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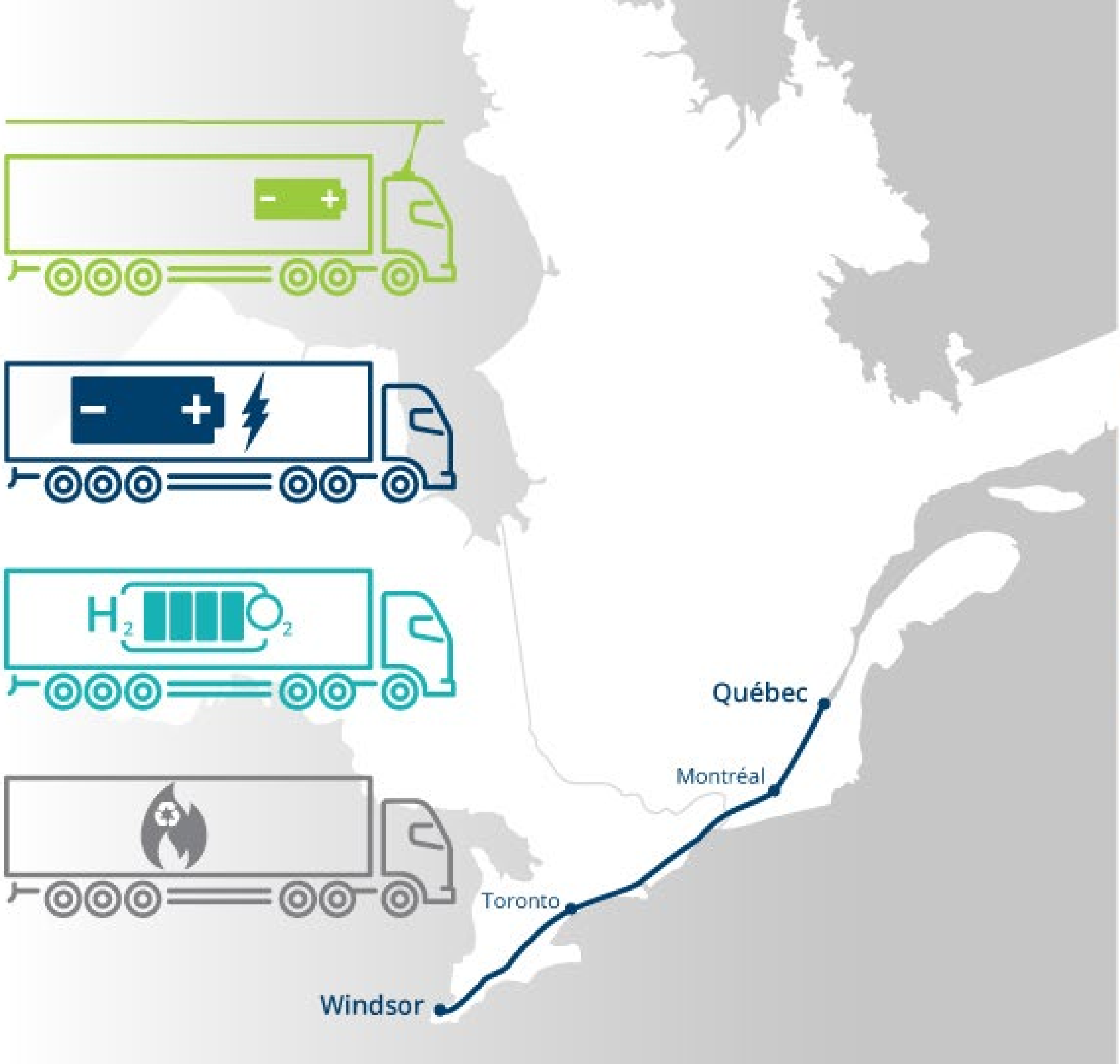

DECARBONIZING LONG-HAUL TRUCKING IN EASTERN CANADA

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

PREPARED FOR
Québec

ACKNOWLEDGEMENT

RESEARCH LEAD – CHAIR IN ENERGY SECTOR MANAGEMENT HEC MONTRÉAL

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FINANCING PARTNER

- **Government of Québec**

INTERMINISTERIAL COMMITTEE

- **Guillaume Paré**, MELCCFP (lead)
- Representatives from MELCCFP, MTMD, MEIE, MFQ

VALIDATION WORKSHOP (PART 1)

- Close to **60 experts** from government, industry and Academia from Canada, US and EU

REPORT REVIEWERS (PART 2)

- **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

PRESENTATION PLAN

1 | Introduction

2 | Net zero technologies for assessment

3 | Methodology, model, assumptions and limitations

4 | Results

5 | Discussion and conclusion

6 | Q&A period

1 | INTRODUCTION

- Freight transportation is one of the most challenging sectors to decarbonize
  - Heavy-duty Class 8 trucks = 24% of Canada's transportation sector's GHGs and growing since 1990
  - Complex (logistics chains, regulations and cross-border traffic…)
  - Supports daily economic activities

- Achieving **Canada's net zero goals by 2050** will require decisive action in this sector, both technologically and logistically

- Current initiatives are insufficient to place Canada, Québec and Ontario on a clear path towards net-zero and zero emission road freight

Web Site: **energie.hec.ca/decabonizing-long-haul-trucking-in-eastern-canada**

WHY DO THIS STUDY?

- Initiatives to decarbonize long-haul road freight are limited due to **lack of transparency, collaboration** and **independent study**. Incoherence within and between governments. Often politicized, technology focused and led by special interests.

