showcase the second most favorable performance, achieving a BCR of 1.1 and positive NPV of $294 million. Substantial savings on fuel and maintenance costs over the life of the truck help offset the higher purchase price. However, operating range, commercial availability and charging time and infrastructure remain as barriers to scaling adoption. Charging times in the order of hours, compared to typical refueling times in minutes, and additional battery weight impacting truck payload capacity can introduce challenges and inefficiencies to operations.

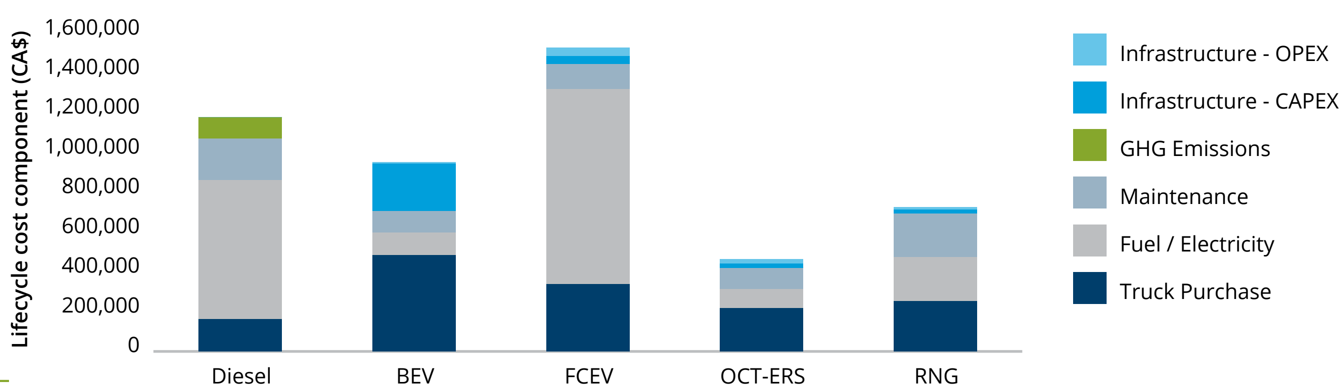
Catenary trucks also have a BCR of 1.1 and NPV of $294 million. Despite the high capital cost for the build-out of the overhead catenary infrastructure, this investment is recovered due to substantially lower operating costs. There are several successful pilot deployments of catenary trucks in Europe, and one in California under the Clean Transportation Program.[6] However, North America lags Europe in terms of experience with catenary infrastructure in road vehicle applications. The upfront capital cost of infrastructure and lack of trials could be a limiting factor for its advancement on Canada's busiest highway corridor.

Green hydrogen fuel cell trucks do not achieve a positive NPV or a BCR above 1. Hydrogen currently lags the pace of large-scale commercialization of other technologies, namely BEVs. The challenges include a lack of fueling infrastructure, the high cost of green hydrogen fuel and high purchase prices for new vehicles as there is limited availability in North America. All these factors currently result in poor economic rationale but is likely to improve as the technology and the supply of green hydrogen continues to develop.

Vehicle perspective

Results using the vehicle perspective show catenary trucks as the best option. This is driven by the longevity of catenary infrastructure. Figure 2 compares the total cost of ownership (TCO) of each technology for an individual truck over a typical 10-year lifecycle, including a proportioned infrastructure cost. RNG and BEV trucks come second in TCO, before diesel trucks. FCEV is the most expensive option at this time.

FIGURE 2. VEHICLE PERSPECTIVE - LIFECYCLE COST COMPARISON OF NET ZERO TECHNOLOGIES VERSUS DIESEL (10-YEAR LIFE)



[4] Énergir, 2023. *Nouveaux raccordements 100 % renouvelables*, Énergir-U, Document 1 dépoé à la Régie de l'énergie, Cause tarifaire 2023-2024, R-4213-2022, www.regie-energie.qc.ca/fr/participants/dossiers/R-4213-2022/doc/R-4213-2022-B-0279-DemAmend-Piece-2023_08_31.pdf

[5] Dagher, R., et al., 2023. *Biomass and carbon neutrality: putting in place an evaluation framework – Current State in Canada*, Institut énergie Trottier and Transition Accelerator, https://iet.polymtl.ca/en/biomass-and-carbon-neutrality/

[6] Impulitti, J., Lehmann, M., 2019. *Electric Truck Pantograph Retrofit Project*, Final project report of the Clean Transportation Program prepared for the California Energy Commission by the South Coast Air Quality Management District, November 2019 | CEC-600-2019-059, www.energy.ca.gov/sites/default/files/2021-05/CEC-600-2019-059.pdf

Source: CPCS, 2023.

Sensitivity analysis

A sensitivity analysis is included to address factors such as the level of technological maturity, assumptions on infrastructure requirements, energy price volatility, innovations and demand factors which may impact the future price of vehicles and infrastructure (see Figure 10). Overall, the sensitivity results are most favorable towards RNG, which has potential to achieve a BCR of 4.3 and NPV of $2.6 billion, should the price of RNG trucks decrease by 25%. Battery electric and catenary trucks also demonstrate robust economic viability. The BEV fleet scenarios are most sensitive to the discount rate, purchase price of BEV trucks and the diesel price. The catenary fleet scenarios are also sensitive to these parameters; however the highest sensitivity is demonstrated for the discount rate. Finally, hydrogen technology does not achieve a positive NPV or a BCR above 1. The most favorable scenario is with the price of green hydrogen decreased 50% from the price used in the base scenario.

Avoided GHG emissions and energy demand

The GHG emissions avoided by making the A20-H401 corridor net zero, given current demand projections for long-haul class 8 transport, are on the order of 2.8 Mt CO_2e/year by 2050. The total energy demand for the trucking fleet is estimated to be on the order of 4.2 PJ (RNG scenario), 261 million kg (green hydrogen scenario) and in the range of 3 to 4 TWh (catenary and BEV scenarios) (see Table 21). Further studies are needed to investigate impacts on energy demand.

Limitations

There are several limitations shared transparently in the report which could form the basis for extending this study into future work. This includes a more detailed analysis into the infrastructure needs and costs, a broader assessment of the freight network flows (e.g., roads connecting to the A20-H401 corridor), forecasting future prices of vehicles, fuels and electricity, and including other monetized benefits such as noise and air pollution. In addition, it must be recognized that each technology assessed can bring unique merits for decarbonizing different segments of the long-haul trucking market. As more data becomes available, vehicle and infrastructure specifications and costs continue to improve there is justification for revisiting analysis on long-haul trucking and expanding the scope of analysis to include other areas of interest which were noted as limitations in this study.

Table of contents

The mandate

As part of a research partnership, the Government of Québec has mandated the Chair in Energy Sector Management at HEC Montréal to carry out, in collaboration with CPCS, a two-year study comparing four technologies to decarbonize long-haul Class 8 trucks, with a focus on the Autoroute 20 and Highway 401 (A20-H401) corridor between Québec City and Windsor. This 1,300 km corridor is Canada's busiest for long-haul trucking as it serves major population centres throughout Ontario and Québec and into the US. The net zero propulsion types considered included battery electric, catenary electric (with battery), hydrogen fuel cell and renewable natural gas (RNG) trucks.

The scope of the project consisted of five steps:

Step 1: Identify in scope the vehicle technologies to assess
Step 2: Literature review of technical and economic parameters
Step 3: Validation of data through expert consultations
Step 4: Define operation parameters for simulation
Step 5: Cost and sensivtivity analysis scenarios.

To support the model development, close to 60 experts were gathered for an online workshop (Step 3: April 25-27, 2023) to validate the modelling approach and key parameters gathered from a literature review (steps 1 and 2) considered in the study. Highlights from the round tables have been summarized in a report titled ***Decarbonizing Long-Haul Trucking in Eastern Canada: Part 1 - Summary of a workshop held on April 25, 26 and 27, 2023***[7].

CPCS led the modeled simulations (Steps 4 and 5) examining the potential deployment of net zero trucking technologies at scale. The analysis was framed to address the following key questions:

1. What is the order of magnitude capital infrastructure investment requirements, fleet purchase, operating and maintenance costs?
2. How does the feasibility compare for the different technologies on the A20-H401 corridor?

The study is a first step towards an open approach. It aims to provide transparent data and assumptions on the technologies, with full references, to enable others to use and update the data, and the simulation model developed. Results can be used in future work, including a review of the technologies within a more systemic approach for decarbonizing long-haul freight (e.g., optimized freight logistics, intermodally and business models)[8] and to assess the impacts of different technological choices on overall electricity and energy demand for reaching GHG reduction targets based on different pathway scenarios (e.g., University of Windsor's Carbon Free Corridor Initiative from Montréal to Chicago; calibrating E3 model, such as North American Times Energy Model (NATEM), with the data from the simulation; data contribution to the Canadian Energy Modelling Hub's open platform).

[7] Whitmore, J., Pineau, P.-O., Roberts, N., 2023. https://energie.hec.ca/decabonizing-long-haul-trucking-in-eastern-canada

[8] Comité sur les changements climatiques, 2023. *Décarbonation du transport lourd de marchandises Construire une voie durable*, submitted to the Government of Québec, July 25 2023, https://cdn-contenu.quebec.ca/cdn-contenu/adm/org/comite-consultatif-changements-climatiques/avis/decarbonation-transport-lourd.pdf

Introduction

GHG emissions from long-haul road freight is one of the greatest challenges for reaching climate objectives given the complexity of the sector and the need for interoperability across North America. In Canada, heavy-duty trucks used for freight movements make up around 24% of the transportation sector's overall emissions. In both Québec and Ontario, the freight sector accounts for about 9% of total emissions. However, the challenge is compounded by the fast-growing emissions of heavy-duty trucks: 67% in Québec and 61% in Ontario between 1990 and 2019.[9] Achieving net zero goals by 2050 imposes decisive concerted action, considering that globalization and increased trade flows, accelerated by e-commerce, will continue to increase demand for goods – and consequently GHG emissions. As a result, there is an urgent need to review options to reverse these trends.

The deployment of net zero truck technologies requires long-term planning due to the infrastructure involved. The lack of transparent, rigorous interregional comparative studies of different net zero technologies for road freight transport in a key corridor in Québec and Ontario, and more broadly in the North American context, limits the effectiveness of government and private actions in this sector. To date, few studies have assessed the feasibility associated with the potential of decarbonization technologies in long-haul trucking in the context of Eastern Canada.

For this reason, the Chair in Energy Sector Management at HEC Montréal and CPCS carried out, in collaboration with the Government of Québec, a techno-economic study comparing the feasibility of Class 8 technologies (weighing more than 27,215 kg) to decarbonize long-haul trucking, with a focus on the Autoroute 20 and Highway 401 (A20-H401) corridor, linking Québec City, Montréal, and Toronto, up to the Windsor-Detroit border crossing[10]. The 1,300 km corridor has some of the busiest truck traffic in Eastern Canada (see Figure 3 and Box 1), which provides for a good starting point for delimiting the scope of the study.

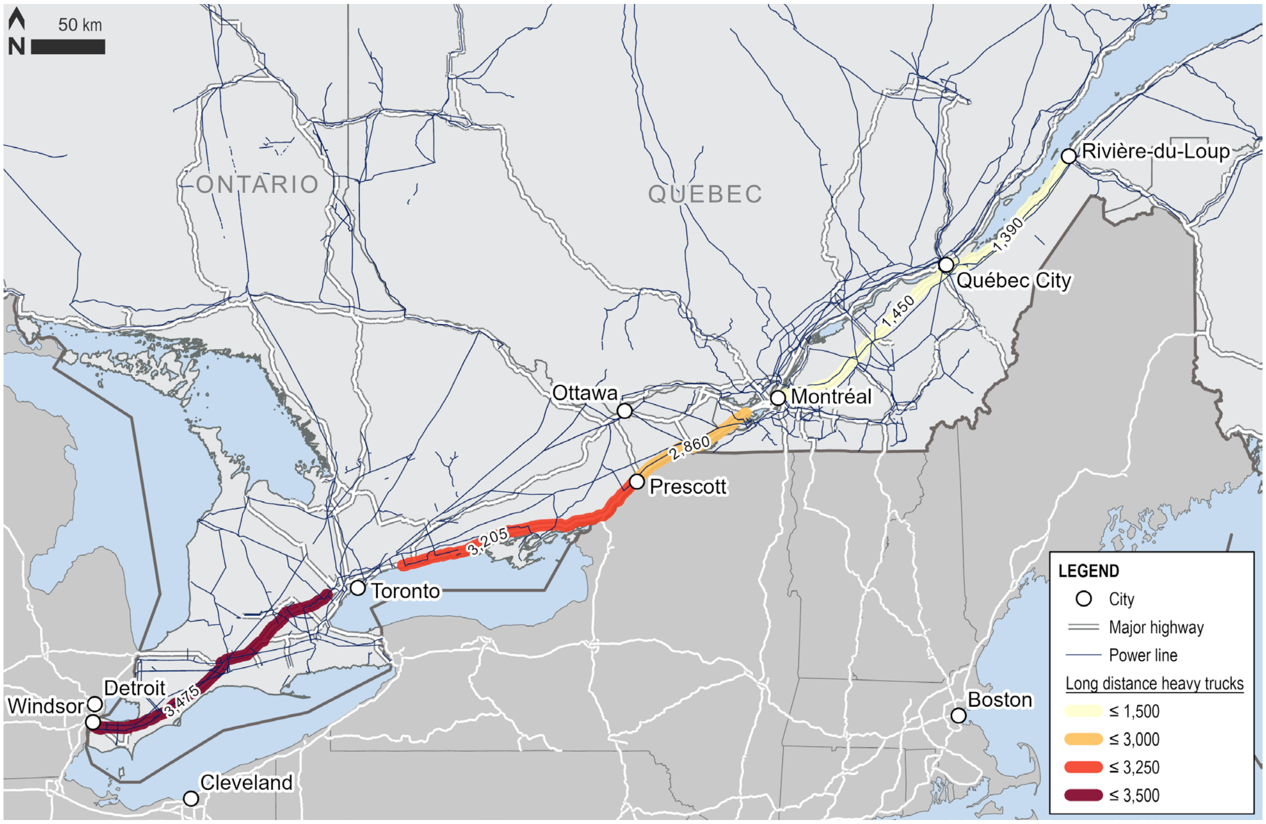
The study aims to contribute to filling data gaps and reducing some of the risks associated with technological and logistical choices by providing more complete information based on a review of the costs and associated technological issues. The study also aims to provide transparent data and assumptions on the technologies, with full references, to allow others to use and update the data, and the simulation model for further studies in the future.

The next section of the report provides an overview of the Federal, Québec and Ontario governments' approach for decarbonizing road freight, as well as a general overview of the four net zero technologies covered in the analysis. The following section presents the techno-economic parameters and methodological approach used for the cost analysis, including the scope and limitations of the study. Modelling results of the simulations and sensitivity analysis are summarized in the final sections.

[9] ECCC, 2023. *National Inventory Report 1990–2021: Greenhouse Gas Sources and Sinks in Canada*. Annex 12 - Provincial and Territorial Greenhouse Gas Emission Tables by Canadian Economic Sector, 1990–2021, Environment and Climate Change Canada.

[10] BTS, 2022. *Border Crossing/Entry Data*, US Department of Transportation – Bureau of Transportation Statistics, https://www.bts.gov/browse-statistical-products-and-data/border-crossing-data/border-crossingentry-data

FIGURE 3. LONG-DISTANCE HEAVY TRUCK VOLUMES (SINGLE DIRECTION) ON SEGMENTS OF THE A20-H401 CORRIDOR



Source: CPCS analysis based on data from the Ontario Ministry of Transportation (MTO) and the Ministère des Transports et de la mobilité durable du Québec (MTMDQ) through their open data portals.

BOX 1. STRATEGIC FEATURES ALONG THE A20-H401 CORRIDOR

- Connections to major air cargo hubs[11]:
  - Toronto Pearson Airport is Canada's largest air cargo hub, handling over 300,000 tonnes/year
  - Pierre Elliot Trudeau and Mirabel International Airports, handling over 160,000 tonnes/year
  - Hamilton International Airport is oriented towards domestic air cargo, handling 122,000 tonnes/year
- Connection to marine transportation hub:
  - Port of Montréal is Canada's second largest container port, handling 41 million tonnes/year, including 1.7 million twenty-foot equivalent units (TEUs) per year[12]
- Connections with intermodal facilities (including rail), warehousing and distribution centres which enable goods movement throughout many of Canada's major population areas
- Links Canada-US cross-border trade at the Windsor-Detroit border (Ambassador and Gordie Howe Bridges) with over 1.4 million truck crossings per year[13]

[11] Statistics Canada, 2020. *Table 23-10-0254-01 Air cargo traffic at Canadian airports, annual*

[12] CPCS analysis of data from Transportation in Canada, 2021. Table M17, preliminary figures.

[13] BTS, 2022. *Border Crossing/Entry Data*, US Department of Transportation – Bureau of Transportation Statistics, www.bts.gov/browse-statistical-products-and-data/border-crossing-data/border-crossingentry-data

Canadian approach for decarbonizing road freight

Reform of the trucking sector, both technologically and logistically, will be key for achieving net zero emissions by 2050.[14] Despite the urgency, few policies from the federal government have started to reverse the growing emission trends. In addition to the federal carbon tax, set to increase to $170/tonne by 2030, the government has relied on three key initiatives to attempt to curb road freight emissions. These include improving standards for heavy-duty trucks, subsidizing alternative truck technologies and fuels, and introducing a clean fuel standard with minimum levels of biofuels in diesel and gasoline.

Progress on developing standards for emissions and engines is complex for several reasons, notably the fact that Canada, with its relatively small market compared to the US, largely follows American standards. Progress is further slowed by the need to demonstrate new standards compatibility with Canada's winter conditions.[15] Finally, some provinces allow for higher axle weights, which enables heavy trucks to carry more payload in comparison to their American counterparts, further complicating cross border traffic and standardization of truck transportation.

Earlier support of alternative technologies mainly focused on natural gas trucks, due to their comparable range and refueling times. For natural gas engines, fuel is low cost and abundant, however trucks have an incremental purchase cost, and fueling infrastructure and services are still not widely available. Independent studies show that converting to natural gas would only reduce GHG emissions by around 3-10% on a well-to-wheel basis compared to diesel trucks.[16, 17]

Hydrogen has additional challenges on the supply-side. Currently, it is mainly obtained from steam reforming of natural gas, which releases CO_2 (grey hydrogen). The process can be made cleaner by capturing and storing these emissions (blue hydrogen), or by using renewable electricity to produce hydrogen from water by electrolysis (green hydrogen). However, carbon capture, utilization and storage (CCUS) technologies currently have limited success rates, and both blue and green hydrogen processes increase the production cost compared to hydrogen from natural gas.

There is now a sharpened focus on federal policy and programs to decarbonize the medium- and heavy-duty vehicle (MHDV) sector which follow advancements already being made for light-duty vehicles. In 2023, the federal government published an *Action Plan for Clean On-Road Transportation* which set a sales targets for 35% of total new MHDV sold by 2030 to be zero emissions and 100% by 2040 (for a subset of vehicle types based on feasibility).[18] The subsequent *Incentives for medium and heavy-duty zero-emission vehicles (iMHZEV) Program* sets out $547.4 million in federal funding over a 4-year period to help close the gap on the purchase price of ZEVs against traditional combustion engine vehicles.