- Few studies have assessed the feasibility associated with the potential of decarbonization technologies in long-haul trucking along prominent highway **corridors through Canadian provinces** and into the USA

- Help provide **transparent data and assumptions on the technologies to allow others to use and update the data and the model for further studies and open collaborations**

- **Results can be used within a more systemic approach for decarbonizing long-haul freight** to assess the impacts of different technological and intermodality choices on electricity grid, infrastructure, energy demand, and on reaching GHG reduction targets based on different pathway scenarios (e.g., Energy Modelling Hub, Carbon Free Corridor - University of Windsor)

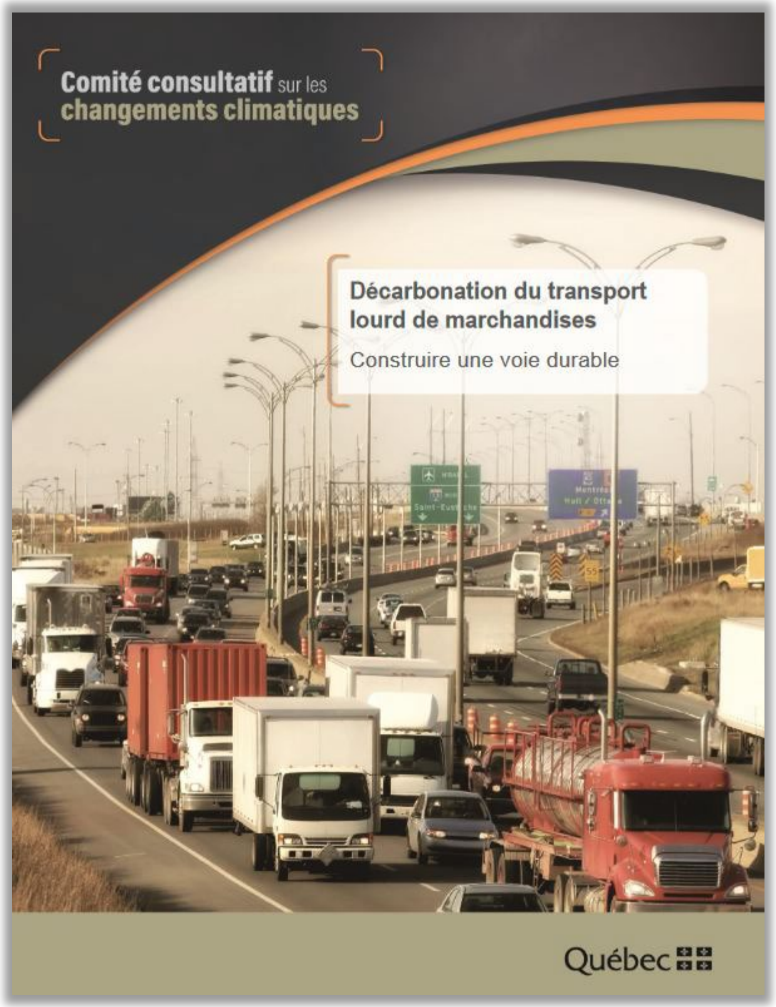
SYSTEMIC APPROACH | Reduce-transfer-improve

Source : Comité consultatif sur les changements climatiques.

Net-zero truck deployment must be within a global strategy that **reduces** demand and **transfers** goods to more energy and GHG efficient freight business models and modes

OUR STUDY'S FOCUS

...and most government approches



See RTI approach described in Sept 2023 Report by Québec's **Advisory Committee on Climate Change**
www.quebec.ca/gouvernement/ministeres-et-organismes/comite-consultatif-changements-climatiques/publications

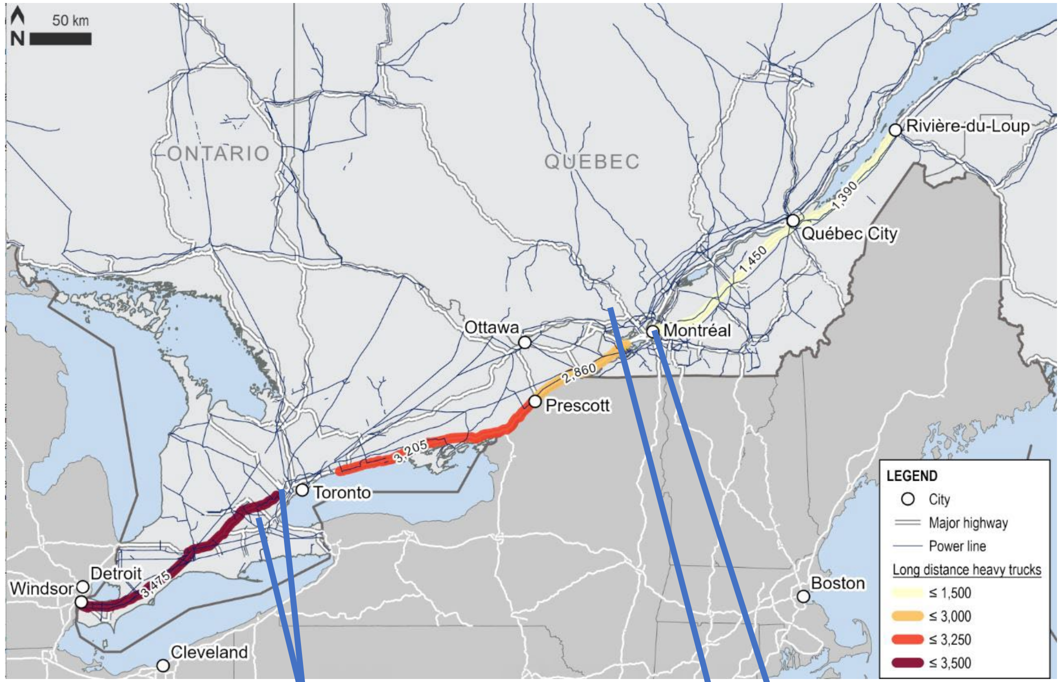
MANDATE AND OBJECTIVE

Conduct a techno-economic assessment comparing Class 8 technologies to decarbonize long-haul trucking (+500 km), with a focus on the highway corridor between Québec City and Windsor

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?

IMPORTANCE OF THE CORRIDOR



Toronto Pearson
300,000 tonnes/year

Hamilton Intl.
122,000 tonnes/year

Port of Montréal
41 Mt per year (total)
1.7 million TEUs

Montréal-Trudeau
81,000 tonnes/year

Mirabel Intl.
79,000 tonnes/year

Corridor highway 401 – Autoroute A20

- Canada's busiest long-haul trucking corridor
- Largest population centres in Canada
  - Greater Toronto Area
  - Montréal
- Hubs for intermodal facilities, warehousing and distribution
- Links cross-border trade with US via Windsor-Detroit
  - Ambassador Bridge
  - Gordie Howe Bridge
- Serves Port of Montréal (2nd largest container port in Canada)
- Connections to major air cargo hubs:
  - Montréal-Trudeau and Mirabel Intl.
  - Toronto Pearson and Hamilton Intl.

Source: Statistics Canada, 2021. Table 23-10-0254-01

PROJECT SCOPE

Step 1
- Identify scope of net zero Class 8 technologies to assess

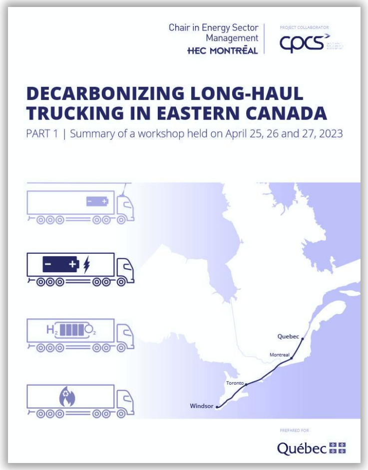
Step 2
- Literature review of techno-economic parameters

Step 3
- Validate data and methodology through expert consultations **(Report part 1)**

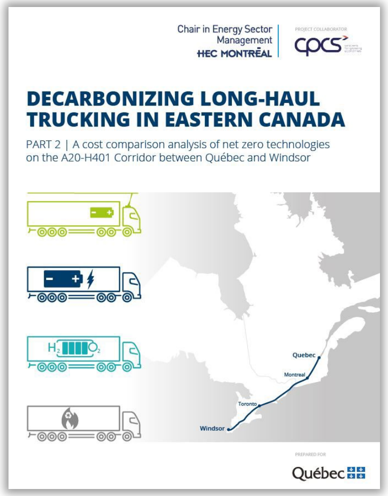
Step 4
- Define operating parameters for simulation and limitations

Step 5
- Cost-benefit and sensitivity analysis scenarios + expert review **(Report part 2)**

PART 1 | Workshop Summary



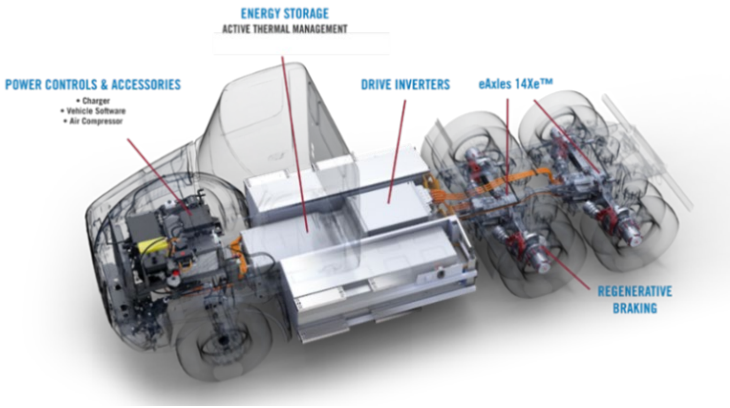
PART 2 | Modelling Results



2 | NET ZERO CLASS 8 TECHNOLOGIES

1. **Battery electric trucks (BEV)**
2. **Green hydrogen fuel cell electric trucks (FCEV)**
3. **Electric road system with overhead catenaries (OCT) w/ dynamic charging of battery pack for range extension**
4. **Renewable natural gas trucks (RNG)**