The federal government published the *Clean Fuel Regulations* (CFR) to require liquid fuel suppliers to gradually reduce the carbon intensity of liquid fuels. This measure is expected to achieve a 15% emission reduction below 2016 levels in the carbon intensity of liquid fuels used in Canada by 2030.[19] To drive innovation at the lowest cost,

---

14 Government of Canada, 2022. *Canadian Net-Zero Emissions Accountability Act*, web page accessed on August 1, 2023, www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050/canadian-net-zero-emissions-accountability-act.html

15 Canada Senate, 2017. *Decarbonizing Transportation in Canada*, Report of the Standing Senate Committee on Energy, the Environment and Natural Resources, June 2017. Retrieved from https://sencanada.ca/content/sen/committee/421/ENEV/reports/TransportationReport_FINAL_e.pdf

16 Mottschall, M., Kasten, P., Rodriguez, F., 2020. *Decarbonization of on-road freight transport and the role of LNG from a German perspective*, ICCT and Okö-Institute, study was commissioned by the German Federal Environment Agency, https://theicct.org/sites/default/files/publications/LNG-in-trucks_May2020.pdf

17 O'Connell, A. et al., 2023. *A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels*, White Paper, https://theicct.org/wp-content/uploads/2023/02/lca-ghg-emissions-hdv-fuels-europe-feb23.pdf

18 Transport Canada, 2023. *Canada's Action Plan for Clean On-Road Transportation*, Government of Canada, https://tc.canada.ca/sites/default/files/2023-03/ROAD-04-ON_ROAD_ACTION_PLAN_REPORT_EN_V09.pdf

19 Government of Canada, 2021. *What is the clean fuel standard?*, web page accessed on August 1, 2023, www.canada.ca/en/environment-climate-change/services/managing-ollution/energy-production/fuel-regulations/clean-fuel-regulations/about.html

the CFR establishes a credit market. The government also announced it will invest $1.5 billion towards a *Clean Fuels Fund* to increase support for domestic production of low-carbon fuels and their adoption, such as hydrogen and biofuels.[20]

The federal government published a *Hydrogen Strategy for Canada*, in December 2020, to accelerate the development of "clean" hydrogen projects. The 2023 Budget introduced a *Clean Hydrogen Investment Tax Credit* based on carbon intensity tiers similar to the *US Inflation Reduction Act* to guide the level of support to clean hydrogen projects. The tax credit will be refundable and phased out after 2030. The lowest carbon intensity tier that meets all eligibility requirements is proposed to receive an investment tax credit of at least 40%.[21]

In May 2023, Canada and the US federal governments announced the first *Canada and United States Alternative Fuel Corridor*. The initiative aims to provide standardized electric vehicle (EV) charging infrastructure every 80 km between Kalamazoo, Michigan, and Québec City. At least one Direct Current (DC) fast charger with Combined Charging System (CCS) ports is to be installed at each location.

At the provincial level, Québec has two notable programs geared towards reducing GHG emissions from heavy trucks:

1. The $77.8 million *Écocamionnage* program which provides financial support for the purchase of battery electric, natural gas and hydrogen fuel cell trucks (up to $175,000 per truck), as well as demonstration projects[22], and

2. The *Transportez vert* program which has a $29.4 million budget to fund the installation of fast charging stations.

In 2022, the Québec government published a *Green Hydrogen and Bioenergy Strategy*[23] along with funding for developing both files. In Ontario, the government has yet to implement similar supportive measures to complement federal programs but has also published a *Low-Carbon Hydrogen Strategy*.[24]

Both federal and provincial initiatives are important, but not sufficient to place Canada on a clear path towards zero-emission road freight. The lack of coordination between and within governments on measures and data-sharing hinders the effectiveness of these actions. Implementing a comprehensive approach for improving cross-border coordination of collaborative pilot projects to evaluate on a common basis the performance of net zero Class 8 technologies, which promotes investment and risk sharing associated with the demonstration and deployment of new technologies, would improve government actions (see examples of partnership initiatives in Appendix 2).

---

[20] Government of Canada, 2022. *Clean Fuels Fund*, web page accessed on August 1, 2023, https://natural-resources.canada.ca/climate-change/canadas-green-future/clean-fuels-fund/23734

[21] Finance Canada, 2022. *Consultation on the Clean Hydrogen Investment Tax Credit*, Government of Canada, www.canada.ca/en/department-finance/programs/consultations/2022/consultation-on-the-investment-tax-credit-for-clean-hydrogen.html

[22] Lemieux, A., 2023. *Québec perspectives and initiatives on road freight transport decarbonization,* MEIE, Government of Québec, presentation on April 25, 2023, https://energie.hec.ca/wp-content/uploads/2023/04/4-LEMIEUX-MTMD_PPT.pdf

[23] Government of Québec, 2022. Québec Green Hydrogen and Bioenergy Strategy, www.quebec.ca/en/government/policies-orientations/strategy-green-hydrogen-bioenergy

[24] Government of Ontario, 2023. *Ontario's Low-Carbon Hydrogen Strategy*, www.ontario.ca/page/ontarios-low-carbon-hydrogen-strategy

Overview of net zero emission technologies

The simulations undertaken in this study examine the potential deployment of four technologies at scale to decarbonize Class 8 long-haul trucks that are compatible with net zero policy by 2050. Table 1 summarizes the key characteristics of each net zero emissions trucking technology considered in the scope of this study.

Cost analysis of the technologies will be compared to those of a diesel truck under a business-as-usual (BAU) reference. The four technologies can be considered net zero for the following reasons:

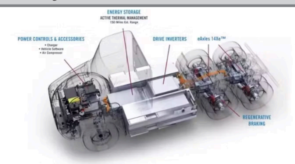
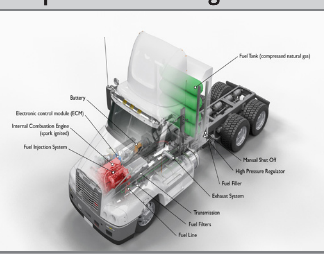
(1) **Battery electric (BEV)** trucks and (2) **Overhead conductive transmission (OCT) – electric road system (ERS) with battery pack for range extension** have no tailpipe emissions and can be considered fully net zero when the electricity supply is from a zero emissions source of energy (e.g., hydroelectric, nuclear, solar or wind).

(3) **Green hydrogen fuel cell electric (FCEV) trucks** only emit water vapour as a by-product of producing electricity from the fuel cell reaction in the engine. FCEVs can be considered a net zero technology when the hydrogen fuel supply is produced from non-fossil energy sources (green hydrogen).

(4) **Compressed renewable natural gas (RNG) trucks** have tailpipe emissions, however they can be considered a net zero technology if the upstream source of producing the gas is made from actual waste (as opposed to crops grown specifically for fuel, or diverted biomass that has other uses). RNG production and use even result in a net reduction in methane emissions.[25] Biofuel production facilities offer a carbon-neutral impact by recycling and repurposing gas which would have been emitted into the atmosphere, thereby netting out the effects of the GHG emissions.

[25] Cyrs, T., Feldmann, J., Gasper, R., 2020. *Renewable Natural Gas as a Climate Strategy: Guidance for State Policymakers*, Working Paper, World Resources Institute, https://doi.org/10.46830/wriwp.19.00006

TABLE 1. TECHNICAL FEATURES OF NET ZERO CLASS 8 TECHNOLOGIES

Net zero technology	Key features
Battery electric[26]	
	• Plug-in chargers are used to supply electrical energy, which is stored in battery packs on-board the vehicle. • Power control systems manage the discharge of batteries to provide electrical energy to the drivetrain (e.g., electric motor(s) and drive axles). Power controls also manage regenerative braking to recapture kinetic energy during braking, which is converted to electrical energy and stored in vehicle batteries to improve energy efficiency compared to diesel trucks.
Hydrogen fuel cell[27]	
	• A hydrogen fueling station supplies fuel, which is stored in pressurized tanks on-board the vehicle. • The propulsion system works as hydrogen is released into fuel cells via a chemical reaction to produce electricity, which is stored in a small battery pack and discharges to power the electrical drivetrain of the vehicle (e.g., electric motors, drive axles). • Efficiency of FCEV (about 31%) is marginally better than diesel trucks (21%)[28].
Catenary truck[29]	
	• Overhead catenary lines supply electricity directly to trucks equipped with deployable pantographs that engage and disengage automatically. • Outside the electrified road systems, trucks run on small a battery (compared to BEVs) to enable autonomy for re-routing or first/last-mile segments. • Catenary trucks with an on-board battery offer some of the most efficient use of energy (up to 76%) compared to diesel because of its direct use of electricity with through dynamic charging on-route which eliminates downtime associated with BEV charging. [30]
Compressed natural gas[31]	
	• A compressed natural gas fueling station supplies fuel, which is stored in pressurized tanks on-board the vehicle. • The vehicle's fuel system regulates the release of high pressure from the storage tanks, through fuel lines for injection into the natural gas engine. A spark ignition system is used to combust the natural gas and provide power to the drive train. • Methane slip (from the vehicle) is higher in natural gas trucks (3.6 to 6.3 g CO_2e/mile) than in diesel trucks (0.005 g CO_2e/mile).[32] More efficient engines can lower leakage, however, relative efficiency of natural gas 15L high performance direct injection (HPDI) engine remains about 5.5% lower than diesel.[33]

Technological challenges, maturity and availability

The time horizon for large-scale commercialization and deployment of net zero technologies is challenging to define. Many factors contribute to this. However, the difficulty to access information from manufacturers and fleet owners, limited truck supply and trials in Canada and a lack of refueling or recharging infrastructure are the most important reasons behind this challenge.[34]

[26] Bulk Transporter, 2020. *Peterbilt taking 579EV orders*, published on November 9, 2020, www.bulktransporter.com/equipment/article/21147170/peterbilt-taking-579ev-orders

[27] OEM, 2020. *Freudenberg Developing Fuel Cells for Heavy-Duty Trucks*, published on September 9, 2020, www.oemoffhighway.com/electronics/power-systems/press-release/21174522/freudenbergnok-freudenberg-developing-fuel-cells-for-heavyduty-trucks

[28] Siemens, 2017. *Climate Friendly Road Freight Factsheet – What's the best strategy for climate-friendly road freight transportation ?,* PDF, https://assets.new.siemens.com/siemens/assets/api/uuid:760942b4-5661-43c1-b9f8-079741d12e6e/smo-factsheet-road-freight-transport-ehighway.pdf

[29] Electrical Review, 2020. Think tank proposes railway-style catenary lines to power electric trucks, published on July 29, 2020, https://electricalreview.co.uk/2020/07/29/think-tank-proposes-railway-style-catenary-lines-to-power-electric-trucks/

[30] Impulitti, J., Lehmann, M., 2019. *Electric Truck Pantograph Retrofit Project*, Final project report of the Clean Transportation Program prepared for the California Energy Commission by the South Coast Air Quality Management District, November 2019 | CEC-600-2019-059, p.51, www.energy.ca.gov/sites/default/files/2021-05/CEC-600-2019-059.pdf

[31] Alternative Fuels Data Center, 2023. *How Do Compressed Natural Gas Class 8 Trucks Work?,* US Department of Energy – Energy Efficiency & Renewable Energy, web page accessed on August 1, 2023, https://afdc.energy.gov/vehicles/how-do-natural-gas-class-8-trucks-work

[32] Dominguez-Faus, R., 2017. *Climate, Energy Transition and the Use of Natural Gas in Freight Transportation: Pros and Cons*, Chair in Energy Sector Management webinar Series", https://energie.hec.ca/wp-content/uploads/2017/04/Dominguezfaus_HECMontreal_NGT_Final.pdf

[33] Dominguez-Faus, R., 2015. *The Carbon Intensity of NGV C8 Trucks*, UC Davis Institute of Transportation Studies, https://steps.ucdavis.edu/wp-content/uploads/2017/05/Dominguezfaus-The-Carbon-Intensity-of-NGVS.pdf

[34] Whitmore, J. Pineau, P.-O., Roberts, N., 2023.

In Canada, the implementation of decarbonization efforts in commercial trucking is still at an early stage. Early adopters are typically well-financed, large fleet owners with access to capital.[35] Currently, it is unclear which technology - or technologies - will emerge in the market as the preferred option.

Reliability and cost are key factors when deciding whether to adopt a new technology. Net zero trucks with simpler components, which are easier to maintain, are also favoured. The trucking sector is hesitant to adopt a new technology without a viable business case or regulatory policies to push adoption. The wait-and-see attitude of the industry leads to a "race to second place"– a trend to be the second to adopt a new technology to reduce risk and learn from the early adopters (see examples in Appendix 3).

Early movers in the US market are likely to influence the technology direction in Canada as large purchase orders from private fleet operators, such as Amazon and Walmart, enable vehicle production to scale up by providing more certainty to truck manufacturers.

Every technological option has its strengths and limits. However, to achieve net zero goals by 2050 it is not enough for a technology to be available, it must also be scalable. Defining the most effective solution for a particular fleet depends on multiple factors, including operational range and duty-cycle, market readiness, scalability and resource efficiency, resilience and capabilities of the supply chains and infrastructure, flexibility, capital and operating costs, and end user values, goals and training.

Energy efficiency, often referred to as the "first fuel", will also be important to factor in the decision-making process given the competition of uses for alternative fuels and electricity in other sectors (e.g., industry, maritime, aviation, building, passenger transportation). Each net zero technology will have different efficiencies that can impact the overall energy demand associated with alternative fuel and electricity use (see Figure 4). [36]

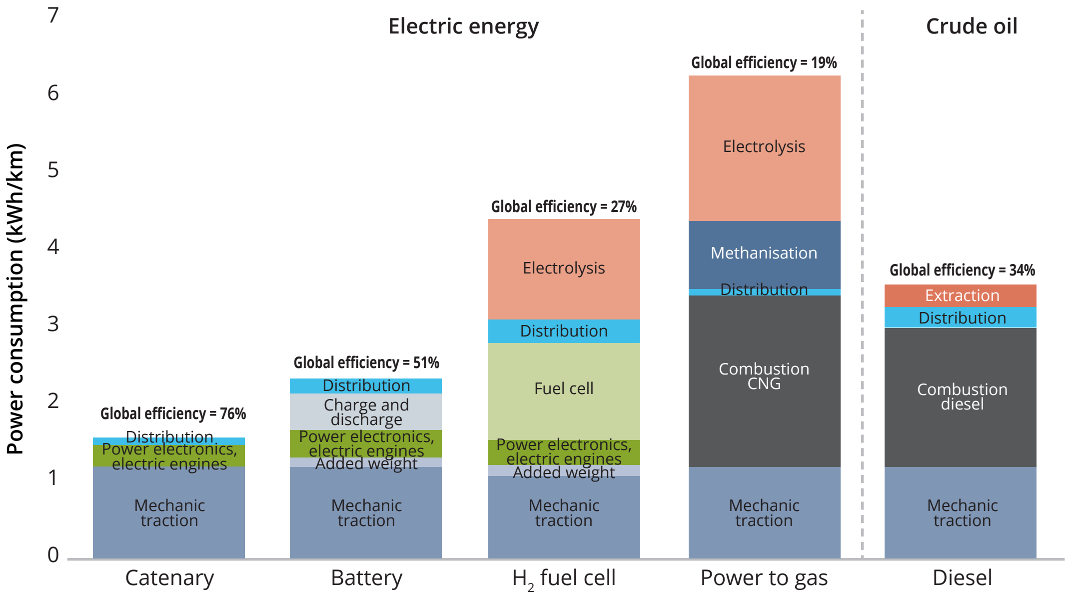
Cold winter condition also implies higher energy consumptions due to higher resistance and cab heating. However, impacts can be managed when planned into logistic operations. Trucks can also face load limitations to reduce road deterioration. Differences in load limits between jurisdictions can impact load factor optimization and net zero technology deployment.

Below are factors that can impact the maturity level and viability of the different net zero technologies considered in this study.

[35] Pembina Institute, 2022. *Virtual workshop to inform an MHDV strategy*, www.pembina.org/event/toronto-person-workshop-inform-mhdv-strategy

[36] Impulitti, J., Lehmann, M., 2019. *Electric Truck Pantograph Retrofit Project*, Final project report of the Clean Transportation Program prepared for the California Energy Commission by the South Coast Air Quality Management District, November 2019 | CEC-600-2019-059, www.energy.ca.gov/sites/default/files/2021-05/CEC-600-2019-059.pdf

FIGURE 4. COMPARISON OF THE WELL-TO-WHEEL EFFICIENCIES OF VARIOUS TRUCK PROPULSION SYSTEMS



Source: Figure 36 in Impulitti and Lehmann, 2019 [p.51]. (Original chart by Siemens AG Deutschland).

Compressed renewable natural gas trucks

Compressed natural gas use in trucking fleets is a relatively mature technology with early adopters such as Groupe Robert having experience operating such trucks on routes between Québec City and Toronto, over the past decade. In this respect, there would not be a significant adoption curve to switch to RNG as a net-zero fuel if the fuel is produced from sustainable sources and made more widely available. Methane slip from the vehicle is higher in natural gas trucks than in diesel trucks.[37] A new 15L engine from Cummins can lower leakage and address criticism of lower horsepower of older model natural gas trucks.[38] However, it is estimated that relative efficiency of natural gas HPDI engine remains about 5.5% lower than diesel.[39]

There are 281 RNG production sites in North America, with 180 under construction and 296 being planned. RNG supply produced sustainably (e.g., made from waste and not diverting biomass from other uses) is limited[40] compared to conventional gas but will increase with new production sites as they become operational. The government of Québec has set a minimum requirement of 10% of the province's gas distribution by 2030. In 2023, RNG represented around 2% of Québec's gas network. The largest production sites are from industrial landfills. However, over 85% of RNG produced in Québec is exported to the US due to more favorable market conditions.[41]

The supply infrastructure between Québec and Windsor counts 13 public access CNG stations with a maximum distance between stations of 250 km. Currently, six of those stations advertise a RNG offering.[42] Potentially all

[37] Dominguez-Faus, R., 2017. *Climate, Energy Transition and the Use of Natural Gas in Freight Transportation: Pros and Cons*, Chair in Energy Sector Management webinar Series", https://energie.hec.ca/wp-content/uploads/2017/04/Dominguezfaus_HECMontreal_NGT_Final.pdf

[38] Cummins has already delivered one 15L CNG truck to Groupe Robert and will being testing the vehicle in 2023, according to Groupe Robert communication on LinkedIn, www.linkedin.com/feed/update/urn:li:activity:7082370275798872066/

[39] Dominguez-Faus, R., "The Carbon Intensity of NGV C8 Trucks, UC Davis Institute of Transportation Studies" (2015) https://steps.ucdavis.edu/wp-content/uploads/2017/05/Dominguezfaus-The-Carbon-Intensity-of-NGVS.pdf

[40] Dagher, R., et al., 2023. *Biomass and carbon neutrality: putting in place an evaluation framework – Current State in Canada*, Institut énergie Trottier and Transition Accelerator, https://iet.polymtl.ca/en/biomass-and-carbon-neutrality/

[41] Whitmore, J., Pineau, P.-O., 2023. *État de l'énergie au Québec 2023*, Chair in Energy Sector Management, HEC Montréal, prepared for the Government of Québec, https://energie.hec.ca/eeq/

[42] NRCan, 2023. *Electric Charging and Alternative Fuelling Stations Locator, Government of Canada*, web page accessed on August 4, 2023, https://natural-resources.canada.ca/energy-efficiency/transportation-alternative-fuels/electric-charging-alternative-fuelling-stationslocator-map/20487#/analyze?fuel=CNG&cng_vehicle_class=HD&show_map=true&cng_psis=3600&country=CA&cng_fill_type=Q&cng_has_rng=true

could offer the purchase of RNG if supported by a demand from their truck fleet customers or a government requirement for station to offer RNG at natural gas stations.