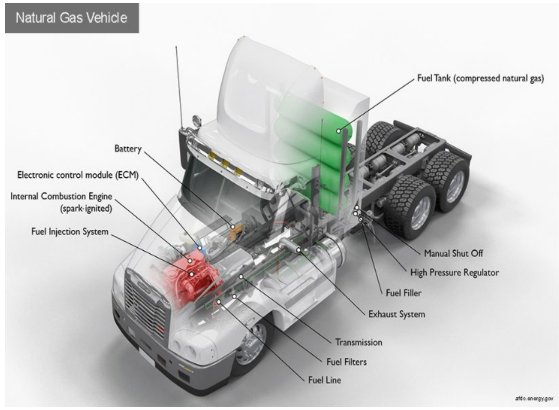
BEV



FCEV

OCT

RNG

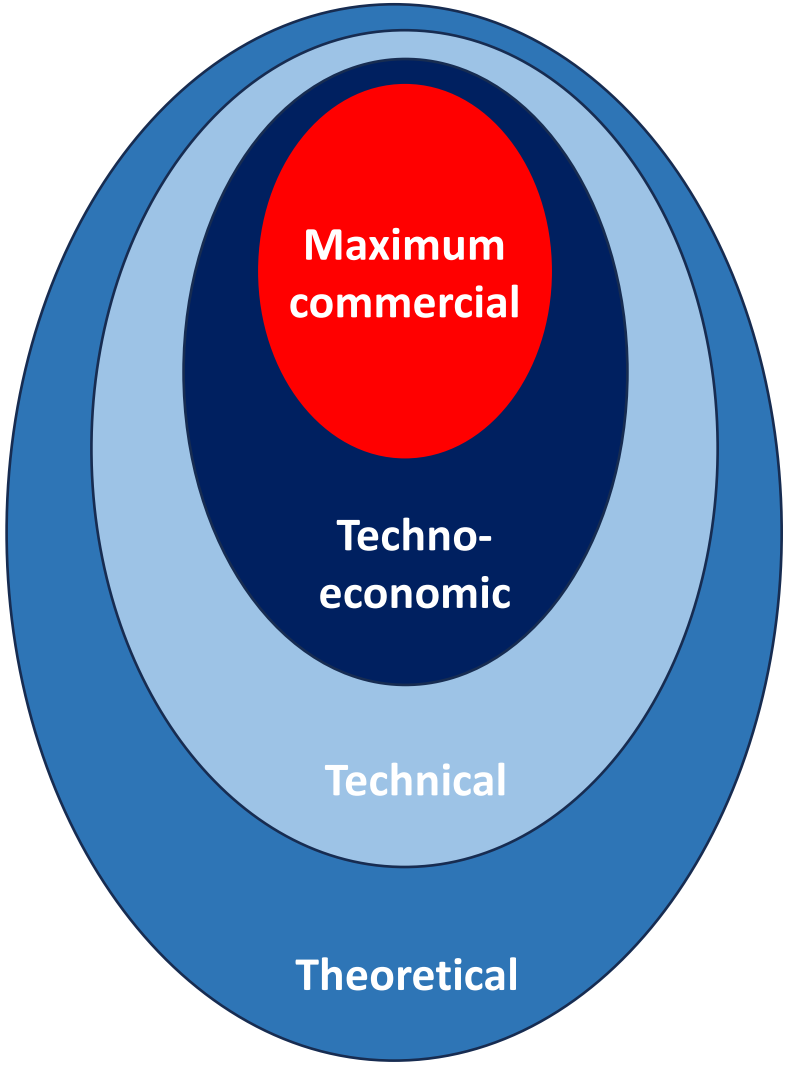


PROJECT ASSESMENT SCOPE

- 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 limitations or market barriers

- **Further studies needed to analyze the maximum commercial potential** which accounts for additional market factors, including
  - Net zero fuel supply and availability (RNG and Green H_2)
  - End use competition of net zero fuels and electricity between road-maritime-aviation transportation, industry and building sectors
  - Evolution of net zero fuel and carbon prices
  - Degree of government intervention

Scope of potentials



3 | METHODOLOGY, MODEL AND ASSUMPTIONS

METHODOLOGICAL APPROCH

Step 1: Identify in scope vehicle technologies to assess

Baseline (BAU):
- Diesel

Net zero technologies:
- RNG
- Battery electric
- Battery w/ catenary
- Hydrogen fuel cell

Step 2: Literature review of technical and economic parameters

- **Vehicle costs and performance specs**
  - Battery / fuel tank size (kWh, L, kg, MJ)
  - Operating range (km)
  - Payload / cargo capacity (kg)
  - Purchase price ($)
  - Major component cost ($) (e.g. battery pack, traction motor, fuel cell, etc.)
  - Energy / fuel consumption (e.g. kWh/km, L/km)
  - Charging / refueling time (minutes, hours)
  - Maintenance ($/km)
  - Operating lifecycle (km, years)
- **Infrastructure costs and performance specs**
  - Unit costs (e.g. $ per station)
  - Charging / refueling capacity and output (kW, L or kg per minute)
  - Cost equivalent per kilometer ($/km) – inclusive of capital and operating / maintenance
- **Socio-economic parameters**
  - Fuel prices ($/L, $/kg, $/MJ)
  - Electricity price ($/kWh)
  - Cost of GHG emissions ($/tonne) – carbon prices (ON and QC)
  - Energy / fuel emissions (CO2e per L or kWh)

Step 3: Validation of data through expert consultations

- **Review input parameters / assumptions on vehicle and infrastructure lifecycle costs with:**
  - Industry, manufacturers, government, academics

Step 4: Define operating parameters for simulation (GIS data)

- **Long-haul trucking, A-20 / 401 statistics**
  - Traffic volumes (number of trucks on highway)
  - Distribution, average of trucking distances (km)
  - Truck stop locations (e.g. potential refueling / recharging) and distance between stops

Step 5: Cost-benefit and sensitivity analysis scenarios

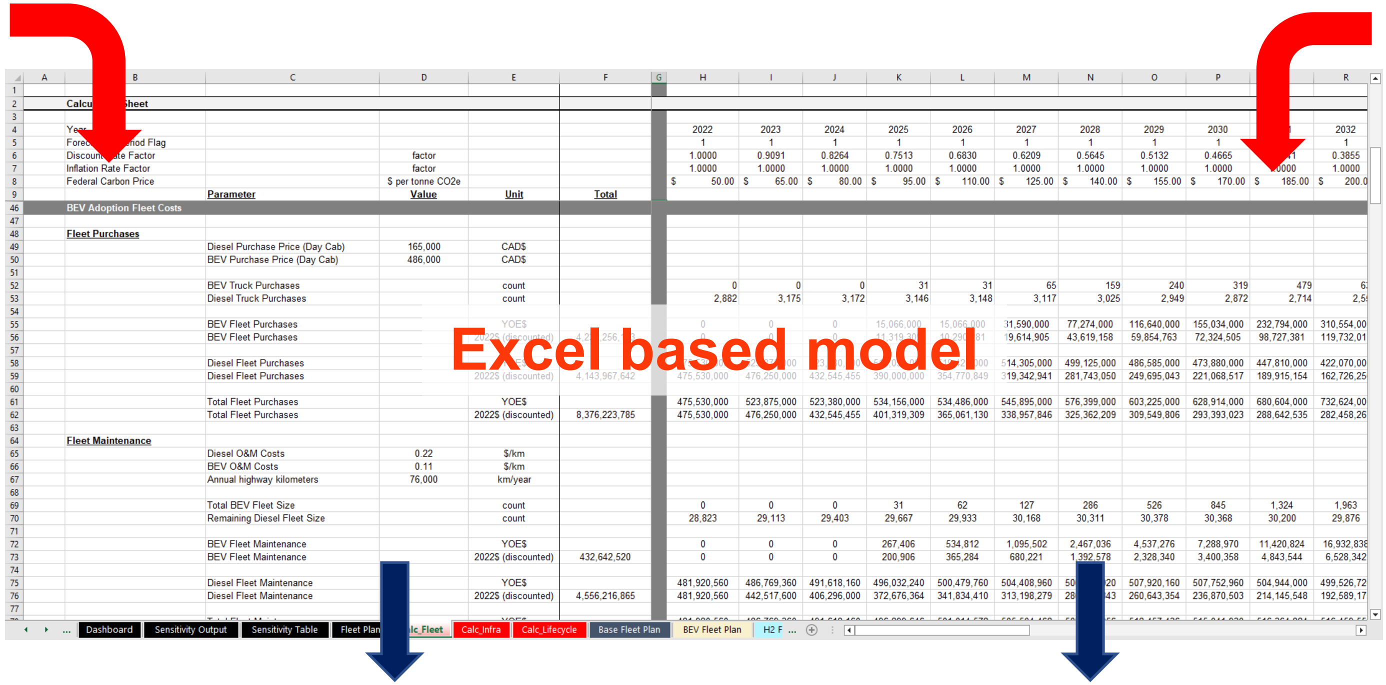
- **Key output metrics:**
  - Total lifecycle cost (vehicle + infrastructure)
    - Breakdown by cost component (e.g. purchase, fuel / electricity, maintenance, infrastructure, etc.)
  - Cost equivalent per kilometer ($/km)
  - Cost $ per tonne CO2e mitigated (technologies compared against diesel as BAU case)
- **Sensitivity analysis:**
  - +/- 25% on key parameters (e.g. purchase price, fuel and electricity prices, infrastructure CAPEX)

- **Out of scope parameters / analysis for CPCS:**
  - Forecasting of fuel prices, component prices and performance improvements (e.g. battery price trends)
  - Forecasting timeline and improvements of upstream electricity / power generation (e.g. grid emissions reduction)
  - End of life costs environmental impacts for disposal / recycling of components

The model compares the costs and benefits with a business-as-usual baseline

Techno-economic parameters of the net zero technologies

Scenario / fleet transition plan for deployment and adoption by the industry



Costs
Vehicles, infrastructure
O&M cost, incl. electricity

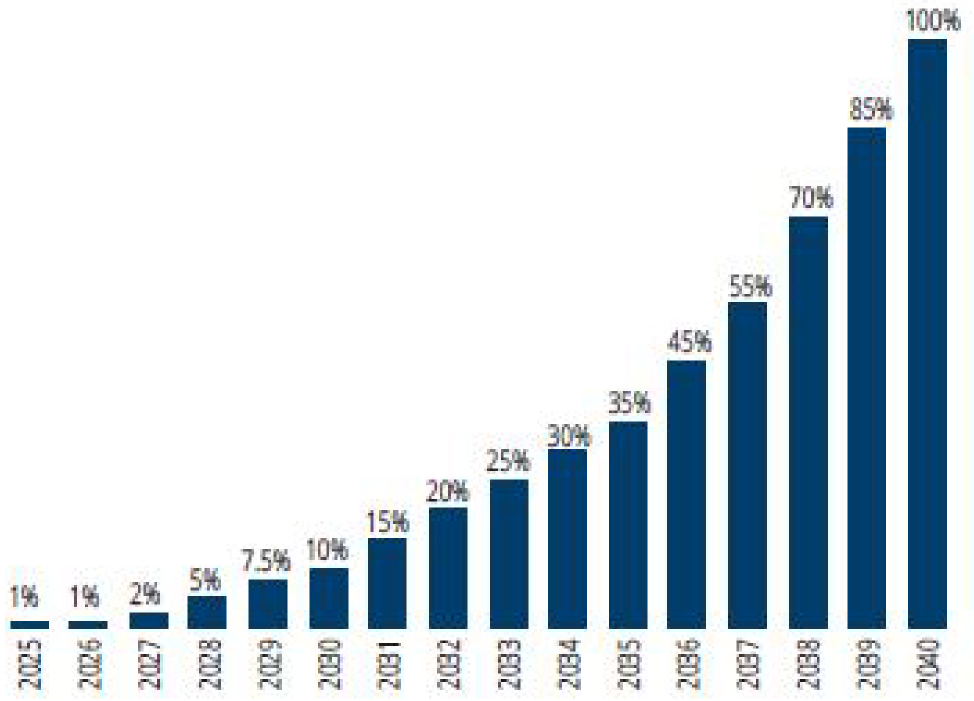
Benefits
Savings on fuel, maintenance
Avoided CO_2