Overhead catenary electric trucks

Catenary electric trucks have not yet been tested on Canadian highways. However, the technology is relatively mature in other transport applications (e.g., streetcars, light-rail transit and electrified regional passenger rail). There are several small-scale pilot deployments of catenary trucks in Europe, and one in California under the Clean Transportation Program.[43] In Sweden, Siemens and Scania partnered on a 2 km e-Highway north of Stockholm, to test diesel-hybrid electric catenary trucks.[44] Germany is testing catenary technology on a 10 km segment of the A5 Autobahn near Frankfurt with diesel-hybrid Scania trucks[45] and in the UK, the Department for Transport (DfT) is considering a 20 km stretch of road near Scunthorpe for a possible trial of electric road systems.[46] The technology offers the advantage of reducing battery size, weight, cost and recharging time compared to BEVs. It is more energy efficient than alternative propulsions as it requires less energy per km and avoids energy losses in the charging cycle of the battery.

Some design features of catenary infrastructure, widely used for rail, require adaptation for long-haul road transportation applications. Rail applications benefit from a fixed guideway, while trucks can move more freely (e.g., switch lanes) and depend on the operator for maintaining the position of the truck underneath the overhead contact wires. This can increase the risk of damage and wear on the catenary. To mitigate these risks, geofencing systems are used to track the position of the truck and ensure the pantograph is only raised when the truck is positioned underneath the contact wires. Trucks are also equipped with lane-keeping assistance to aid the driver in maintaining the lateral position of the truck underneath the catenary. Pantographs are also equipped with different types of sensors (e.g., position and voltage) to measure its contact behaviour and position relative to overhead wires. For example, if contact forces are outside a specified range or the pantograph's carbon stripes are worn below a certain level of acceptance, the system will detect this wear and the pantograph will automatically retract.

Overhead lines also run at higher voltage (around 600 V) to minimize energy losses over long distances, which raises safety concerns with lines running above public highways. To address this issue, wire break detection and an automatic earthing system (AES) technology can be implemented to prevent accidental high voltage exposure. In Germany, emergency services are trained to respond to incidents in the vicinity of catenary systems in a manner similar to incidents with light-rail transit (LRT), trolley buses and other electrified transportation systems. In general, the safety aspects and mitigations concerning catenary systems are well understood and addressed.[47]

Ice on catenary wires can lead to arcing (jump of electricity between pantograph and catenary), but de-icing measures are considered mature given the technology has over a century of use and experience in cold climates.

Battery electric trucks

Battery electric trucks are gaining traction by emerging as viable alternatives for short-haul trips with return-to-base operations (e.g., drayage and first/last mile service). For long-haul transportation, the battery weight will be a limiting factor, since it reduces the load capacity. Charging time (max 350kW) is longer than alternative

---

43 Impulitti, J., Lehmann, M., 2019. *Electric Truck Pantograph Retrofit Project*, Final project report of the Clean Transportation Program prepared for the California Energy Commission by the South Coast Air Quality Management District, November 2019 | CEC-600-2019-059, www.energy.ca.gov/sites/default/files/2021-05/CEC-600-2019-059.pdf

44 Siemens, 2016. *World's first eHighway opens in Sweden,* Press release, published on June 22, 2016, https://press.siemens.com/global/en/pressrelease/worlds-first-ehighway-opens-sweden#:~:text=For%20the%20next%20two%20years%2C%20a%20Siemens%20catenary,with%20Siemens%2C%20to%20operate%20under%20the%20catenary%20system

45 Kane, M., 2020. *Germany: A5 Autobahn Gets Catenary Overhead Lines For xEV Trucks*, InsideEVs, published on August 22, 2020, https://insideevs.com/news/440388/germany-a5-autobahn-catenary-overhead-lines-trucks/

46 Commercial Fleet, 2021. *UK 'electric road' study part of £20m electric truck trials*, published on July 27, 2023, www.commercialfleet.org/news/truck-news/2021/07/27/uk-road-to-be-electrified-in-20m-electric-truck-trials

47 Siemens, 2023. Personal email communication, July 10, 2023

propulsions, and the autonomy is less than 500 km. Transportation and logistics (T&L) companies and private fleets are both moving in this direction. Manufacturers such as Tesla, Freightliner and Peterbilt are all working to improve the operating range and charging time.

Fleet-operated charges represent a high cost but offer better BEV operation management opportunities for charging. Start-ups, pilot projects and shared station hubs are also being deployed. However, for BEV to be used in long-haul transportation, public access charging stations will need to be deployed and strategically located where trucking activities crossover with charging activities to ensure supply can meet the demand.[48] For Megawatt Charging Systems (MCS)[49], trucks will need to handle higher voltages (1,500 V) and currents than currently available. Cross-border standards for such charging infrastructure will be required. The recently announced *Canada and United States Alternative Fuel Corridor*, which aims to install EV charging infrastructure at every 80 km, may accelerate opportunities for electrification of Class 8 trucks.

Technological challenges in the context of cold climates are viewed as manageable (at temperatures above -20°C) when planned into logistic operations. However, very cold winter conditions can imply higher energy consumption (about 20%) due to higher air resistance and cab heating. Issues can be managed if the vehicle is plugged into charger at the depot to maintain battery temperature in advance of operating.

Compared to diesel trucks, there are BEV parameters that have already reached parity (e.g., safety, remote diagnostics), while most are expected to be reached by 2025-2030. Initial cost, refueling/recharging time and overall maturity are on a longer horizon. Multiple fleet owners, such as Loblaws and Kruger Energy, have already tested models in Québec and have placed deposits for additional trucks (see Appendix 3).

In August 2023, the federal government announced it will invest $1.5 million to establish a "zero-emission trucking testbed" in the Montreal area. The project, launched with FPInnovations, represents the largest of the investments to support work in medium- and heavy-duty on-road applications under the Zero-Emission Trucking Program. It will focus on collecting performance data in real-world conditions of at least five battery-electric vehicles operated by a minimum of three fleets between March 2024 and March 2025. The project will "instrument and monitor" how battery-electric Class 8 trucks perform in real-world settings compare to diesel-powered trucks performing similar work on the same routes. The final report will be delivered by March 2025.[50]

Green hydrogen fuel cell trucks

Hydrogen fuel cell trucks offer the advantage of a greater operating range in comparison to BEVs. However, adoption is still in an early stage with limited vehicle and green hydrogen fuel supply availability. There is only one public access station offering hydrogen along the A20-H401 corridor located in Québec City. A non-retail station available to only a certain subset of customers is in Mississauga, Ontario.[51]

The technology for producing green hydrogen exists, however it accounts for only a very small part of global hydrogen production (less than 1 %, with the rest mainly produced from fossil fuels). The cost of production varies significantly depending on the production process, and its distribution is a challenge due to its low energy density per volume. It is very light compared to other fuels. Like natural gas, hydrogen can be compressed or liquefied to increase its volumetric energy density, but even when liquefied its density (8.74 MJ per liter) is about four times less that of diesel and half that of liquefied natural gas. To liquefy hydrogen, its temperature must

---

48 Dimatulac, T., et al, 2023. *Modeling the Grid Impact of Long Haul Electric Vehicles (LHEVs) in Ontario*, Carbon Free Corridor, University of Windsor, presentation on April 25, 2023, https://energie.hec.ca/wp-content/uploads/2023/04/12-VANI-UW_PPT.pdf

49 Kane, M., 2022. *CharIN Launches Megawatt Charging System (MCS) In North America*, InsideEVs, published on October 19, 2022, https://insideevs.com/news/617089/charin-megawatt-charging-system-north-america/

50 Smith, J., 2023. $3 million invested in zero-emission trucking projects including new testbed, *Truck News*, published on August 31, 2023, HYPERLINK «http://www.trucknews.com/sustainability/3-million-invested-in-zero-emission-trucking-projects-including-new-testbed/1003177774/»www.trucknews.com/sustainability/3-million-invested-in-zero-emission-trucking-projects-including-new-testbed/1003177774/

51 RNCan, 2023. *Electric Charging and Alternative Fuelling Stations Locator*, we page accessed August 45, 2023.

be lowered to -253°C, which requires more energy and additional costs than natural gas, which liquefies at temperatures of -162°C.[52]

Hydrogen's contribution to decarbonizing long-haul trucking will depend on the innovations and the trade-offs that will be made between overall energy efficiency, costs and the logistical trade-offs involved in recharging vehicles. The Alberta Zero Emissions Truck Electrification Collaboration (AZETEC) program in Alberta is Canada's only pilot of long distance zero emission trucks to date. However, there are notable pilots elsewhere in North America. California is making strides in this direction with several larger scale pilot demonstrations. Currently, only select prototype and proof-of-concept FCEVs are available and there is yet to be large scale commercialization in North America.

There have been several advancements in the infrastructure required to supply the fuel or electricity to the net zero technologies noted above, as well as small scale pilot deployments in commercial trucking fleets. Early adopters have mostly deployed hydrogen trucks on short-haul routes.

[52] Whitmore, J., Pineau, P.-O., 2023. *État de l'énergie au Québec 2023*, Chair in Energy Sector Management. HEC Montréal.

Model and Methodology

Modelling approach

Our model allows the simulation of the net-zero technologies on the A20-H401 corridor, in its widest possible extent from Rivière-du-Loup in the province of Québec up to Windsor at the Ontario/US border. It is based on a cost-benefit model in Excel and relies on real truck flow data extracted from a Geographical Information System (GIS). The modelling methodology builds on a previous analysis of diesel-hybrid catenary technology for Class 8 trucks on same corridor carried out by CPCS and HEC Montréal.[53]

The entire extent of the route under study has been divided into eight segments, as illustrated in Table 2 below (see also Figure 3).

TABLE 2. HIGHWAY SEGMENTS OF THE A20-H401 CORRIDOR USED IN THE SIMULATION

Highway segment	Length (km)
1. Windsor – Toronto	321
2. Toronto (city area)	97
3. Toronto – Prescott	288
4. Prescott – Montréal	146
5. Montréal (city area)	72
6. Montréal – Québec City	215
8. Québec City (city area)	38
9. Québec City – Rivière-du-Loup	167

Source: Distances from Google Maps

The simulator calculates, for each year over a 30-year horizon, the costs of each net zero technology as compared with a BAU baseline where the fleet would remain entirely diesel-based. The simulation considers in particular:

- Capital and operating expenditure (CAPEX and OPEX) for net zero Class 8 trucks,
- Fuel cost savings, as compared with diesel trucks,
- Maintenance cost savings, as compared with diesel trucks,
- Capital and operating expenditure (CAPEX and OPEX) for supporting charging and refueling infrastructure,
- Avoided GHG emissions (priced according to the federal carbon pricing scheme), as compared with diesel trucks.

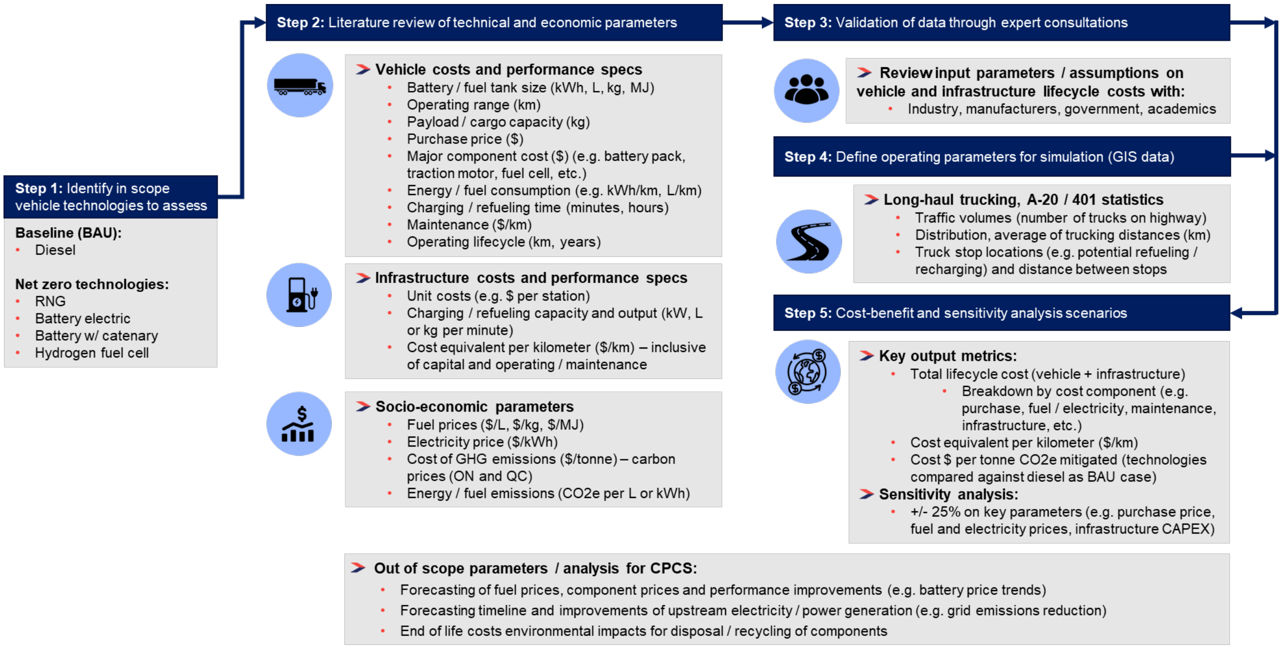
Net zero Class 8 technologies are analyzed under two scenarios:

1. **Business-as-usual scenario** where all trucks remain as diesel until 2050,
2. **Net zero transition scenario** where all trucks transition to an entirely homogenous net zero fleet by 2050, following the fleet adoption scenarios and assumed infrastructure phasing detailed in the *Data and Assumptions* section below. Separate scenarios are run for the adoption of each of the following technologies: (1) BEV; (2) FCEV; (3) OCT-ERS; (4) RNG.

[53] Kayser-Bril, C., Ba, R., Whitmore, J., Kinjarapu, A, 2021. *Decarbonization of long-haul trucking in Eastern Canada – Simulation of the e-Highway technology on the A20-H401 highway corridor*, CPCS and Chair in Energy Sector Management, HEC Montréal.

Figure 5 provides an overview of the modelling approach, parameters considered and out-of-scope items. Limitations are described in a separate section below.

FIGURE 5. SUMMARY OF MODELLING APPROACH



Source: CPCS, 2023.

Scope and limits of the analysis

The following items are <u>not in the scope</u> of modelling analysis but are important for a systemic view and could be included in future studies.

1. **Analysis on additional routes (roads / highways) connecting to the A20-H401 corridor.** The scope of this study focuses exclusively on the A20-H401. Further analysis could include expanding the scope beyond the corridor to better understand a more system-wide perspective on long-haul trucking origin-destination pairings throughout Ontario, Québec and cross-border into the US. This would offer the opportunity for further analysis on how energy infrastructure could be established in Canada and the US to support net zero long-haul trucking (e.g., origin-destination pairings and opportunities for where to best locate charging or fueling infrastructure, including outside of the corridor, to support the operation of long-haul trucking routes).

2. **Impact of vehicle weight on road maintenance.** BEVs are generally heavier than comparable combustion engine vehicles. The operation of heavier BEV trucks will have a direct impact on the cost of road maintenance, which increases by a power of four (x^4) as a function of vehicle weight.[54] As an extension of this study, the cost impact of BEVs on road maintenance could be investigated further and modeled into the analysis.

3. **Additional mitigation benefits of air pollutants.** The scope of this study is on quantifying the benefits of mitigating carbon dioxide and equivalent GHG emissions (CO_2e). Further analysis could explore the benefits of mitigating air pollutants such as particulate matter (PM), nitrogen oxides (NOx) and others, linking air quality to respiratory health.

[54] The fourth power law was derived from the American Association of State Highway Officials between 1958 and 1961 (Highway Research Board 1962).

4. **End-of-life costs and considerations.** This study does not explore the options, feasibility and associated costs for the end-of-life of vehicles and infrastructure (e.g., disposal or recycling of lithium-ion batteries). There are several technologies emerging which target end-of-life considerations for new zero emission technologies, however data on costs and feasibility demonstrations are currently limited.

5. **Availability of renewable energy supply.** This study builds the analysis on the presumption that there could be sufficient RNG, green hydrogen and renewable electricity to supply the energy demands for all Class 8 long-haul trucks operating on the corridor. Further analysis could consider a more in-depth look at constraints on energy production and supply (e.g., is there enough renewable energy supply? Or how would the energy demand for long-haul trucking compete against demands within the transportation sector, such as aviation and marine, and with other sectors?).[55]

6. **Forecasting of energy prices.** This study uses present day energy prices and leverages a sensitivity analysis on key parameters in the analysis (including energy prices) to examine how price changes may impact the overall economic viability of the different technologies. An alternative approach would be to construct a detailed forecast of energy prices. However, energy prices are volatile and thereby challenging to develop accurate long-term forecasts.

7. **Forecasting of component prices and performance improvements.** This study uses present day costs for vehicles and infrastructure and follows the same approach of a sensitivity analysis (as noted above for energy prices) to assess the impact of future component price changes or performance improvements (e.g., a decline in battery pack or fuel cell prices) on the results and overall economic viability of the different technologies. An alternative approach would be to develop a detailed long-term forecast of component prices. However, given the early stage of technological maturity and range of current prices available (e.g., BEV trucks with an 800 km (500 mile) range costing between $350,000 to $622,000)[56] there is not a strong base year on which to establish a detailed long-term forecast.

8. **Detailed analysis of infrastructure types and costs.** This study includes a high-level assessment of infrastructure costs, based on scaling reference cost estimates according to the total energy demand. There is a wide range of cost estimates for certain infrastructure due to a variation in technology. For example, hydrogen fuel stations may be constructed to produce hydrogen on-site via electrolysis with a renewable energy supply or receive the "green" hydrogen from an off-site supply (e.g., delivered to the fueling station by truck in a compressed gaseous tube trailer or liquified hydrogen fueling trailer, or supplied by pipeline).

   As hydrogen fueling infrastructure in Canada is still at an early stage it is not clear which could be the predominant mode of supplying "green" hydrogen along the A20-H401 corridor. Furthermore, there may be a mix of different fueling station types along the corridor (yet to be determined) which would influence the cost estimate. Currently there is one public hydrogen fueling station installed near Québec City and none in Ontario.[57]

9. **Costs and GHG emissions associated with upstream energy.** This study does not consider the cost of upstream transmission and distribution (T&D) infrastructure which will be needed to transfer the energy from the point of production/generation to the site of refueling or charging. This includes any pipeline distribution network for hydrogen and/or RNG as well as any electrical grid T&D upgrades to feed service to fast charging stations or overhead catenary lines. The benefits

[55] Dagher, R., et al., 2023. *Biomass and carbon neutrality: putting in place an evaluation framework – Current State in Canada*, Institut énergie Trottier and Transition Accelerator, https://iet.polymtl.ca/en/biomass-and-carbon-neutrality/

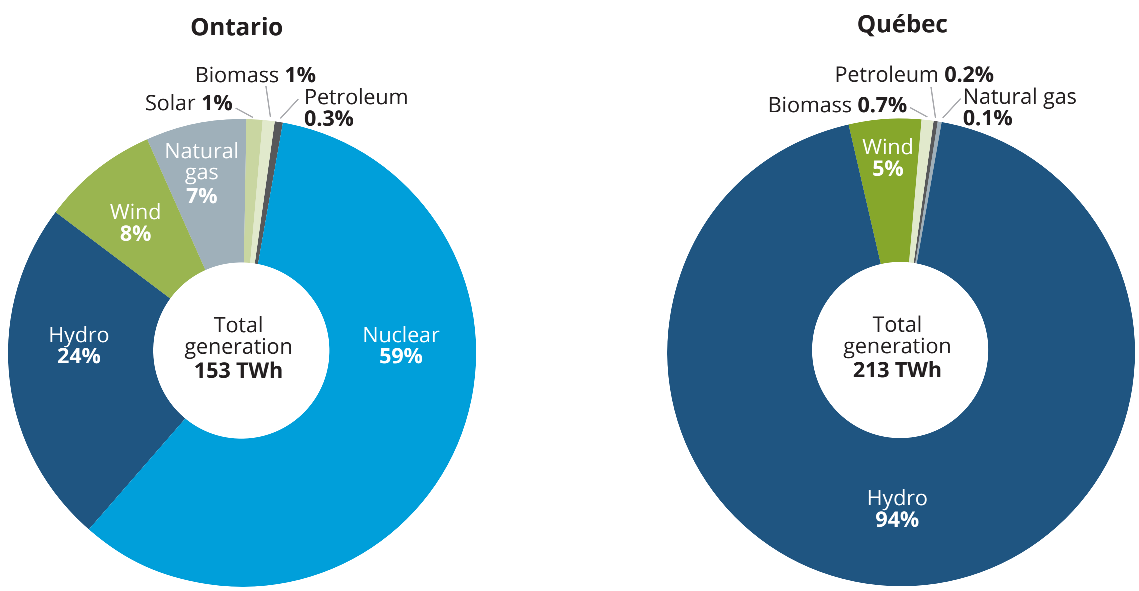
[56] ICCT, 2022. *A meta-study on the purchase costs for zero-emission trucks*, https://theicct.org/publication/purchase-cost-ze-trucks-feb22/#:~:text=This%20study%20reviews%20recent%20literature%20on%20current%20and,range%20as%20a%20function%20of%20total%20battery%20capacity.

[57] Natural Resources Canada, 2022. *Electric charging and alternative fuelling stations locator*, https://natural-resources.canada.ca/energy-efficiency/transportation-alternative-fuels/electric-charging-alternative-fuelling-stationslocator-map/20487#/find/nearest?fuel=HY

of enhancements to upstream T&D infrastructure will likely extend to multiple stakeholders (not only trucking fleet operators). Therefore, it can be challenging to A) cost this infrastructure and B) accurately attribute a portion of its cost to the scope of this analysis. The scope of this analysis is limited to the infrastructure at the point of charging / refueling, which will be built directly for the benefit of the trucking fleet.

10. **Decarbonization path of electricity power generation.** Furthermore, this study does not forecast the decarbonization path of the overall electricity generation mix in Ontario and Québec. However, Ontario and Québec's electricity generation is largely non-emitting (see Figure 6).[58]

FIGURE 6. ELECTRICITY GENERATION PROFILES IN ONTARIO AND QUÉBEC



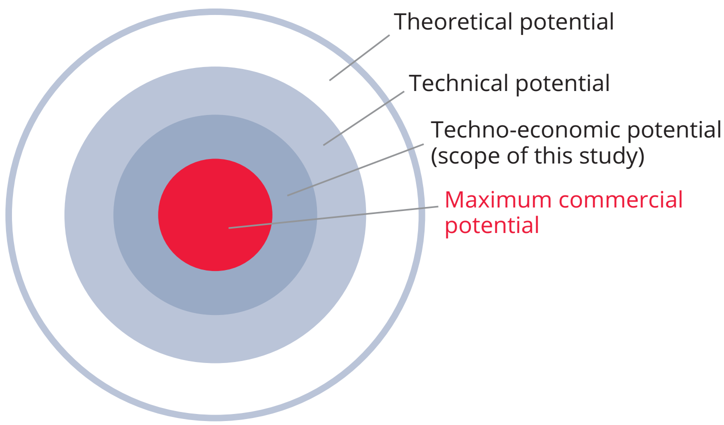
Source: Canada Energy Regulator, 2021.

11. **Other upstream factors in the energy supply chain.** This study does not assess additional elements of the energy supply chain, which could be important in providing a more holistic perspective on sustainability of the various net zero technologies. This includes the supply chain of critical minerals for electric vehicle batteries, land use for renewable electricity generation (e.g., solar and wind farms) and the production of biofuels.

12. **Maximum commercial potential.** The analysis only assesses the techno-economic potential which is the portion of the technical potential for which net zero technology operating and infrastructure costs make it economically viable for operators under current pricing conditions, before taking into consideration any adoption, energy supply or market barriers (See Figure 6-1). Further studies will need to analyze the "maximum commercial potential" which accounts for additional market factors including forecasted net zero fuel prices and supply availability, competition for the end use of net zero fuels and clean electricity, the degree of government intervention, and future carbon prices.

[58] Canada Energy Regulator, 2021. *Provincial and Territorial Energy Profiles*, https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-ontario.html

FIGURE 6-1. SCOPE OF ASSESSSMENT OF THE NET ZERO TRUCK TECHNOLOGIES



Source: Figure based on J. Harvey and Associates Environmental Consulting, 2017

Data sources and assumptions

CPCS and the Chair collaborated on an extensive literature review to consolidate modelling parameters and conducted a validation exercise of the parameters through interactive workshops held on April 25-27, 2023 with experts from industry, government and academia.[59] The following section presents an overview of data sources and assumptions used in the simulations.

Truck traffic

The simulation is based on the flows of Class 8 heavy trucks active on long-distance trips on the A20-H401 corridor. Specific and up-to-date information is not directly available from existing data sources, therefore we developed a methodology to arrive at an accurate estimate, as detailed in the next paragraphs.

Our analysis considers a sub-segment of Class 8 trucks which are running long-haul on the Québec-Windsor corridor. This is an important distinction, especially in the immediate city areas surrounding Toronto, Montréal and Québec City, as in these centres there are many Class 8 trucks running short-haul trips.

The truck traffic information was obtained from the Ontario Ministry of Transportation (MTO), and the Ministère des Transports et de la mobilité durable du Québec (MTMDQ) through their open data portals. Both MTO and MTMDQ provide information on the average annual daily traffic (AADT), and the modal share of trucks on their respective highways (see Table 3).

We have assumed that for each segment, the truck AADT counts towards the middle of the segment (far from any major population center) would be representative of the long-haul trucks covering the entire length the segment. However, the truck AADT from both MTO and MTMDQ define heavy vehicles as vehicles transporting goods and people and include vehicles above 4,500 kg in their truck AADT reporting. These are generally vehicles belonging to Class 3 and above, which includes light, medium and heavy trucks, and buses.

To retain only Class 8 and above, we have turned to similar corridors in North America for which a more granular count of trucks is available. We found that, far from any major population center, the share of heavy trucks is relatively stable and varies between 66% and 80%. We have retained 75% for the study.

59 Whitmore, J., P.-O. Pineau, P.-O., Roberts, N. 2023. *Decarbonizing Long-Haul Trucking in Eastern Canada: Part 1 - Summary of a workshop held on April 25, 26 and 27, 2023,* prepared by the Chair in Energy Sector Management - HEC Montréal for the Government of Québec.

Over the simulation horizon, truck traffic growth is assumed to be linear. An annual truck traffic growth rate of 1% is assumed to escalate truck traffic counts recorded in MTO and MTMDQ in previous years, bringing them to 2022 levels. Annual increments are equivalent to 1% throughout the modelling exercise.

TABLE 3. ANNUAL HEAVY TRUCK FLOWS (SINGLE DIRECTION) CLASS 8 LONG-HAUL

Highway segment	Class 8 long haul truck flows
1. Windsor – Toronto	1,308,000
2. Toronto (city area)	1,257,000
3. Toronto – Prescott	1,206,000
4. Prescott – Montréal	1,075,000
5. Montréal (city area)	810,000
6. Montréal – Québec City	544,000
8. Québec City (city area)	534,000
9. Québec City – Rivière-du-Loup	523,000

Sources: CPCS analysis based on data from the MTO and the MTDMQ through their open data portals. Values are rounded to the nearest thousand.[60]

Techno-economic parameters of the truck technologies

An overview of the key techno-economic parameters and assumptions used in the cost analysis are presented in this section. Modelling inputs and assumptions held constant (regardless of the technology being assessed) are covered in Table 4. These include, for example, discount rates, modelling base years and carbon prices. Parameters defining the diesel truck baseline are listed in Table 5, while subsequent tables provide the parameters and assumptions used to analyze the four net zero Class 8 technologies: battery electric (Table 6); hydrogen fuel cell (Table 7); catenary (Table 8); and renewable natural gas (Table 9).

All costs are expressed in Canadian dollars. The midpoint value is used for modelling any input parameter expressed as a range of values. The next section presents the results of a sensitivity analysis applied to the midpoint value.

[60] MTMDQ and MTO provide average annual daily traffic (AADT) and truck modal share for different years. CPCS has applied a 1% per year growth rate, based on historical traffic data, to expand the truck AADT to 2022.

TABLE 4. GENERAL MODELLING PARAMETERS CONSTANT FOR ALL TECHNOLOGIES

Parameter	Value (unit)	Source / assumption notes
Discount rate (real)	10%	Aligns with guidance published by MTMDQ (*Guide de l'analyse avantages-coûts des projets publics en transport routier* – 2016)
Modelling base year	2022	Last full year completed at time of analysis
Modelling horizon year	2050	To align modelling horizon to net zero 2050 target
Carbon price (2022)	\$50 t CO_2e	Government of Canada federal carbon price
Annual carbon price escalation	\$15 t CO_2e	Escalating linearly to \$170 t CO_2e by 2030 and assumed to remain at \$170 t CO_2e per year thereafter [61]
Diesel emissions factor	2.6 kg CO_2e/L	Natural Resources Canada's 2017 National Inventory Report
Electricity price	5-13 ¢/kWh	Hydro Québec comparison of electricity prices (2022) for Montréal and Toronto, assumes consumption on the order of 400 to 3,060 MWh/month with demand on the range of 1 MW to 5 MW [10]
Class 8 truck lifecycle	10 years	Estimate from Ontario and Québec provincial trucking associations
Average annual truck kilometers (total)	95,000 km	Based on statistics from Ontario and Québec trucking fleets
Average annual truck kilometers (on highway)	76,000 km	Assumption, 80% of total annual kilometers, based on statistics of highway versus other road kilometers [62]
Average truck payload	20 tonnes	Government of Canada - 2018 SmartWay trends and statistics
Energy prices assumed (CA\$)		
Diesel fuel price	\$1.96/L	NRCan - Average Daily Retail Prices for Diesel [4]
Electricity price	5-13 ¢/kWh	Hydro Québec comparison of electricity prices (2022) for Montréal and Toronto, assumes consumption on the order of 400 to 3,060 MWh/month with demand on the range of 1 MW to 5 MW [10]
Cost of green hydrogen	\$9.5 - \$13.5 kg of H_2	NREL, "Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks" (2021) [24]
Cost of RNG	\$15.80 - \$16.34 / GJ (\$0.59 - \$0.61 / m^3)	Énergir Québec [28]

Sources: See also Appendix 4.

TABLE 5. BASELINE DIESEL CLASS 8 TRUCK MODELLING PARAMETERS AND ASSUMPTIONS

Parameter	Value (unit)	Sources / assumption notes
Fuel efficiency	35 - 40 L/100km (13 - 15 MJ/km)	US Federal Highway Administration (FHWA) [1] ICCT, "Zero emissions trucks: An overview of state-of-the-art technologies and their potential" (2013) [2] ICCT, "Efficiency technology Potential for heavy-duty diesel Vehicles in the United States through 2035" (2021) [3]
Diesel fuel price	\$1.96/L	NRCan - Average Daily Retail Prices for Diesel [4]
Purchase price	\$125,000 - \$205,000	ICCT, "A Meta-study of purchase costs for zero-emission trucks" (2021) [5]
Maintenance cost	\$0.22/km	Pedinotti-Castelle. M, Pineau, P.-O. and Amor. B, 2022. Decarbonization of road freight transportation in Québec. HEC Montréal – Table A-7 [19]

Sources: See Appendix 4.

61 Government of Canada, 2021. *Update to the Pan-Canadian Approach to Carbon Pollution Pricing 2023-2030*, www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/carbon-pollution-pricing-federal-benchmark-information/federal-benchmark-2023-2030.html

62 Assumption inferred from US Office of Highway Policy information, using US relation of Interstate versus other road mileage ratio as a proxy for a similar ratio applied to the Canadian long-haul trucking context on the H401-A20 corridor. Reference: FHWA, 2018. *Annual Vehicle Distance Traveled in Miles and Related Data – 2015*, US Department of Transportation, https://www.fhwa.dot.gov/policyinformation/statistics/2015/vm1.cfm

TABLE 6. BATTERY ELECTRIC (BEV) CLASS 8 TRUCK MODELLING PARAMETERS AND ASSUMPTIONS

Parameters	Value (unit)	Sources / assumption notes
Battery size (range)	850 - 900 kWh (~800 km)	In alignment with preliminary estimates on the Tesla semi-truck [31]
Energy consumption	1.15 - 1.52 kWh/km (4.1 - 5.5 MJ/km)	Earl et al., 2018. Analysis of long-haul battery electric trucks in the EU: Marketplace and technology, economic, environmental, and policy perspectives [8] ATRI, "Charging Infrastructure Challenges for the U.S. Electric Vehicle Fleet" (2022) [9]
Purchase price	$430,000 - $575,000	ICCT, "A Meta-study of purchase costs for zero-emission trucks" (2021). Based on National Renewable Energy Laboratory (Hunter et al., 2021) trucks ~800 km (500 mile) range [5]
Maintenance cost	$0.08 - $0.147/km	California Air Resources Board "Advanced Clean Trucks Total Cost of Ownership Discussion Document" (2019) [6] University of California Davis, "A Comparison of Zero-Emission Highway Trucking Technologies. Institute of Transportation Studies" (2018) [7]

Sources: See Appendix 4.

TABLE 7. HYDROGEN FUEL CELLS (FCEV) CLASS 8 TRUCK MODELLING PARAMETERS AND ASSUMPTIONS

Parameter	Value (unit)	Sources / assumption notes
Energy consumption	0.07 - 0.11 kg/km (8.4 - 12.2 MJ/km)	ICCT, "A Meta-study of purchase costs for zero-emission trucks" (2021) [5] InsideEVs, "Daimler Presents GenH2 Truck Fuel-Cell Concept Truck" (2020) [13] Hyundai, "Hyundai XCIENT Fuel Cell Heads to Europe for Commercial Use" (2020) [15]
Cost of green hydrogen	$9.5 - $13.5 kg of H_2	NREL, "Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks" (2021) [24]
Purchase price	$328,000 - $351,000	ICCT, "A Meta-study of purchase costs for zero-emission trucks" (2021). Based on National Renewable Energy Laboratory (Hunter et al., 2021) trucks ~800 km (500 mile) range [5]
Maintenance cost	$0.117 - $0.147/km	California Air Resources Board "Advanced Clean Trucks Total Cost of Ownership Discussion Document" (2019) [6]

Sources: See Appendix 4.

TABLE 8. OVERHEAD CATENARY TRANSMISSION CLASS 8 TRUCK MODELLIG PARAMETERS AND ASSUMPTIONS

Parameter	Value (unit)	Sources / assumption notes
Battery size (range)	130 - 260 kWh (100 - 200 km)	StratON, "Assessment and deployment strategies for catenary-bound heavy-duty vehicles" (2020) [27]
Energy consumption	1.1 kWh/km (3.9 MJ/km)	Siemens field trials of catenary trucks in Germany [26]
Purchase price	$190,000 - $250,000	StratON, "Assessment and deployment strategies for catenary-bound heavy-duty vehicles" (2020) [27]
Maintenance cost	$0.08 - $0.147/km	Assumption, that BEV and OCT-ERS trucks should have similar maintenance cost, key difference is the addition of the pantograph (minimal maintenance).[63] [26]

Sources: See Appendix 4.

[63] Pantograph maintenance require check and replacement (if necessary) for carbon strips every 6-12 months during the regular maintenance check-up.

TABLE 9. RENEWABLE NATURAL GAS (RNG) CLASS 8 TRUCK MODELLING PARAMETERS AND ASSUMPTIONS

Parameter	Value (unit)	Source / assumption notes
Energy consumption	1.451 GJ/100km (14.5 MJ/km)	Pedinotti-Castelle. M, Pineau, P.-O. and Amor. B, 2022. Decarbonization of road freight transportation in Québec. HEC Montréal – Table A-7 [19]
Purchase price	+$90,000	Énergir [28] (incremental cost versus a comparable diesel truck)
Maintenance cost	$0.23/km [64]	Pedinotti-Castelle. M, Pineau, P.-O. and Amor. B, 2022. Decarbonization of road freight transportation in Québec. HEC Montréal – Table A-7 [19]

Sources: See Appendix 4.

Deployment scenarios and adoption of the technology

The analysis models a transition plan for Class 8 diesel long-haul trucks ultimately phasing out of the trucking fleet via lifecycle replacements and being replaced with an alternative net zero emissions technology. In summary, the following approach is used to develop the fleet adoption plans for each technology:

1. **Determine annual lifecycle replacements.** Calculate the number of trucks in each year scheduled to undergo an end-of-life lifecycle replacement. Assume that the age distribution of the fleet is consistent such that according to an average lifecycle of 10 years then 10% of the fleet is replaced each year.
2. **Determine the growth portion of the fleet.** Calculate the number of new trucks added to the fleet according to the assumed 1% annual growth rate.
3. **Calculate the total annual truck purchases** by adding the results from ifecycle replacement purchase and growth purchases.
4. **Calculate the number of net zero emission trucks added to the fleet** by multiplying the annual truck purchases against the assumed percentage of new vehicle sales being the alternative net zero technology. Note that the modelling methodology takes into consideration federal sales mandates for MHDVs as key milestones in developing the year-by-year adoption curve built from the percentage of new vehicle sales as net zero.

   The key milestone is 100% of MHDVs sold by 2040 shall be zero emissions. An exponential increase up to this 2040 target is assumed. Therefore, the entire trucking fleet is modelled to transition to net zero by 2050 due to the assumption that a Class 8 long-haul truck operates with a 10-year average lifecycle.[65]
5. **Calculate the remaining diesel portion of the fleet** by subtracting the number of net zero trucks purchased from the total number of trucks purchased on an annual basis and tally the cumulative total number of diesel versus net zero trucks in each subsequent year of the modelling period by repeating steps 1 – 4 described above.

Furthermore, the fleet adoption plans include an element of modelling technological maturity by addressing that certain net zero technologies are more mature and commercially available (e.g., RNG) and could thereby have a higher uptake (percentage of new vehicle sales / fleet replacements) in earlier years in comparison to technologies which are still in early stages of pilot vehicle development and testing (e.g., FCEVs). For example, the introduction of RNG trucks into the fleet may start as early as 2024 whereas notable adoption of FCEVs is likely to start later (e.g., by 2027) as commercial production still needs time to scale.