Economic metrics
NPV ($M), EIRR (%), abatement cost ($ per tCO_2e)

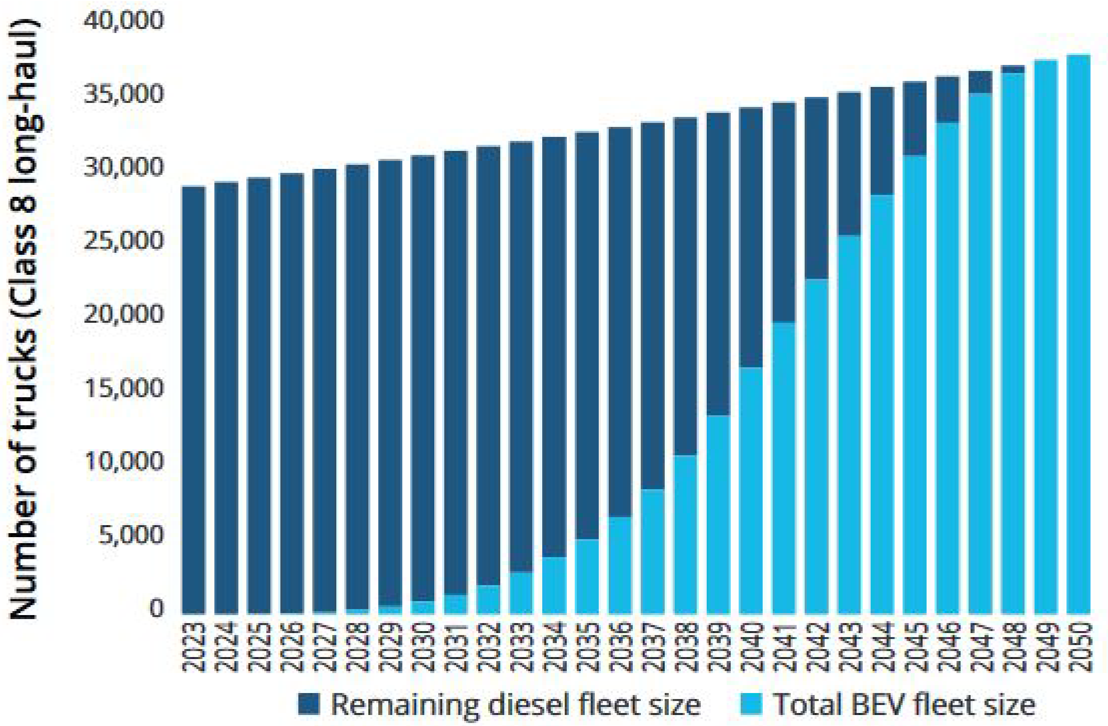
ASSUMPTIONS | Adoption curve

BEV EXAMPLE

Assumed forecast on percentage of new trucks sales



Fleet transition modeled for BEV trucks



- Average truck lifecycle 10 years, 10% **fleet renewal** each year
- 1% annual growth rate in **fleet size**, based on past trends
- Alignment with federal sales mandates, **100% ZEVs sold by 2040**

ASSUMPTIONS | Phased infrastructure implementation

1. Estimate fleet energy demands
2. Assumptions on charging / refueling station output
3. Divide total energy demand by station output
4. Scale infrastructure according to future energy needs
5. Use in model for CAPEX, OPEX

CATENARY EXAMPLE

Infrastructure phased installment – highly trafficked segments first

Highway segment	Priority	Infrastructure installation period	OCT 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)

LIMITES OF ANALYSIS

1. Analysis on additional routes (roads / highways) connecting to the A20-H401 corridor
2. Impact of vehicle weight on road maintenance
3. Additional mitigation benefits of air pollutants
4. End-of-life costs and considerations
5. Availability of renewable energy supply
6. Forecasting of energy prices
7. Forecasting of component prices and performance improvements
8. Detailed analysis of infrastructure types and costs
9. Costs and GHG emissions associated with upstream energy
10. Decarbonization path of electricity power generation
11. Other upstream factors in the energy supply chain

4 | RESULTS

TWO PERSPECTIVES

Each net zero technology was assessed under two perspectives:

1. 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

2. TRUCK PERSPECTIVE

Assessing the total lifecycle costs of a single Class 8 long-haul truck over its typical 10-year life

CORRIDOR PERSPECTIVE

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
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%

- **RNG, BEV and OCT all have potential for negative GHG abatement costs**, meaning that cost savings can be achieved from implementing these technologies relative to diesel trucks.