The adoption of catenary (OCT-ERS) trucks is also assumed to start later as lead time will be needed to build out the catenary infrastructure along the various highway segments before these trucks can operate. The next

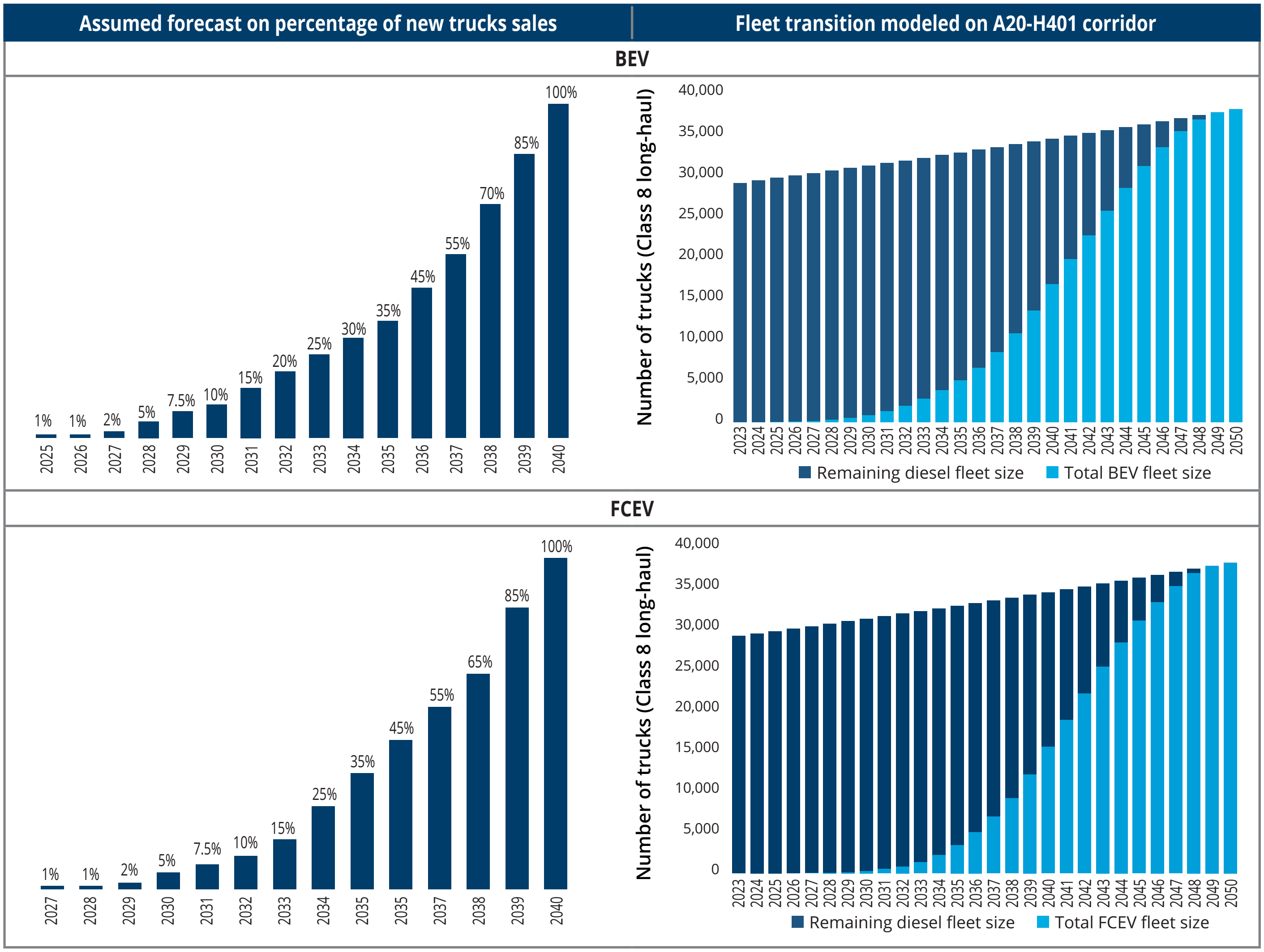
[64] Maintenance should be comparable to a diesel truck (slightly higher due to qualifications needed for maintenance staff, specialized tools for servicing compressed gas tanks and fuel systems).

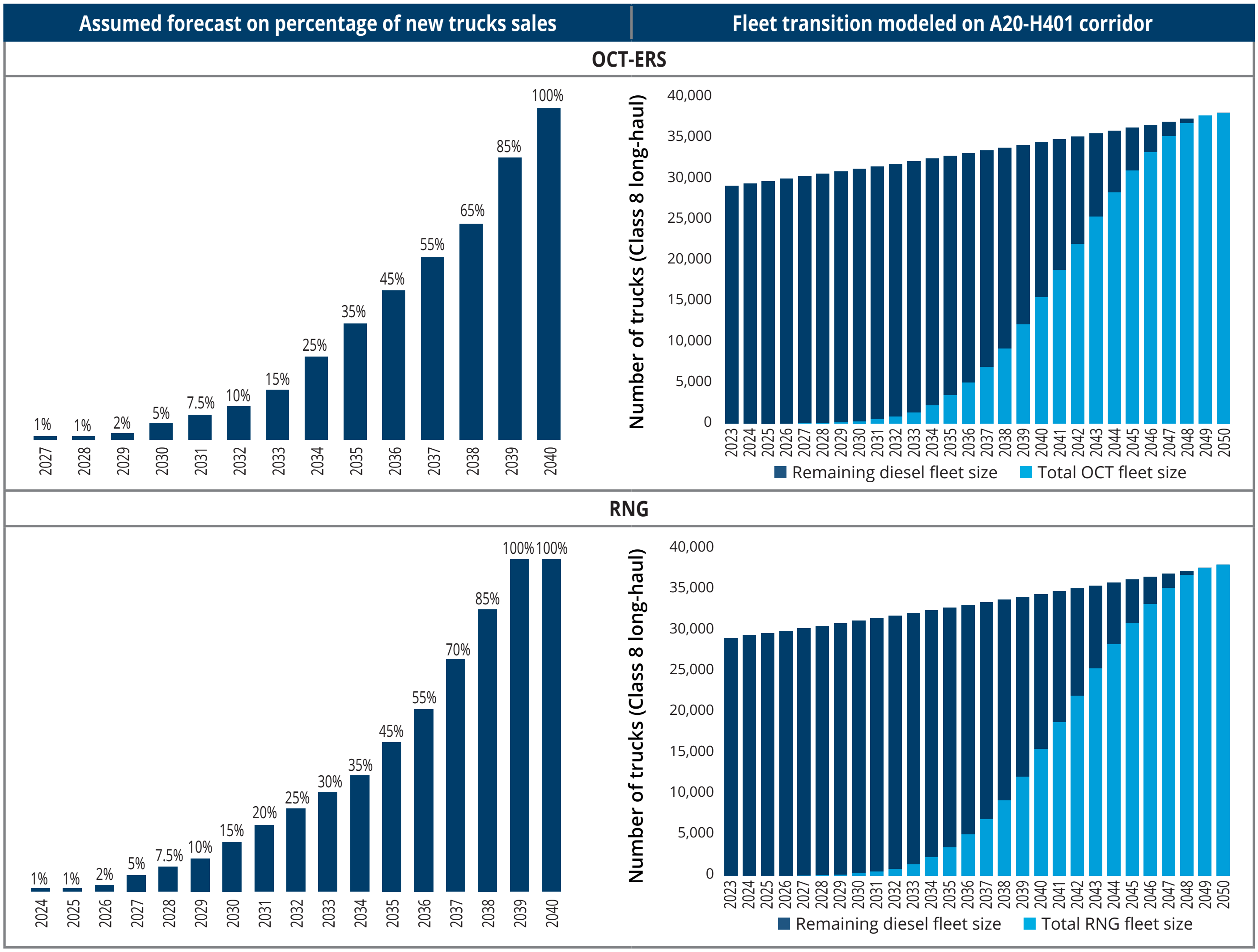
[65] Note that the portion of new vehicle sales in the Class 8 long-haul trucking sub-segment of the MHDV market is likely to fall below the interim target for the entire market segment (35% of MDHVs sold by 2030 being zero emissions). Class 8 long-haul trucks have more operational challenges to transition to zero emission vehicles in comparison to other vehicles in the MHDV market, which will likely be earlier adopters and thereby contribute more greatly to achieving the 2030 sales target (e.g., medium-duty trucks and trucks used for more shorter or regional haul and return-to-base fleets).

section further details the assumptions used for phasing and providing high-level costing on the supporting refueling and charging infrastructure.

The modelling approach for the fleet transition plans is demonstrated in Figure 7 for the entire corridor.

FIGURE 7. DEPLOYMENT SCENARIOS FOR DIFFERENT NET ZERO TECHNOLOGIES





Source: CPCS, 2023.

Assumptions on refueling and charging infrastructure

The modelling approach for phasing and providing high-level costing on the supporting energy infrastructure is summarized in the respective sections below. The basis of the infrastructure assessment is the fleet transition plan for each technology. This informs the infrastructure estimates as supporting charging / refueling stations or catenary will need to be installed and ready to supply the required energy demands of the fleet in advance of the fleet reaching such demands (e.g., installation of catenary before the first OCT-ERS trucks begin to operate on a segment of the highway and installation of hydrogen fueling stations to meet the annual hydrogen fuel consumption of the fleet).

Battery electric fast charging infrastructure

The following steps are used to provide a high-level estimate for the plug-in fast charging infrastructure sizing and cost into the analysis:

1. **Estimate the energy demands for the BEV trucking fleet** operating along the corridor (calculated based on the number of BEV trucks, annual kilometers per truck and average energy consumption kWh/km). The result is kWh/year total demand.

2. **Estimate the energy output of a single fast charger** (350 kW) based on 24 hours/day, 365 days/year and a 20% charger utilization rate.[66] With a fast-charging station output of 350 kW it would take more than 2 hours to fully recharge a battery of the size required for long-haul trucking and considered in this analysis (~850 to 900 kWh). This is likely to introduce significant operational changes for fleet operators to accommodate charging times. However, there is ongoing work to decrease charging times with initiatives such as Megawatt charging.[67]
3. **Calculate the number of fast charging stations** by dividing the total fleet energy demand by the assumed output of a fast-charging station.
4. **Phase the installation of the EV charging stations** such that the infrastructure capacity (e.g., energy output of the fast-charging network) is installed in advance of the BEV trucking fleet demand scaling to match that level. A 2-year lead time is assumed to account for charging stations, related equipment and for construction / installation to scale the charging network in advance of the BEV trucking fleet.

A summary of the BEV infrastructure modelling inputs and assumptions is provided in Table 10. Note all costs are expressed in Canadian dollars.

TABLE 10. BATTERY ELECTRIC CHARGING INFRASTRUCTURE MODELLING ASSUMPTIONS

Parameter	Value (unit)	Source / assumption notes
Fast charger power output	350 kW (Level 3)	Assumption, aligns with the highest power rating on plug-in chargers currently available in Canada.[68]
Capital cost (equipment plus installation)	$181,000 - $298,000	American Transportation Research Institute (2022) [69] [11]
Annual maintenance cost	$545/ charger	US Department of Energy (2022) [70] [12]
Utilization of fast charging stations	20%	PwC, "Electric vehicles and charging infrastructure" (2023) [33]
Charger lifecycle	10 years	Assumption, US Department of Energy (2022) [34]

Sources: See Appendix 4.

Green hydrogen refueling stations

A similar approach is followed for providing a high-level estimate on sizing and costing hydrogen fueling infrastructure for the FCEV fleet under its adoption scenario.

1. **Estimate the energy demands for the FCEV trucking fleet** operating along the corridor (calculated based on the number of FCEV trucks, annual kilometers per truck and average energy consumption kg/km). The result is kg/year total demand for hydrogen.
2. **Scale the cost estimate of green hydrogen fueling infrastructure** according to the typical cost and output of a large commercial refueling station, its daily dispensed hydrogen output and the total energy demands of the FCEV fleet.

   Note there is a large degree of uncertainty in estimating the CAPEX range for hydrogen fueling stations. CAPEX can vary greatly according to the delivery method and business model of the fueling station (e.g., hydrogen produced on-site via electrolysis, delivered via pipeline or tanker truck). A midpoint of the cost range is used in the analysis with an accompanying sensitivity analysis to account for the variability in this parameter.

[66] PwC, 2023. *Electric vehicles and the charging infrastructure: a new mindset?,* www.pwc.com/us/en/industrial-products/publications/assets/pwc-electric-vehicles-charging-infrastructure-mindset.pdf

[67] CharIN, 2023. *Megawatt Charging System (MCS)*, https://www.charin.global/technology/mcs/

[68] ABB, "Terra HP Charger – Up to 350 kW" (2023) https://new.abb.com/ev-charging/high-power-charging

[69] ATRI, "Charging Infrastructure Challenges for the U.S. Electric Vehicle Fleet" (2022) https://truckingresearch.org/2022/12/charging-infrastructure-challenges-for-the-u-s-electric-vehicle-fleet/

[70] Alternative Fuels Data Center, "Charging Infrastructure Operation and Maintenance" (2023) https://afdc.energy.gov/fuels/electricity_infrastructure_maintenance_and_operation.html

3. **Phase the installation of the green hydrogen fueling infrastructure** such that the infrastructure capacity (e.g., fueling station output capacity) is installed in advance of the FCEV trucking fleet demand scaling to match the energy demands of that level. A 2-year lead time is assumed.

A summary of the hydrogen infrastructure modelling inputs and key assumptions is provided in Table 11. Note all costs are expressed in Canadian dollars.

TABLE 11. HYDROGEN REFUELING INFRASTRUCTURE MODELLING ASSUMPTIONS

Parameter	Value (unit)	Source / assumption notes
Cost for a H_2 refueling station (CAPEX)	\$2,000 - \$5,000 per kg H_2 dispensed per day	Transport & Environment, "How to decarbonise long-haul trucking in Germany. An analysis of available vehicle technologies and their associated costs" (2021) [15] US Department of Energy, "*Hydrogen Fueling Stations Cost, Hydrogen Program Record*" (2020) [17] The low end of the range would align with a station with delivered hydrogen, whereas the high end would be for a station with on-site hydrogen production. Use midpoint of the range to accommodate for uncertainty and CAPEX variability for gaseous versus liquid delivered hydrogen or on-site production.
Hydrogen refueling station maintenance	\$0.50 per kg	Maintenance cost is expressed per kg of hydrogen fuel dispensed. Estimate is from industry expert during project workshop engagements [30]
Hydrogen fueling station lifecycle	20 years	Assumption, Change Energy Services typical design life used in modelling lifecycle costs for hydrogen refueling stations [30]

Sources: See Appendix 4.

Overhead catenary transmission infrastructure

The assumption for the vehicle specification modeled for the OCT-ERS trucks includes a battery pack capable of providing autonomy around of 150 km, enough for the trucks to disconnect from the catenary and operate on the battery only for short highway segments through city areas and for first/last mile connections off highway to logistics hubs.

The installation of catenary infrastructure along highway segments through city areas has been excluded from the simulation. Most long-distance trips originate not from the cities themselves, but rather from logistics hubs on city peripheries. Furthermore, the cost of constructing and maintaining the infrastructure is likely to be significantly higher, and more complex in densely built areas. Table 12 provides a summary of the highway segments for which installed catenary infrastructure is modeled in the analysis.

TABLE 12. HIGHWAY SEGMENTS WITH OVERHEAD CATENARY INFRASTRUCTURE

Highway segment	Length (km)	Class 8 long haul truck flows	Include / exclude
Windsor – Toronto	321	1,308,000	Include
Toronto (city area)	97	1,257,000	Exclude
Toronto – Prescott	288	1,206,000	Include
Prescott – Montréal	146	1,075,000	Include
Montréal (city area)	72	810,000	Exclude
Montréal – Québec City	215	544,000	Include
Québec City (city area)	38	534,000	Exclude
Québec City – Rivière-du-Loup	167	523,000	Include

Sources: Distances from Google Maps, CPCS analysis of truck flow data from MTO and MTMDQ.

The analysis assumes a phased installation of catenary infrastructure, rather than assuming the infrastructure is built out in its entirety before the first OCT-ERS trucks being to operate. Installation is prioritized in accordance with the most heavily trafficked highway segments first, to maximize the utility of the catenary infrastructure in earlier years as the OCT-ERS trucking fleet begins to scale. Table 13 provides a summary of the phasing assumptions, aligning the timing of infrastructure installation with the assumed fleet adoption plan (e.g., ensuring infrastructure capacity is built in advance of OCT-ERS trucks beginning to operate on the highway).

TABLE 13. OVERHEAD CATENARY INFRASTRUCTURE PHASING ASSUMPTIONS

Highway segment	Priority	Infrastructure installation period [71]	OCT-ERS fleet size by completion year
Windsor – Toronto	1	2024 – 2027	31 trucks (2027)
Toronto – Prescott	2	2028 – 2031	526 trucks (2031)
Prescott – Montréal	3	2028 – 2031	526 trucks (2031)
Montréal – Québec City	4	2032 – 2035	3,470 trucks (2035)
Québec City – Rivière-du-Loup	5	2036 – 2039	12,137 trucks (2039)

Source: CPCS, 2023.

Table 14 lists the inputs and assumptions used to cost the capital expenditure (CAPEX) for installing the catenary infrastructure and for annual maintenance. Note all costs are expressed in Canadian dollars.

TABLE 14. OVERHEAD CATENARY INFRASTRUCTURE MODELLING ASSUMPTIONS

Parameter	Value (unit)	Source / assumption notes
CAPEX (price includes both directions of travel)	\$2.4 - \$4.8 million per km	CPCS and Chair in Energy Sector Management - HEC Montréal "Decarbonization of long-haul trucking in Eastern Canada – Simulation of the e-Highway technology on the A20-H401 highway corridor" (2021) [18] Cost estimate assumes installed power for the catenary in the range of 2 MW/km to 4 MW/km
Maintenance cost	2% of CAPEX	CPCS and Chair in Energy Sector Management - HEC Montréal "Decarbonization of long-haul trucking in Eastern Canada – Simulation of the e-Highway technology on the A20-H401 highway corridor" (2021) [18] Assumption, based on typical maintenance costs for electrical infrastructure.
Catenary infrastructure lifecycle	50 years	Assumption, CPCS subject matter expertise of similar infrastructure in the electrified passenger rail sector [72]

Sources: See Appendix 4.

Renewable natural gas refueling infrastructure

The approach for arriving at a high-level estimate on the size and cost for RNG fueling infrastructure is analogous to that presented for the hydrogen fueling infrastructure. However, the CAPEX range for an RNG fueling station is much narrower, in comparison to a hydrogen refueling station, due to the maturity of compressed natural gas and its use in heavy-duty fleets, including long-haul trucking. As a result, there is greater certainty in benchmarking RNG infrastructure cost.

1. **Estimate the energy demands for the RNG trucking fleet** operating along the corridor (calculated based on the number of RNG trucks, annual kilometers per truck and average energy consumption MJ/km). The result is MJ/year total demand for RNG.
2. **Scale the cost estimate of RNG fueling infrastructure** according to the typical cost and output of a large commercial refueling station, its daily dispensed RNG output and the total energy demands of the RNG fleet.

[71] Catenary infrastructure for each highway segment identified is assumed to be installed / built out over a 4-year period with CAPEX spread equally of the 4-years. For example, The Windsor to Toronto segment will be built out 25% in each of 2024, 2025, 2026 and commissioned in 2027 with completion of the remaining 25%. This will support fleet transition to OCT-ERS trucks starting in 2027 with 31 trucks becoming operational in this year, according to the assumed fleet adoption plan.