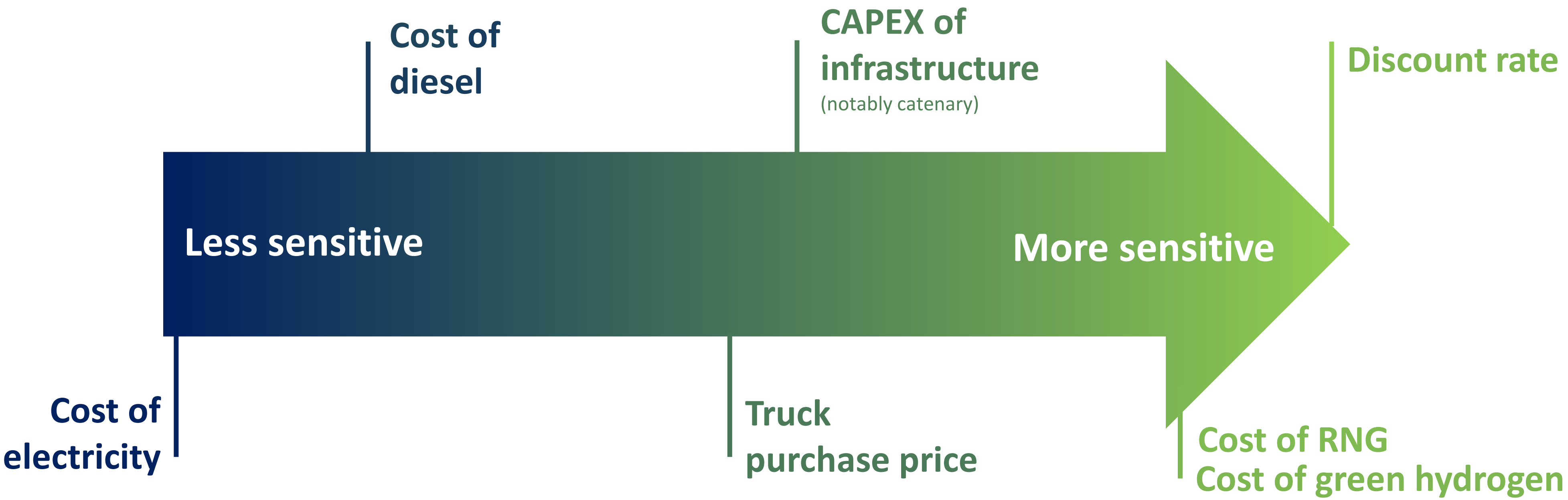
- **RNG: On a strictly economic evaluation, RNG trucks tended to perform the best under base assumptions**
  - Positive NPV: $1,606 million; BCR: 2.2

- **BEV: Electric battery trucks (in a tie with catenary trucks) showcase the second most favorable performance**
  - Positive NPV: $294 million; BCR: 1.1

- **OCT-ERS**: **Despite the high capital cost for the overhead infrastructure, investment is recovered due to lower operating costs**
  - Positive NPV: $294 million; BCR: 1.1

- **FCEV: Hydrogen trucks do not achieve a positive NPV or a BCR above 1**
  - Lower hydrogen fuel prices and FCEV purchase costs will make a more favourable economic case

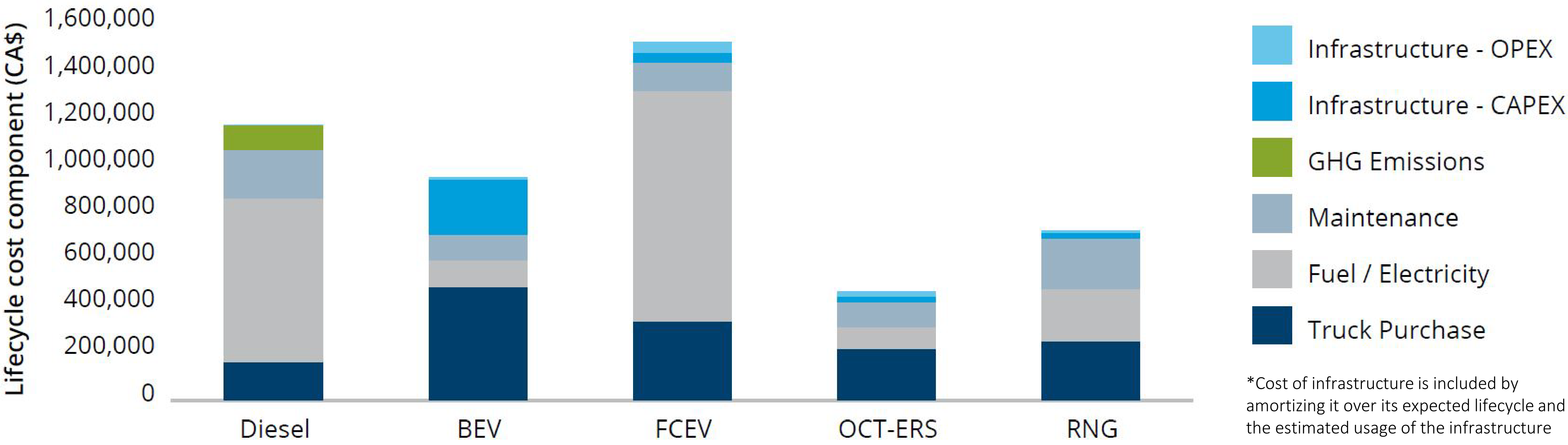
CORRIDOR PERSPECTIVE | SENSITIVITY



PARAMETERS

- Truck purchase price +/- 25%
- Cost of diesel fuel +/-25%
- Cost of electricity +/-25%
- Cost of green hydrogen +/-50%
- Cost of RNG +/-50%
- Infrastructure +/-50%
- Discount rate (3% and 7%)

TRUCK PERSPECTIVE



*Cost of infrastructure is included by amortizing it over its expected lifecycle and the estimated usage of the infrastructure

- **Lifecycle cost for all net zero technologies is lower than diesel, except for hydrogen (FCEV)** due to high cost of green hydrogen, vehicle and fueling stations

- **Catenary trucks (OCT-ERS) have the lowest lifecycle cost per truck**

- **Catenary benefits by dispersing infrastructure costs over a longer lifespan** (50 years) and large number of trucks utilizing the infrastructure, which helps to lower the cost per truck

AVOIDED EMISSIONS AND ENERGY DEMAND

- **Avoided GHG emissions** 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.