[72] There are overhead catenary systems in the UK which are over 75 years old. Some components may require replacement earlier in the lifecycle. For example, conductor wires may last around 20 years (or more, depending on usage) and supports (masts) may last 50 years or more.

3. **Phase the installation of the hydrogen fueling infrastructure** such that the infrastructure capacity (e.g., fueling station output capacity) is installed in advance of the RNG trucking fleet demand scaling to match the energy demands of that level. A 2-year lead time is assumed.

A summary of the modelling inputs and key assumptions used for RNG fueling infrastructure is provided in Table 15. Note all costs are expressed in Canadian dollars.

TABLE 15. RNG INFRASTRUCTURE MODELLING ASSUMPTIONS

Parameter	Value (unit)	Source / assumption notes
Cost for a RNG refueling station (CAPEX)	\$10.7 - \$12 per MJ/day	US Department of Energy, "Costs Associated with Compressed Natural Gas Vehicle Fueling Infrastructure" (2014) [29]
RNG refueling station maintenance	\$0.03 per m^3	Maintenance cost is expressed per cubic meter (m^3) of RNG dispensed.[73] Estimate from industry expert during project workshop engagements [30]
RNG fueling station lifecycle	20 years	Assumption, Change Energy Services typical design life used in modelling lifecycle costs for natural gas refueling stations [30]

Sources: See Appendix 4.

[73] Value from personal communication with Ry Smith (Change Energy Services). Based on his 30-year history of designing, developing, and assisting with the operations of CNG and H2 vehicle refuelling stations. Although there is no formal report, the learning has been incorporated into Change Energy Services techno-economic assessment modelling which includes: (1) allowances for weekly inspections and preventative maintenance service (including parts and labour); (2) allowances for major and minor overhauls of equipment triggered by hours of operation; (3) hours of operation are calculated based on consumption rates. It should be noted that, as with any new technology, it is likely that there will be additional costs is the early years of roll-out as new Standard Operation Procedures are developed.

Modelling results and analysis

Economic viability of the technologies

The following are the principal economic measures used to compare the economic viability and attractiveness of the different net zero technologies under their transition scenarios by illustrating their performance against the baseline diesel scenario. The following measures are used:

- **Net present value (NPV)** is the difference between the present value of all benefits and costs. Benefits and costs in future years are converted into their present value by applying the discount rate and formula. This approach addresses the time value of money (including monetized benefits) whereby the discounting mechanism accounts for greater uncertainty in benefits and costs materializing the further they are into the future (e.g., benefits occurring in 2030 will be valued less in terms of present value, when compared to the same benefits occurring in 2025). A NPV greater than zero indicates that the benefits of the scenario exceed its costs.

- **Benefit-cost ratio (BCR)** is calculated as the ratio of benefits to costs, using their present value over the modelling period (2022 – 2050). A BCR greater than one indicates that the scenario's benefits exceed its costs. A higher BCR is a measure of a more beneficial outcome.

- **Economic internal rate of return (EIRR)** is an indicator of economic viability. It is a measure of the net benefits of a project (or scenario), expressed as a percentage of the initial investment. It can be understood as the annual rate of return that will be generated by a project – in a way similar to an interest rate. Unlike a financial internal rate of return (IRR) which compares costs to project revenues, an economic rate of return compares costs to wider societal benefits (such as GHG emissions reduction), which are converted to dollar figures for the purpose of the analysis. A higher EIRR is indicative of a more beneficial project (or scenario).

The economic measures are analyzed through two different perspectives. The first one is a **"corridor" perspective** which enables the total investment cost and benefits of decarbonizing the entire Class 8 long-haul trucking fleet operating along A20-H401 corridor to be assessed. This perspective can be useful for government gauging investment costs.

The second is the **"vehicle" perspective** focuses on comparing the total lifecycle cost of a single truck, which can be more illustrative to fleet owners and operators, informing decisions should supporting infrastructure be in place.

Corridor perspective results

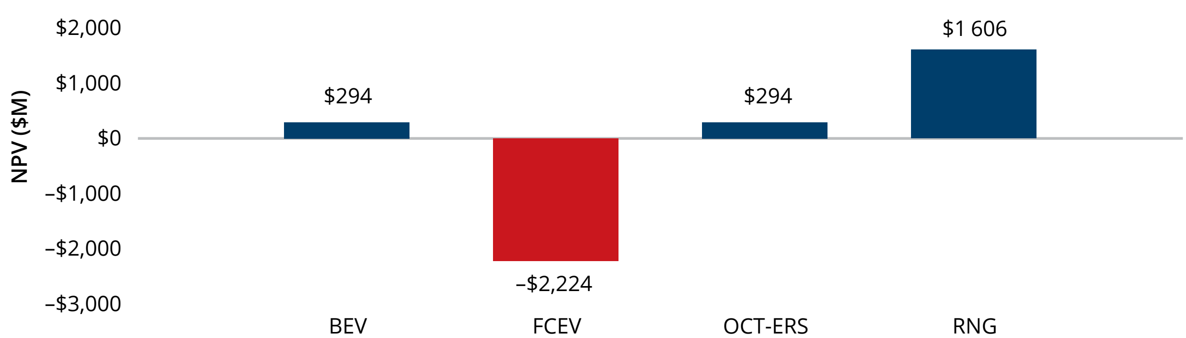
The following Table 16 and Figure 8 provide a summary of economic metrics calculated as modelling outputs for each of the net zero technology adoption scenarios over the modelling period from 2022 to 2050.

TABLE 16. SUMMARY STATISTICS OF ECONOMIC VALUATION PER TECHNOLOGY

Technology	NPV ($M)	Benefits ($M)	Costs ($M)	BCR	EIRR
Battery electric (BEV)	$294	$3,380	$3,086	1.1	4.0%
Hydrogen (FCEV)	-$2,224	$870	$3,094	0.3	N/A [74]
Catenary (OCT-ERS)	$294	$3,115	$2,821	1.1	0.9%
Renewable natural gas (RNG)	$1,606	$2,903	$1,297	2.2	29.4%

Source: CPCS, 2023.

FIGURE 8. SUMMARY NPV (2022 CA$ IN MILLIONS) COMPARISON PER TECHNOLOGY



Source: CPCS, 2023.

The key findings from the analysis (in absence of any sensitivity analysis) can be summarized as follows:

1. **The RNG scenario has the most favorable economic results with the highest NPV of $1,606 million and a BCR of 2.2.** The positive results are influenced by the relatively low incremental cost of purchasing a RNG truck versus a diesel truck, the maturity of RNG technology (enabling an earlier start of adoption) and the operational cost savings of RNG fuel versus diesel.
2. **Battery electric (BEV) trucks (in a tie with catenary trucks) showcase the second most favorable performance, achieving a BCR of 1.1 and positive NPV of $294 million.** Substantial savings on fuel and maintenance cost over the life of the Class 8 trucks help offset the higher purchase price of BEVs. The key parameters which hold back a better performance of the BEV adoption scenario currently are the high purchase cost of BEV trucks and the cost of fast charging infrastructure.
3. **Catenary trucks also have a BCR of 1.1 and NPV of $294 million.** Despite the high capital cost for the build out of the overhead catenary infrastructure this investment is recovered due to the substantially lower operating costs of the OCT-ERS trucks on the consummation of electricity versus diesel fuel and lower maintenance costs, due to a simplified electric powertrain.
4. **The hydrogen (FCEV) scenario does not have a positive NPV and has a BCR below 1.** The key drivers behind this result are the high cost of green hydrogen as an alternative fuel, the capital cost of FCEV trucks and fueling infrastructure. Furthermore, the state of technological maturity and commercial availability of FCEV trucks is such that the start of adoption is modeled to start later (in comparison to other technologies, 2027 versus 2025). This later start of the adoption curve foregoes the benefits of GHG emissions reduction in earlier years.

[74] EIRR cannot be calculated because the FCEV adoption scenario has a negative NPV.

The source of incremental benefits and costs for each net zero technology (relative to diesel) is presented in Table 17. All technologies come with an increased cost for fleet (truck purchases), fueling/charging infrastructure.

The main benefits are operational cost savings (relative to diesel) on fuel and vehicle maintenance, and mitigated GHG emissions (priced according to the federal carbon price). Two exceptions are the price of green hydrogen, which results in a higher operational expense for fuel, and a slightly higher cost in RNG truck maintenance, in comparison to diesel trucks.

TABLE 17. SUMMARY OF NET ZERO TECHNOLOGY BENEFITS AND COSTS RELATIVE TO DIESEL

Component	BEV	FCEV	OCT-ERS	RNG
Truck purchase	Cost	Cost	Cost	Cost
Truck maintenance	Benefit	Benefit	Benefit	Cost
Energy (fuel or electricity)	Benefit	Cost	Benefit	Benefit
GHG emissions	Benefit	Benefit	Benefit	Benefit
Infrastructure	Cost	Cost	Cost	Cost
Infrastructure maintenance	Cost	Cost	Cost	Cost

Source: CPCS, 2023.

A breakdown of the various trucking fleet and infrastructure costs as well as benefits is presented in Table 18 for the different fleet adoption scenarios run on the A20-H401 corridor (2022 to 2050), including the base case of continuing to operate a diesel only fleet. Note the "diesel" outputs in the net zero technology scenarios are due to the residual diesel fleet in operation before it is phased out via lifecycle replacements by 2050.

TABLE 18. DETAILED NPV (2022 CA$ IN MILLIONS) OF THE DIFFERENT FLEET SCENARIOS

NPV (2022$ in millions)	Fleet scenario				
	Diesel	BEV	FCEV	OCT-ERS	RNG
Truck purchases	**$5,581**	**$8,376**	**$6,971**	**$6,019**	**$6,459**
Diesel	$5,581	$4,144	$4,266	$4,266	$3,970
Alternative ZEV	-	$4,232	$2,704	$1,752	$2,489
Fleet maintenance	**$5,395**	**$4,989**	**$5,093**	**$5,029**	**$5,438**
Diesel	$5,395	$4,556	$4,640	$4,640	$4,437
Alternative ZEV	-	$433	$453	$389	$1,001
Energy (Fuel / electricity)	**$18,024**	**$15,680**	**$19,053**	**$15,842**	**$15,839**
Diesel	$18,024	$15,222	$15,502	$15,502	$14,824
Alternative ZEV	-	$458	$3,550	$340	$1,015
Infrastructure	**-**	**$291**	**$675**	**$2,383**	**$374**
Capital	-	$288	$521	$1,999	$324
Maintenance	-	$3	$154	$383	$51
Totals	**$28,999**	**$29,336**	**$31,791**	**$29,273**	**$28,111**
Fleet	$28,999	$29,045	$31,117	$26,890	$27,737
Infrastructure	-	$291	$675	$2,383	$374
GHG emissions					
Total GHG Emissions (MtCO_2e)	71.4	43.1	44.4	44.4	40.6
Mitigated GHG Emissions (MtCO_2e)		28.3	27.0	27.0	30.9
Cost of GHG emissions	$3,106	$2,476	$2,538	$2,538	$2,387

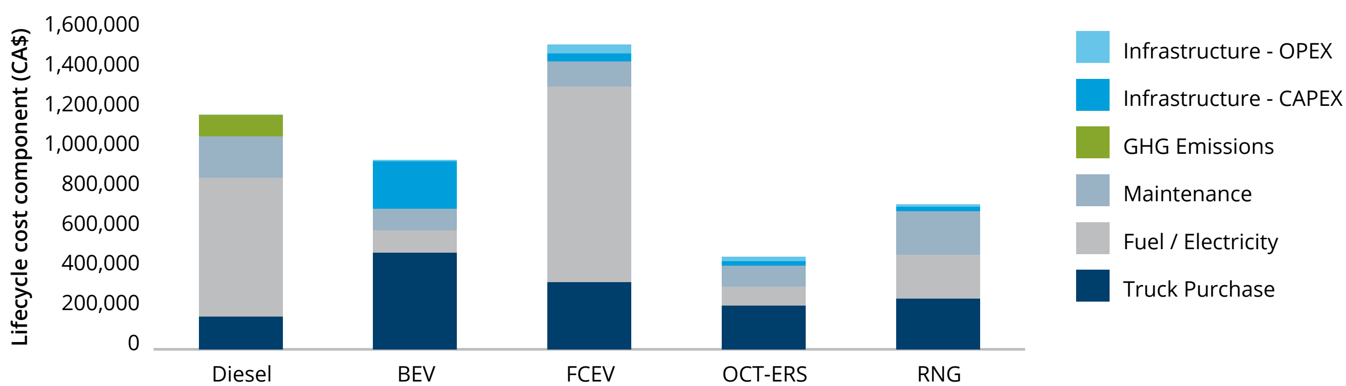
Source: CPCS, 2023.

Vehicle (truck) perspective results

The following analysis takes the perspective of comparing the lifecycle costs of a single Class 8 long-haul truck over its typical 10-year life.[75]

The cost of infrastructure is included by amortizing it over its expected lifecycle and the estimated usage of the infrastructure. For example, the cost of catenary infrastructure applied to one OCT-ERS truck is estimated as the total catenary infrastructure cost amortized over a 50-year and proportioned to one truck by dividing the amortized cost by 38,000 trucks (the total number of trucks operating on the corridor by 2050 which would be utilizing the infrastructure annually, should a 100% transition to OCT-ERS trucks occur).

FIGURE 9. LIFECYCLE COST COMPARISON OF NET ZERO TECHNOLOGIES VERSUS DIESEL (10-YEAR LIFE)



Source: CPCS, 2023.

The lifecycle costs shown in Figure 9 are presented again in Table 19 in tabular form. Additional metrics in Table 19 include the total lifecycle cost expressed per tonne-kilometer (based on average truck loads and lifecycle kilometers, refer to inputs assumptions in Table 4) as well as an abatement cost of GHG emissions. The abatement cost is calculated as the incremental cost of the net zero technology (versus diesel) divided by the GHG emissions reduction over the truck's 10-year life. Outputs are shown with and without infrastructure cost components.

[75] Estimate from Ontario and Québec provincial trucking associations

TABLE 19. LIFECYCLE COST COMPARISON OF TECHNOLOGIES (CA$)

Lifecycle cost	Technology				
	Diesel	BEV	FCEV	OCT-ERS	RNG
Purchase	$165,000	$486,000	$339,500	$220,000	$255,000
Maintenance	$209,000	$107,825	$125,400	$107,825	$218,500
Fuel / Electricity	$698,250	$114,143	$983,250	$94,050	$221,550
GHG emissions	$107,445	0	0	0	0
Infrastructure	0	$244,950	$83,743	$42,990	$32,520
Lifecycle cost (including infrastructure cost component)					
Total cost	$1,179,695	$952,918	$1,531,893	$464,865	$727,569
Annualized cost	$117,970	$95,292	$153,189	$46,487	$72,757
Cost per tonne-km	0.62	0.50	0.81	0.24	0.38
Abatement cost	N/A	–$245	$380	–$772	–$488
Lifecycle cost (excluding infrastructure cost component)					
Total cost	$1,179,695	$707,968	$1,448,150	$421,875	$695,050
Annualized cost	$117,970	$70,797	$144,815	$42,188	$69,505
Cost per tonne-km	0.96	0.57	1.17	0.34	0.56
Abatement cost	N/A	–$509	$290	–$818	–$523

Source: CPCS, 2023.

The lifecycle cost for all net zero technologies is lower than diesel, except for hydrogen (FCEV). This demonstrates that for most technologies cost savings can be accrued over the lifecycle of the vehicle while also reducing GHG emissions. This is reflected in the negative abatement cost. Even if GHG emissions were not a cost, these results show that it would make economic sense to switch to net zero technologies under the current conditions analyzed, apart from green hydrogen.

The catenary trucks (OCT-ERS) have the lowest lifecycle cost and greatly benefit from being able to disperse the infrastructure costs over a longer lifespan (50 years) and large number of trucks utilizing the infrastructure, which helps to lower the cost per truck. In the corridor simulation for catenary trucks there is considerable upfront capital cost to install the supporting infrastructure. This infrastructure would have a useful life of 50 years thus extending beyond the modelling horizon of 2050. However, since the modelling period is capped at 2050, the catenary truck scenarios are attributed the full amount of the infrastructure capital cost which impacts their economic performance (e.g., NPV and EIRR).

RNG and BEV trucks also compare favorably against diesel when accounting for lifecycle costs. Their fuel and maintenance savings help offset the higher initial purchase price for these trucks.

The high cost of green hydrogen is one of the main drawbacks of FCEV technology as it currently amounts to a higher fuel expense, in comparison to diesel. The monetized GHG emissions reduction and reduced maintenance expense of a FCEV truck are not enough to offset the higher purchase price and fuel expense over the lifecycle of the vehicle.

Key factors influencing the economic viability

There are several modelling parameters which may impact the economic viability and attractiveness of a particular technology. A sensitivity analysis is included to address factors such as the level of technological maturity, assumptions on infrastructure requirements, energy price volatility, innovations and demand factors which may impact the future price of vehicles and infrastructure. The sensitivity analysis yields a range of potential economic output metrics (e.g., NPV, BCR, EIRR) which can help demonstrate the robustness of a particular technology to variability in cost parameters. Tables in Appendix 4 summarize the parameters and the four net zero technology scenarios for which sensitivity analysis is applied, whereas Figure 10 shows the relative impact of such parameters on economic viability.

The sensitivity results are most favorable towards RNG, which has potential to achieve a BCR of 4.3 and NPV of $2.6 billion under the scenario where the price of RNG trucks is 25% lower ($191,250 versus the base assumption of $255,000). The discount rate can have a large impact on the NPV of the RNG scenario, raising the NPV to nearly $7 billion with a discount rate of 3%.

Battery electric and catenary trucks also demonstrate robust economic viability with the BCR of the adoption scenarios for these technologies falling only slightly below 1 to 0.8 under the range of sensitivity analysis considered. The BEV fleet scenarios are most sensitive to the discount rate, purchase price of BEV trucks and the diesel price. The catenary fleet scenarios are also sensitive to these parameters, however the highest sensitivity is demonstrated for the discount rate. A lower discount rate enables the future benefits in GHG mitigation, reduced operating and maintenance expenditure to be more impactful in NPV to offset the high capital cost of the catenary infrastructure.

Overall, the use of a lower discount rate is beneficial to RNG, battery electric and catenary scenarios as future benefits (e.g., lower fuel and maintenance costs, mitigated GHG emissions) are less heavily discounted and thus more impactful to increasing the NPV.

Alternatively, hydrogen technology does not achieve a positive NPV or a BCR above 1. The most favorable scenario is with the price of green hydrogen decreased 50% from the price used in the base scenario ($5.75/kg versus the base assumption of $11.50/kg). A BCR of 0.7 is achieved in this case. In addition, the use of a lower discount rate (e.g., 3% or 7%) makes the hydrogen scenario less favorable. The annual expenditure on fuel (green hydrogen) is greater than diesel fuel and is therefore a disbenefit throughout later years of the forecast and more influential on the NPV with the use of a lower discount rate.

FIGURE 10. SENSITIVITY OF PARAMETERS ON ECONOMIC VIABILITY

Source: CPCS, 2023.

A summary ranking each technology by NPV under each sensitivity scenario is presented in Table 20. RNG tends to perform most consistently with the highest NPV while hydrogen has the lowest NPV. The ranking of BEV versus catenary changes depending on the scenario.

TABLE 20. SUMMARY OF SENSITIVITY SCENARIOS, TECHNOLOGY RANK BY NPV

Sensitivity scenario	Rank of technology by highest NPV ($M)			
	1st	2nd	3rd	4th
Baseline	**RNG**	**Catenary**	**BEV**	**FCEV**
BEV truck purchase +25%	RNG	Catenary	BEV	FCEV
BEV truck purchase -25%	RNG	BEV	Catenary	FCEV
FCEV truck purchase +25%	RNG	Catenary	BEV	FCEV
FCEV truck purchase -25%	RNG	Catenary	BEV	FCEV
Catenary truck purchase +25%	RNG	BEV	Catenary	FCEV
Catenary truck purchase -25%	RNG	Catenary	BEV	FCEV
RNG truck purchase +25%	RNG	Catenary	BEV	FCEV
RNG truck purchase -25%	RNG	Catenary	BEV	FCEV
Diesel fuel +25%	RNG	BEV	Catenary	FCEV
Diesel fuel -25%	Catenary	RNG	BEV	FCEV
Electricity +25%	RNG	Catenary	BEV	FCEV
Electricity -25%	RNG	BEV	Catenary	FCEV
Hydrogen fuel +50%	RNG	Catenary	BEV	FCEV
Hydrogen fuel -50%	RNG	Catenary	BEV	FCEV
RNG fuel +50%	RNG	Catenary	BEV	FCEV
RNG fuel -50%	RNG	Catenary	BEV	FCEV
BEV infrastructure +50%	RNG	Catenary	BEV	FCEV
BEV infrastructure -50%	RNG	BEV	Catenary	FCEV
FCEV infrastructure +50%	RNG	Catenary	BEV	FCEV
FCEV infrastructure -50%	RNG	Catenary	BEV	FCEV
Catenary infrastructure +50%	RNG	BEV	Catenary	FCEV
Catenary infrastructure -50%	RNG	Catenary	BEV	FCEV
RNG infrastructure +50%	RNG	Catenary	BEV	FCEV
RNG infrastructure -50%	RNG	Catenary	BEV	FCEV
Discount rate (at 3%)	Catenary	RNG	BEV	FCEV
Discount rate (at 7%)	RNG	Catenary	BEV	FCEV

Source: CPCS, 2023.

Perspectives on total energy demand

Any transition to net zero for long-haul trucks along the A20-H401 corridor will require substantial infrastructure investment to meet future energy demands. Table 21 is used to illustrate the modeled energy demand for each technology by 2050, in comparison to the current energy production in Ontario and Québec.

Overall, there are significant gaps and a need for considerably scaling the production of RNG and green hydrogen. Whereas for battery electric and catenary trucks the total annual fleet electricity demand by 2050 will amount to approximately 10% of the current generation in Ontario and Québec combined, thereby demonstrating a need to also increase electricity generation, transmission and distribution capabilities. More studies are needed to evaluate future energy demand from net zero long-haul trucking options.

TABLE 21. ESTIMATE ON TOTAL FLEET ENERGY DEMAND BY 2050

Technology	Total fleet annual energy demand by 2050	Current energy production in ON	Current energy production in QC	Combined production ON + QC
Battery electric (BEV)	3.8 TWh	153 TWh	213 TWh	366 TWh
Hydrogen (FCEV)	261 million kg [76]	Unknown	185 million kg	Unknown Canada: 3,000 million kg
Catenary (OCT-ERS)	3.2 TWh	153 TWh	213 TWh	366 TWh
Renewable natural gas (RNG)	4.2 PJ	2.7 PJ	3.8 PJ	6.5 PJ

Sources: Canada Energy Regulator, Whitmore and Pineau (2023) and Statistics Canada, 2023. Table 25-10-0029-01 - Supply and demand of primary and secondary energy in terajoules.

[76] Equivalent to 14 TWh if produced from electrolysis.

Conclusion and recommendations

The analysis conducted is subject to several limitations. The state of advancement towards deploying zero emission trucks in Canada, particularly along the A20-H401 corridor is at a very early stage with only a handful of pilot demonstrations to mention (none in long-haul applications).

Modelling uncertainty and key trends. Given the early-stage maturity of the technologies being assessed and the high-level analysis conducted, there is a wide range of cost and performance parameters available in the research and literature. This study attempted to consolidate and document key modelling parameters and assumptions in a transparent manner so that future work can build upon this analysis. There are several areas recommended for future work described under the section titled *Scope and limits of analysis*.

Opportunities for further analysis with improved data. This study and analysis did not dive into a detailed analysis on the different sub-segments of long-haul trucking activity along the A20-H401 corridor. There is a need for improved data collection and accessibility of such data, to better understand the trucking market in Ontario and Québec. This will enable a more tailored assessment of which technologies could offer the best solution to decarbonization based on unique segments of the market (e.g., understanding origin-destination pairings of trips, commodities and goods transported, ways to optimize routings and optimize the load factor of trucks). For example, BEVs could be more applicable to lighter-haul, larger volume loads (e.g., grocery produce) whereas hydrogen could be more suitable for heavier-haul loads (e.g., steel beam and other construction materials).

Recommendation for a technology neutral approach. Due to an absence of detailed data on the trucking market, it could be preferable to maintain a technology neutral approach to policy development at this time as different technologies may be better suited to decarbonizing different segments of the long-haul trucking market. The scenarios under the analysis assume a homogenous transition to a single technology when there will likely be opportunities for a multitude of different technologies to contribute to the net zero transition.

Despite the caveats noted above and the theoretical modelling exercise of the analysis there are some key takeaways from the results of each technology:

- **RNG** offers a compelling economic rationale for a place in the net zero transition, supported by maturity of natural gas technology. However, RNG trucks still have tailpipe emissions and face criticism of fugitive upstream emissions associated with the storage and transportation of RNG fuel. Furthermore, there is concern over widespread availability and supply limitations of RNG, particularly if demand continues to grow from the transportation sector and other competing sectors (e.g., use for heating in buildings and for industries).[77]

- **Battery electric trucks** continue to receive a significant investment. This is leading to advancements in reducing the cost of batteries, improved range and charging times, all of which will help to address barriers to adoption. The upfront cost to purchase a BEV and charging infrastructure is still prohibitive to many fleets. However, when a lifecycle perspective is taken, BEVs can demonstrate lower total cost of ownership, in comparison to diesel trucks.

Operating range, commercial availability and charging time and infrastructure remain as barriers to scaling adoption. In particular, the time for recharging a BEV can be on the order of a couple hours, compared to minutes for refueling a diesel, hydrogen or RNG truck. Thereby, this can introduce challenges and inefficiencies to operations. Furthermore, the additional battery weight onboard a BEV can reduce the truck's payload capacity, again leading to operational changes to reconfigure or transport a reduced load. The power demands for fast

[77] Dagher, R., et al., 2023. *Biomass and carbon neutrality: putting in place an evaluation framework – Current State in Canada*, Institut énergie Trottier and Transition Accelerator, https://iet.polymtl.ca/en/biomass-and-carbon-neutrality/

charging a BEV also pose significant challenges to the electrical grid, power transmission and distribution systems, by placing a high demand in a very localized charging area and contributing to challenges in managing peak demand on the overall electrical system.

- **Hydrogen fuel cell trucks** currently lag the pace of large-scale commercialization of other technologies, namely BEVs. FCEVs offer the benefits of a greater operating range and a shorter refueling time, in comparison to BEVs. However, adoption hurdles for FCEV technology include a lack of hydrogen fueling infrastructure, the high cost of green hydrogen fuel and high purchase prices for new vehicles as there is limited availability in North America. All of these factors result in the poor economic rationale (at this time) for FCEVs, however the economics will likely improve as FCEV technology and the supply of green hydrogen continues to develop.

- **Catenary trucks** have demonstrated successful pilot deployments at small scale in Europe and in California. They offer significant benefits in terms of lower operating and maintenance costs. Furthermore, trucks connecting to overhead catenary can operate with smaller battery packs, thereby reducing the vehicle purchase price. However, North America lags Europe in terms of experience with catenary infrastructure in road vehicle applications. The upfront capital cost of infrastructure and lack of trials could be a limiting factor for its advancement on Canada's busiest highway corridor.

In summary, net zero technology in the transportation sector is rapidly advancing. In the short term, it may be preferable to maintain a technology neutral approach as a variety of technologies may each bring unique merits for decarbonizing different segments of the long-haul trucking market. As more data becomes available, vehicle and infrastructure specifications and costs continue to improve there is justification for revisiting analysis on long-haul trucking and expanding the scope of analysis to include other areas of interest which were noted as limitations in this study.

Appendix 1 | Abbreviations and units

Abbreviation	Definition
AADT	Average annual daily traffic
AB	Alberta
ATRI	American Transportation Research Institute
AZETEC	Alberta Zero Emissions Truck Electrification Collaboration
BAU	Business-as-usual
BC	British Columbia
BCR	Benefit-cost ratio
BEV	Battery electric vehicle
CAPEX	Capital expenditure
CARB	California Air Resources Board
CFAF	Canadian Freight Analysis Framework
CharIN	Charging Interface Initiative
DC	Direct Current
DOE	Department of Energy
EIRR	Economic internal rate of return
FCEV	Fuel cell electric vehicle
FHWA	Federal Highway Administration
GHG	Greenhouse gas
GIS	Geographic information system
GTHA	Greater Toronto Hamilton Area
HPDI	High Performance Direct Injection
ICCT	International Council on Clean Transportation
IRR	Internal rate of return
ITPTE	Institute for Transport Planning and Traffic Engineering
MCS	Megawatt charging system
MHDVs	Medium- and heavy-duty vehicles
MTO	Ontario Ministry of Transportation
MTMDQ	Ministère des Transports et de la Mobilité durable du Québec
N/A	Not applicable
NATEM	North American Times Energy Model
NPV	Net present value
NREL	National Renewable Energy Laboratory
OCT-ERS	Overhead conductive transmission - electric road system
OPEC	Organisation of the Petroleum Exporting Countries
OPEX	Operating expenditure
RNG	Renewable natural gas
T&D	Transmission and distribution
T&L	Transportation and logistics
UK	United Kingdom
US	United States
V	Volt
ZEV	Zero emission vehicle

Unit	Definition
CO2e	Carbon dioxide and equivalent emissions
GJ	Gigajoules
kg	kilograms
km	kilometres
kWh	Kilowatt hours
L	Litres
m^3	cubic metre
MJ	Megajoule
Mt CO_2e	Million tonnes of CO_2e
MW	Megawatts
MWh	Megawatt hours
PJ	Petajoule
TEUs	Twenty-foot equivalent units

Appendix 2 | Examples of strategic partnerships

Megawatt Charging System (MCS)

The Charging Interface Initiative (CharIN) is a global non-profit organization which has been working in collaboration with industry partners to develop and test a harmonized MCS for heavy-duty commercial battery electric vehicles, notably electric long-haul trucks. The Daimler headquarters in Portland, Oregon will be the testing ground for the MCS. Final publication of the charging standard is expected to be released in 2024.[78]

Germany's ELISA project - Electrified, Innovative Heavy Traffic on Motorways

ELISA is Germany's first collaborative testbed project for electric heavy commercial trucks to charge their batteries using overhead catenary. The project is funded by the German Federal Ministry for the Environment and led by a sub-department of the Hessian Ministry of Economics, Energy, Transport and Housing, (Hessen Mobil) with industry partners Siemens and ENTEGA AG. The Institute for Transport Planning and Traffic Engineering (ITPTE) of the Technical University of Darmstadt oversees the accompanying scientific research.[79]

The Hesse region has the highest traffic congestion of all German federal states with an average flow of 2 million vehicles daily. The trial on both sides of the highway, between Frankfurt and Darmstadt, is 10 km long and operational since May 2019. The stretch is to be extended to 17 km. Extensive field testing will undergo until the end of 2022.[80] All test data such as battery charging state, or fuel rate, and 148 other parameters, is transmitted via a data logger/roof sensor on the truck to the overhead line and onto the researchers from the ITPTE. This is followed up with weekly evaluation interviews with the drivers.

Canada and US Alternative Fuel Corridor

In May 2023, Canada and the US federal governments announced the first Canada and United States Alternative Fuel Corridor. The corridor runs from Kalamazoo, in Michigan, to Québec City. This corridor will have EV charging infrastructure installed every 80 km, including at least one Direct Current (DC) fast charger with Combined Charging System (CCS) ports at each location.

The corridor passes along the I-94 highway, through the tunnel in Detroit to the Canadian side of the border, Highway 401 through Toronto, connecting to Autoroute 20 through Montréal and, Autoroute 40 through Québec City.

Alberta's AZETEC Pilot Program

The Alberta Zero-Emissions Truck Electrification Collaboration (AZETEC) is Canada's first long-haul pilot of zero emissions technology. This pilot features two hydrogen fuel cell trucks, which will operate between Calgary and Edmonton. The trucks have an estimated operating range of 700 km. The trucks consist of a Freightliner Cascadia Class 8 chassis with a fuel cell provided by Ballard Power Systems.

---

[78] Electric Autonomy, "CharIN stages North American launch of its universal charging standard for commercial heavy-duty electric vehicles" (2022) https://electricautonomy.ca/2022/10/13/charin-megawatt-charging-system-standard-north-america/

[79] Interreg Europe 2020, "*Project ELISA – electrified, innovative heavy traffic on highways*" (2023) https://www.interregeurope.eu/good-practices/project-elisa-electrified-innovative-heavy-traffic-on-highways

[80] IWAR, "*ELISA*, Technical University of Darmstadt" (2023) https://www.iwar.tu-darmstadt.de/sur/forschung_sur/projekte_sur/elisa/index.en.jsp

The AZETEC is led by the Alberta Motor Transport Association with industry partners. Bison Transport and Trimac Transport will serve as the operators during the two-year trial. Suncor will supply the hydrogen fuel to two facilities in Edmonton, owned and operated by Air Products and Praxair.[81]

Blue Road Network of CNG stations

In 2011, the Blue Road was implemented as the first public network of compressed and liquefied natural gas refueling stations for Canada's transportation industry. Currently, there are 13 stations between Québec City and Windsor, along Highway 401 and Autoroute 20, of which 6 stations offer RNG.[82] The maximum distance between stations is 250 km.[83] Additional stations will continue to be installed in a flexible and strategic manner throughout Ontario and Québec.

Hydrogen Fuel Cell Truck Manufacturing

Overall, the availability of hydrogen fuel cell trucks is very limited with only a handful of models in development for pilot programs. However, there have been several announcements of manufacturers partnering on the development of hydrogen fuel cell trucks for long-haul applications. These partnerships include the following:

- Volvo Group and Daimler have established a joint venture for commercializing fuel cell technology. Early pilots are scheduled to start within the next 3-years and large-scale production is planned from 2025 onward.[84]
- Hino Trucks and Toyota announced a partnership to start developing hydrogen fuel cell trucks, leveraging Hino's truck chassis and Toyota's fuel cell technology.[85]
- The US Department of Energy has provided grant funding to a collaboration between Navistar and Cummins for the development of a hydrogen fuel cell truck, to be trialed in California.[86]

Collaborations on Vehicle and Fueling Infrastructure

Navistar has announced a strategic partnership with General Motors and OneH2. Navistar will develop a long-haul truck with General Motors' fuel cell technology and OneH2 will provide hydrogen fueling infrastructure. J.B. Hunt Transport Inc., a private T&L company in the US, will be the first to pilot the technology in 2023. Navistar plans for commercialization of the hydrogen truck model by 2024.[87]

81 CESAR, "$15-million project to test hydrogen fuel in Alberta's freight transportation sector" (2019) https://www.cesarnet.ca/blog/15-million-project-test-hydrogen-fuel-alberta-s-freight-transportation-sector

82 Énergir, "The Blue Road, a growing network of resorts" (2023) https://www.cesarnet.ca/blog/15-million-project-test-hydrogen-fuel-alberta-s-freight-transportation-sector

83 NRCan, "Electric Charging and Alternative Fuelling Stations Locator" (2023) https://natural-resources.canada.ca/energy-efficiency/transportation-alternative-fuels/electric-charging-alternative-fuelling-stationslocator-map/20487#/analyze?fuel=CNG&cng_vehicle_class=HD&show_map=true&cng_psis=3600&country=CA&cng_fill_type=Q&cng_has_rng=true

84 Transport Topics, "Trucking Takes Initial Steps Toward a Zero-Emission Future" (2020) https://www.ttnews.com/articles/trucking-takes-initial-steps-toward-zero-emission-future

85 Toyota, "Toyota and Hino to Jointly Develop Heavy-Duty Fuel Cell Truck" (2020) https://global.toyota/en/newsroom/corporate/32024083.html

86 Cummins, "Cummins and Navistar to collaborate on heavy-duty Class 8 truck powered by hydrogen fuel cells" (2020) https://www.cummins.com/news/releases/2020/11/11/cummins-and-navistar-collaborate-heavy-duty-class-8-truck-powered-hydrogen

87 Navistar, "Navistar Collaborates with General Motors And OneH2 To Launch Hydrogen Truck Ecosystem" (2021) https://news.navistar.com/2021-01-27-Navistar-Collaborates-with-General-Motors-And-OneH2-To-Launch-Hydrogen-Truck-Ecosystem

Appendix 3 | Examples of early adopters in Canada

TABLE 22. EARLY ADOPTERS OF NET ZERO TRUCKS IN CANADA

Company	Classification	Corporate Bio	Decarbonization Efforts
Kruger		Kruger is a Québec-based paper manufacturing company that has an energy division. It delivers across Eastern Canada from its plant near Joliette. Kruger Energy owns the trucks, but the equipment is operated by third-party companies.	Kruger received two **Peterbilt 579EVs BEV** class 8 trucks in September 2022. It has placed deposits on 65 electric trucks from Peterbilt, Lion and Tesla.[88] The electric trucks shuttle 24/7 between two locations 71 km apart. Kruger Energy is looking to share its experience with others (e.g., SAQ, Molson Coors, the Port of Montreal).[89]
Amazon	Private fleet operator	North America's largest e-commerce retailer. Amazon owns a private fleet of long-haul trucks, first/last mile delivery vans and other vehicles to manage its supply chains and its express delivery service. Amazon plans to convert delivery fleet to run on **100% renewable energy by 2030**.[90]	Amazon **plans to procure up to 2,500 battery electric trucks** from Lion Electric Co. by 2025.[91]
Walmart	Private fleet operator	North America's largest big-box retailer and **third largest private fleet operator** with over 7,400 trucks.[92]	Walmart intends to **electrify all its vehicles, including long-haul trucks, by 2040**. Walmart Canada has tripled reservations of battery electric Tesla semi-trucks to a total of 130 vehicles. [93]
Loblaws	Private fleet operator	Loblaws is Canada's largest food and pharmacy retailer. Loblaws owns and operates warehousing, distribution centres and a fleet of trucks for first/last mile service, of which 160 are cabin trucks. Loblaws has stated their goal of having a **net-zero fleet by 2030**.[94]	In 2023, Loblaws announced that it will put its very first fully electric **Freightliner eCascadia** heavy truck into service. for hauling grocery produce from from its warehouse in Boucherville. The battery trucks can reach 370 km.[95] **Five additional battery electric trucks** are scheduled for delivery 2023/24.
Trimac Transport	T&L company	Bulk freight trucking company, headquartered in Calgary, AB. Trimac Transport owns and **operates about 2,100 trucks**.[96]	Trimac is one of two operators in Alberta's AZETEC hydrogen trucking pilot.