- **Outlook on energy demand**
  - RNG and FCEV: significant gap in data and to considerably scale the production
  - BEV and OCT: energy demand by 2050 will amount to approximately 1% of the current generation in Ontario and Québec combined
  - **Significant upgrades to electrical T&D infrastructure will be required**

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 [72]	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	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.

5 | DICUSSION AND CONCLUSION

DISCUSSION | BENEFITS AND CHALLENGES (1)

Class 8 Technology	Benefits	Challenges
Battery electric (BEV)	• Savings on fuel, maintenance • Overall lower lifecycle cost • Positive NPV, EIRR • High energy efficiency	• Additional battery weight impacts on payload, road wear • Charging time (~hours) impact on efficiency • High localized power demand for fast charging • Upfront capital for trucks, infrastructure • Commercial availability / maturity
Renewable natural gas (RNG)	• Technological maturity • Operating range, refueling time, payload similar to diesel • Interchangeability with CNG • Overall lower lifecycle cost • Positive NPV, EIRR	• Limited supplies and availability of sustainably-sourced RNG • High end-use competition (e.g., building, industry, maritime, aviation) • Upstream fugitive emissions associated with the storage and transportation of RNG fuel • Tailpipe emissions • Energy inefficient compared to diesel

DISCUSSION | BENEFITS AND CHALLENGES (2)

Class 8 Technology	Benefits	Challenges
Catenary (OCT-ERS)	• Technological maturity in rail and urban mass transit • Fewer range and payload constraints (compared to BEV) • Savings on fuel, maintenance • Lowest overall life-cycle costs • Positive NPV, EIRR • Highest energy efficiency	• High CAPEX for infrastructure • Less familiarity in North American context • Needs decisive government leadership
Green hydrogen (FCEV)	• Operating range, refueling time • Payload similar to diesel	• High cost of green hydrogen • Limited supplies and availability of green hydrogen • Limited commercial availability / maturity of trucks and fuel stations • High upfront costs for trucks and infrastructure • Poor economics (currently) negative NPV and EIRR • High end-use competition (e.g., industry, fertilizers, maritime, aviation) • Lowest energy efficiency

CONCLUSIONS

Reducing GHGs saves money.
RNG, battery-powered trucks and catenary trucks all have the potential to reduce total lifecycle cost.

Catenary trucks have the potential to reduce operating costs and overall energy demand.
If infrastructure investments are made, operating costs are significantly reduced for vehicle operators.

Long-term perspective and coordination required.
Whichever net zero technology is chosen, increased government leadership is needed for their deployment.

Net zero technology in the transportation sector is rapidly advancing.
Need for revisiting analysis as truck / infrastructure specifications improve.

Modeling uncertainty and key trends.
Wide ranges exist for cost and performance parameters given the early-stage maturity of technologies.

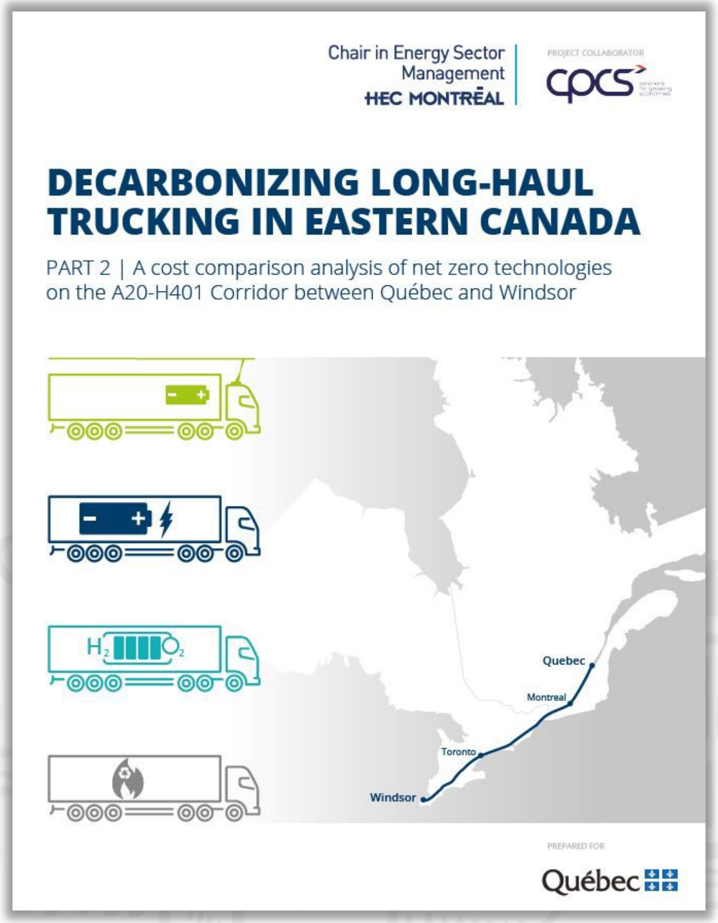
Need access to improved and transparent data, studies and more field trials.
Allows for better accounting of the trucking market and enables a tailored assessment of net zero options based on data of technologies operating under real conditions.

Need a more systemic approach (reduce-transfer-improve) that accounts for the **maximum commercial potential**

- E.g., sustainable RNG and Green H_2 fuel supply and availability; end use competition of net-zero fuels between road-maritime-aviation transportation, industry and building sectors; future electricity, fuel and carbon prices

Download the reports (Parts 1 and 2), presentation, recording, and Excel simulator:

energie.hec.ca/decabonizing-long-haul-trucking-in-eastern-canada



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6 | Questions