88 Bouchard, S., 2023, *Kruger Energy learning lessons from electric trucks*, Truck News, published on March 13, 2023, https://www.trucknews.com/sustainability/kruger-energy-learning-lessons-from-electric-trucks/1003173524/

89 Baril, H., 2023. *Verdir le transport lourd, une boucle à la fois*, La Presse, published on January 19, 2023, https://www.trucknews.com/sustainability/kruger-energy-learning-lessons-from-electric-trucks/1003173524/

90 New York Post, "Amazon pledges 100% renewable energy by 2030" (2019) https://nypost.com/2019/09/20/amazon-pledges-100-percent-renewable-energy-by-2030/

91 Electrive, "Huge order for Lion Electric trucks from Amazon" (2021) https://www.electrive.com/2021/01/11/huge-order-for-lion-electric-trucks-from-amazon/

92 Transport Topics, "Walmart Aims to Eliminate Emissions From Its Fleet by 2040" (2020) https://www.ttnews.com/articles/walmart-aims-eliminate-emissions-its-fleet-2040

93 Transport Topics, "Trucking Takes Initial Steps Toward a Zero-Emission Future" (2020) https://www.ttnews.com/articles/trucking-takes-initial-steps-toward-zero-emission-future

94 Loblaw Companies Ltd., "Loblaw Companies Limited moves forward with plans to electrify fleet with the introduction of Freightliner eCascadia" (2021) https://www.loblaw.ca/en/loblaw-companies-limited-moves-forward-with-plans-to-electrify-fleet-with-the-introduction-of-freightliner-ecascadia/

95 Transport Routier, 2023. *Le premier camion lourd entièrement électrique de Loblaw arrive dans le grand Montréal*, published on April 17, 2023, https://www.transportroutier.ca/nouvelles/le-premier-camion-lourd-entierement-electrique-de-loblaw-arrive-dans-le-grand-montreal/

96 Trimble Transportation, "Trimac Transportation" (2022) https://transportation.trimble.com/resources/case-studies/trimac-transportation-2

Company	Classification	Corporate Bio	Decarbonization Efforts
Bison Transport	T&L company	Largest long-haul trucking company in Canada with a fleet of **over 1,400 trucks**.[97] Bison Transport is headquartered in Winnipeg, MB.	Bison is one of two operators in Alberta's AZETEC hydrogen trucking pilot.[98] Bison has **deployed two battery electric Freightliner eCascadia trucks** on a cross-border route between Bison's terminal in Delta, BC and a customer location in Washington state.[99]
Pride Group Logistics	T&L company	Pride Group specializes in the transport of temperature-controlled goods and pharmaceuticals, **operating around 400 trucks**, throughout Canada and the US, with a focus on markets in Ontario and Québec.[100]	**Pride Group has placed the largest order in Canada for 100 battery electric trucks**, Lion6 and Lion8 (Class 6 and 8 models) from Lion Electric Co.[101]
CNTL	T&L company	CNTL, a subsidiary of CN Rail, provides pickup and delivery of intermodal containers between CN terminals and customer locations. **CNTL relies on over 1,000 owner operators** for movement of 1.5 million containers to/from 23 intermodal terminals across Canada.[102]	**CNTL purchased 50 electric trucks** (Class 8) from Lion Electric Co. to be used for container transport from intermodal facilities to customer locations.[103]
Camionnage CP	T&L company	Camionnage CP, based in Greater Montréal, **operates a fleet of over 65 long-haul trucks and 150 drayage trucks**.[104]	Camionnage CP announced the **purchase of a pilot battery electric truck** (Kenworth T680E) for use in **drayage operations** with the Port of Montréal.[105]
Metro Supply Chain Group	T&L company	Metro Supply Chain Group, headquartered in Vaughan, ON, operates a fleet of vehicles for first/last mile delivery to major urban and suburban areas across Canada.	**Metro has ordered six battery electric trucks**, three from Lion Electric Co. and three from BYD, with plans to purchase an additional six battery electric trucks in 2022.[106]

Sources: Multiple, cited in footnotes

97 Trucking Monitor, "Top 15 Trucking Companies in Canada for 2022" (2022) https://www.truckingmonitor.com/top-canadian-trucking-companies/#:~:text=Top%2015%20Trucking%20Companies%20in%20Canada%20for%202022,...%208%20Mullen%20Trucking%20Corporation%20...%20More%20items

98 CESAR, "$15-million project to test hydrogen fuel in Alberta's freight transportation sector" (2019) https://www.cesarnet.ca/blog/15-million-project-test-hydrogen-fuel-alberta-s-freight-transportation-sector

99 Bison Transport, "Bison Transport Tests Full Battery Electric Vehicles (BEV)" (2021) https://www.bisontransport.com/news/article/1/139

100 Pride Group Logistics, "Pride Group Logistics expands US presence with the acquisition of Arnold Transportation Services, Inc." (2022) https://shipwithpride.com/en/pride-logistics-resources-news.php#:~:text=About%20Pride%20Group%20Logistics%3A%20Pride%20Group%20Logistics%20is,with%20terminals%20in%20Ontario%2C%20Quebec%2C%20Alberta%2C%20and%20Illinois.

101 Truck News, "Lion Electric lands largest order with Pride Group" (2021) https://www.trucknews.com/sustainability/lion-electric-lands-largest-order-with-pride-group/1003149939/

102 CN, "CNTL Trucking Services" (2022) https://www.cn.ca/en/our-services/trucking/cntl/

103 CN, "CN Launches New Pilot Project Using Electric Trucks" (2019) https://www.cn.ca/en/news/2019/04/cn-launches-new-pilot-project-using-electric-trucks/

104 Camionnage CP, "Transport Services" (2022) https://www.camionnagecp.com/transport

105 Electric Autonomy, "Kenworth electric truck coming to Canada after Camionnage order" (2021) https://electricautonomy.ca/2021/09/11/kenworth-electric-truck-camionnage-canada/#:~:text=Camionnage%20CP%20has%20placed%20the%20%E2%80%9Cfirst%20order%E2%80%9D%20in,Port%20of%20Montreal%20to%20warehouses%20in%20the%20area.

106 Electric Autonomy, "Metro Supply Chain Group to deploy six electric trucks in 2021 with more to follow" (2021) https://electricautonomy.ca/2021/04/16/metro-supply-chain-electric-trucks/

Appendix 4 | Data sources

[1] Federal Highway Administration [FHWA], 2019. *Table VM-1: Annual Vehicle Distance Traveled in Miles and Released Data – 2019* , Highway Statistics Series 2019, U.S. Department of Transportation, www.fhwa.dot.gov/policyinformation/statistics/2019/vm1.cfm (accessed on October 13, 2022)

[2] Boer, E., Aarnink, S., Kleiner, F., Pagenkopf, J. 2013. *Zero emissions trucks: An overview of state-of-the-art technologies and their potential*, DELFT and CE Delft, commissioned by the ICCT,. https://theicct.org/wp-content/uploads/2021/06/CE_Delft_4841_Zero_emissions_trucks_Def.pdf

[3] Buysse, C., Sharpe, B., Delgado, O., 2021. *Efficiency technology Potential for heavy-duty diesel Vehicles in the United States through 2035*, International Council on Clean Transportation, https://theicct.org/wp-content/uploads/2021/12/efficiency-tech-potential-hdvs-us-2035-nov21.pdf

[4] Natural Resources Canada, "Monthly Retail Prices for Diesel in 2022" (2022) https://www2.nrcan.gc.ca/eneene/sources/pripri/prices_bycity_e.cfm?productID=5&locationID=66&locationID=8&locationID=39&locationID=28&locationID=17&frequency=M&priceYear=2022&Redisplay=

[5] Sharp, B., Basma, H., 2022. *A Meta-study of purchase costs for zero-emission trucks*, ICCT, https://theicct.org/wp-content/uploads/2022/02/purchase-cost-ze-trucks-feb22-1.pdf

[6] California Air Resources Board [CARB], 2019. *Advanced Clean Trucks Total Cost of Ownership Discussion Document. Preliminary Draft for Comment*, February 22, 2019, https://ww2.arb.ca.gov/sites/default/files/2020-06/190225tco_ADA.pdf

[7] Zhao, H., Wang, Q., Fulton, L., Jaller, M., Burke, A., 2018. *A Comparison of Zero-Emission Highway Trucking Technologies.* Institute of Transportation Studies, University of California, Davis, Research Report UC-ITS-2017-50, https://escholarship.org/uc/item/1584b5z9

[8] Earl *et al.,* 2018. *Analysis of long-haul battery electric trucks in the EU: Marketplace and technology, economic, environmental, and policy perspectives,* Amended paper (August 2018) originally presented at the 8th Commercial Vehicle Workshop in Graz, 17-18 May 2018, www.transportenvironment.org/wp-content/uploads/2021/07/20180725_T&E_Battery_Electric_Trucks_EU_FINAL.pdf

[9] American Transportation Research Institute [ATRI], 2022. *Charging Infrastructure Challenges for the U.S. Electric Vehicle Fleet*, December 2022, https://truckingresearch.org/2022/12/06/charging-infrastructure-challenges-for-the-u-s-electric-vehicle-fleet/

[10] Hydro-Québec, 2022. *Comparison of electricity prices*, https://www.hydroquebec.com/business/customer-space/rates/comparison-electricity-prices.html

[11] American Transportation Research Institute [ATRI], 2022. *Charging Infrastructure Challenges for the U.S. Electric Vehicle Fleet*, December 2022, https://truckingresearch.org/2022/12/06/charging-infrastructure-challenges-for-the-u-s-electric-vehicle-fleet/

[12] U.S. Department of Energy [DOE], 2022.*Charging Infrastructure Operation and Maintenance*, Alternative Fuels Data Center, web page, https://afdc.energy.gov/fuels/electricity_infrastructure_maintenance_and_operation.html (accessed on October 5, 2022)

[13] Kane, K., 2020. "Daimler Presents GenH2 Truck Fuel-Cell Concept Truck", *Insideevs*, News article published on September 17, 2020, https://insideevs.com/news/444480/mercedes-genh2-truck-fuel-cell-concept-truck/

[14] Hyundai, 2020. *Hyundai XCIENT Fuel Cell Heads to Europe for Commercial Use*, Press release, July 6 2020, www.hyundai.news/eu/articles/press-releases/hyundai-xcient-fuel-cell-heads-to-europe-for-commercial-use.html

[15] Transport & Environment, 2021. *How to ecarbonize long-haul trucking in Germany. An analysis of available vehicle technologies and their associated costs*, www.transportenvironment.org/wp-content/uploads/2021/07/2021_04_TE_how_to_decarbonise_long_haul_trucking_in_Germany_final.pdf

[16] Meillaud, L., 2020. "Une deuxième station à l'hydrogène prévue au Québec", *H2 Today*, News article published on March 11, 2020, https ://hydrogentoday.info/une-deuxieme-station-a-lhydrogene-prevue-au-quebec/#:~:text=La%20toute%20premi%C3%A8re%20station%20publique%20de%20ravitaillement%20en,%24%29%20et%20Ressources%20naturelles%20Canada%20%281%20million%20%24%29

[17] Koleva, M., Melania, M., 2020. *Hydrogen Fueling Stations Cost*, Hydrogen Program Record, U.S. Department of Energy, www.hydrogen.energy.gov/pdfs/21002-hydrogen-fueling-station-cost.pdf

[18] Kayser-Bril, C., Ba, R., Whitmore, J., Kinjarapi, A., 2021. *Decarbonization of long-haul trucking in Eastern Canada – Simulation of the e-Highway technology on the A20-H401 highway corridor*, CPCS and Chair in Energy Sector Management – HEC Montréal, https://energie.hec.ca/canada-ehighway/

[19] Pedinotti-Castelle. M, Pineau, P.-O., Amor, B., 2020. *Décarbonisation du transport routier des marchandises au Québec : Scénarios de réduction des émissions de GES et électrification*, Chair in Energy Sector Management – HEC Montréal, Rapports d'étude, No 4 |2020], https ://energie.hec.ca/cgse-hec-re042020/

[20] Moultak, M., Lutsey, N., Hall, D., 2017. Transitioning to zero-emission heavy-duty freight Vehicles, https://theicct.org/wp-content/uploads/2021/06/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf

[21] Pollution Probe, "What Does the Future Hold for Natural Gas?" (2019) https://www.pollutionprobe.org/wp-content/uploads/Future-of-Natural-Gas_November-2019_Summary.pdf

[22] Department of Finance Canada, 2021. *Fuel Charge Rates for Listed Provinces and Territories for 2023 to 2030*, Government of Canada, web page, last modified on March 3, 2021, www.canada.ca/en/department-finance/news/2021/12/fuel-charge-rates-for-listed-provinces-and-territories-for-2023-to-2030.html (accessed on February 1, 2023)

[23] Ledna, C., et al. 2022. *Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis*, NREL, www.nrel.gov/docs/fy22osti/82081.pdf

[24] NREL, C. Hunter et al. *Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks*, 2021, https://www.nrel.gov/docs/fy21osti/71796.pdf

[25] Burke, A., 2022. *Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results*, Institute of transportation studies, UC Davis, https://escholarship.org/content/qt1g89p8dn/qt1g89p8dn.pdf

[26] Åkerman, P. 2023 eHighway – Siemens Mobility (Germany) – Meeting

[27] StratON. 2020. Assessment and deployment strategies for catenary-bound heavy-duty, https://www.oeko.de/fileadmin/oekodoc/StratON-O-Lkw-Endbericht.pdf

[28] Doyon F. 2023 *Renewable natural gas (RNG) Decarbonize long-haul trucking today*, https://energie.hec.ca/wp-content/uploads/2023/04/7-DOYON-ENERGIR_PPT.pdf

[29] US Department of Energy. 2014 Costs Associated with Compressed Natural Gas Vehicle Fueling Infrastructure, https://www.osti.gov/biblio/1156975/

[30] Smith R. 2023 Change Energy Services – Meeting

[31] Bower G. 2021. InsideEVs *Tesla Semi 4680 Battery Pack Engineering Analysis*, https://insideevs.com/news/521840/tesla-semi-480-battery-analysis/

[32] Khan M. et al. 2022 The Transition Accelerator, *Techno-economics of a new hydrogen value chain supporting heavy-duty transport*, https://transitionaccelerator.ca/techno-economics-of-a-new-hydrogen-value-chain-supporting-heavy-duty-transport/

[33] PwC, 2023, *Electric vehicles and charging infrastructure, https://www.pwc.com/us/en/industrial-products/publications/assets/pwc-electric-vehicles-charging-infrastructure-mindset.pdf*

Appendix 5 | Sensitivity analysis

TABLE 23. SUMMARY OF PARAMETERS FOR SENSITIVITY ANALYSIS

Parameter	Sensitivity	Rationale
Truck purchase price	+/– 25%	Continued research, development and commercialization of zero emission technologies may help to drive down the price of batteries, fuel cells and other components which could impact the future price of Class 8 trucks. On the other hand, competition from other jurisdictions to purchase zero emission trucks (e.g., California) may impact sector competitiveness and the purchase prices in Ontario and Québec.
Diesel	+/– 25%	Diesel prices are subject to volatility from a variety of macroeconomic factors on the demand side (e.g., economic conditions and industrial activity) and on the supply side (e.g., OPEC decisions on production), both may impact the future of diesel prices.
Electricity	+/– 25%	Electricity prices are complex and depend on several factors including time of use, supply, peak demand and location. Furthermore, different rate structures may emerge as electric vehicle charging continues to mature.
Hydrogen	+/– 50%	Currently, green hydrogen production is limited. Future price volatility may arise due to both supply and demand side factors for green hydrogen as a fuel source (e.g., limitations on supply and competition with other transportation modes for use as a fuel source).
RNG	+/– 50%	RNG is currently available, albeit in limited scale. Future price volatility may arise due to both supply and demand side factors (e.g., availability of supply and competing use cases for heating buildings and for other transportation modes).
Infrastructure	+/– 50%	Infrastructure costs can expect to vary greatly as there is limited deployment of alternative fueling and fast charging stations in Canada, specifically along the Highway 401 – A20 corridor to serve as a basis for scaling reference-based cost estimates. Furthermore, different business models, infrastructure solutions and site-specific conditions (e.g., type of hydrogen fueling station – Section 2.2) will all contribute to variability of estimating future infrastructure costs.
Discount rate	3%, 7%	Guidelines from the federal government suggest discount rates lower than 10% in some cases of project evaluation

Source: CPCS, 2023.

TABLE 24. SUMMARY OF BEV SENSITIVITY SCENARIOS

Scenario	NPV ($M)	BCR	EIRR
Base scenario	$294	**1.1**	**4.0%**
Truck purchase +25%	–$764	0.8	N/A
Truck purchase –25%	$1,352	1.7	21.8%
Diesel fuel +25%	$994	1.3	12.1%
Diesel fuel –25%	–$407	0.9	N/A
Electricity +25%	$179	1.1	2.5%
Electricity –25%	$408	1.1	5.4%
Infrastructure +50%	$150	1.0	1.9%
Infrastructure –50%	$438	1.1	6.2%
Discount rate (at 3%)	$2,722	1.3	11.1%
Discount rate (at 7%)	$835	1.2	6.9%

Source: CPCS, 2023.

TABLE 25. SUMMARY OF FCEV SENSITIVITY SCENARIOS

Scenario	NPV ($M)	BCR	EIRR
Base scenario	**–$2,224**	**0.3**	**N/A**
Truck purchase +25%	–$2,900	0.2	N/A
Truck purchase –25%	–$1,548	0.4	N/A
Diesel fuel +25%	–$1,593	0.4	N/A
Diesel fuel –25%	–$2,854	0.2	N/A
Hydrogen +50%	–$3,999	0.2	N/A
Hydrogen –50%	–$449	0.7	N/A
Infrastructure +50%	–$2,484	0.3	N/A
Infrastructure –50%	–$1,964	0.3	N/A
Discount rate (at 3%)	–$7,908	0.3	N/A
Discount rate (at 7%)	–$3,741	0.3	N/A

Source: CPCS, 2023.

TABLE 26. SUMMARY OF OCT-ERS SENSITIVITY SCENARIOS

Scenario	NPV ($M)	BCR	EIRR
Base scenario	**$295**	**1.1**	**0.9%**
Truck purchase +25%	–$143	0.9	N/A
Truck purchase –25%	$733	1.3	2.1%
Diesel fuel +25%	$925	1.3	2.5%
Diesel fuel –25%	–$336	0.9	N/A
Electricity +25%	$210	1.1	0.6%
Electricity –25%	$380	1.1	1.1%
Infrastructure +50%	–$896	0.8	N/A
Infrastructure –50%	$1,486	1.9	6.2%
Discount rate (at 3%)	$7,074	2.2	7.7%
Discount rate (at 7%)	$1,872	1.5	3.7%

Source: CPCS, 2023.

TABLE 27. SUMMARY OF RNG SENSITIVITY SCENARIOS

Scenario	NPV ($M)	BCR	EIRR
Base scenario	**$1,606**	**2.2**	**29.4%**
Truck purchase +25%	$985	1.5	15.3%
Truck purchase –25%	$2,229	4.3	50.3%
Diesel fuel +50%	$2,569	3.3	58.9%
Diesel fuel –50%	$969	1.9	24.9%
RNG +50%	$1,099	1.8	21.4%
RNG –50%	$2,114	2.6	36.9%
Infrastructure +50%	$1,445	2.0	22.2%
Infrastructure –50%	$1,769	2.6	42.0%
Discount rate (at 3%)	$6,970	2.7	38.2%
Discount rate (at 7%)	$2,958	2.4	33.0%

Source: CPCS, 2023.