NATURAL GAS AS A FUEL FOR MINE HAUL TRUCKS

NRCan Contract #: 3000631963

FINAL REPORT

Submitted to:

Natural Resources Canada

580 Booth Street

Ottawa, ON K1A 0E4

Prepared by:

InterGroup Consultants Ltd.

500-280 Smith Street

Winnipeg, MB R3C 1K2

March 30, 2017

InterGroup

CONSULTANTS

InterGroup® CONSULTANTS

Suite 500-280 Smith Street
Winnipeg, Manitoba
R3C 1K2
tel: (204) 942-0654
fax: (204) 943-3922
e-mail: intergroup@intergroup.ca

March 30, 2017

Todd Stiles, Senior Manager,
Heavy Duty Vehicles Programs,
Transportation and Alternative Fuels Division,
Office of Energy Efficiency/Energy Sector
Natural Resources Canada
580 Booth Street
Ottawa, ON K1A 0E4

Todd.Stiles@canada.ca

Dear Mr. Stiles:

Re: NRCan Contract #: 3000631963 - Natural Gas as a Fuel for Mine Haul Trucks Study

Please find enclosed a PDF version and a Microsoft Word version of the Final Report for Natural Resources Canada on the above contract study prepared by InterGroup Consultants Ltd. in association PROLOG Canada.

The Final Report reviews current challenges and opportunities associated with fueling mine haul trucks with natural gas in Canada and provides summary conclusions and recommendations for future work. It also addresses the comments provided by NRCan and others on the March 3, 2017 Draft Report.

Thank you for the opportunity to work on this report.

Yours truly,

INTERGROUP CONSULTANTS LTD.

Cam Osler
Chair/Principal

Attachment

EXECUTIVE SUMMARY

InterGroup Consultants Ltd. ("InterGroup") was retained by Natural Resources Canada ("NRCan") in January 2017 to produce a report on natural gas as a fuel for mine haul trucks (the "Study").

The overall objective of the Study was to summarize current challenges and opportunities associated with fueling off-road mine haul trucks with natural gas in Canada.

The basic opportunity presented is a displacement of diesel fuel with natural gas to obtain lower fuel costs and reductions in Greenhouse Gases (GHG) and air pollutants. The basic challenge is gaining access to reliable technology for natural gas use in mine haul trucks and establishing the infrastructure required to secure and use natural gas at open pit mine sites.

The Study covered an assessment of potential market features, survey of current state of natural gas fuel mine truck technologies, assessment of a few defined scenarios for natural gas use to displace diesel fuel for mine haul trucks, and a summary of conclusions and recommendation on future work.

Assessment of **potential market features** for mine haul trucks in Canada indicated as follows:

- A total of 1,991 mine haul truck units currently in use in Canada (90 tonne payload up to 363 tonne payload). The vast majority of these mine haul trucks are in Alberta (60%), B.C. (20%), Quebec (5%), Ontario (4%), and Newfoundland & Labrador (3%) in the sectors of oil sands, coal, copper, gold, and iron. Almost 60% of these units are 218 or more tonne payload.
- Diesel fuel requirements in Canada today for mine haul trucks are estimated at 1,650 to 1,800 million litres per year, indicating a large potential for natural gas to displace diesel. Oil sands account for about 45% to 50% of this Canadian total. Fuel requirements are concentrated in the larger mine haul truck units, with 52% of the total fuel for units 290 tonnes or more payload and a further 27% for units of 218-255 tonnes payload.

Assessment of the **market opportunity for natural gas use** in mine haul trucks highlighted the need for liquefied natural gas (LNG) in order to enable adequate mine haul truck fuel storage over at least a full 12 hour shift, and for the LNG supply to be provided to the mine site by adequate year-round road access. Delivered costs at mine sites for natural gas versus diesel fuel are affected by the following:

- Commodity costs for crude oil and natural gas - show projected low prices for natural gas relative to crude oil today and in the coming decades, e.g., NEB forecasts show crude oil price per GJ at 3.3 times higher cost than natural gas in 2015, increasing to 4 times higher cost by 2040.
- Delivery fuel costs at each mine site - these include refining costs and market pricing for diesel fuel, liquefaction processing costs for LNG, and transportation costs for the fuel to each mine site. Examples at northern locations (e.g., Yukon) show commodity costs accounting for 50% or less of delivered diesel fuel cost and less than 20% of delivered LNG cost.
- Mine site locations and available LNG supplies - costs for mine haul truck LNG use can vary considerably depending on mine site location and the level of LNG supply development in the region. LNG supply availability for domestic markets in Canada has been improving dramatically throughout most regions in recent years.

- Reductions in crude oil prices in recent years - these reductions reduced the absolute dollar commodity cost saving per GJ from use of natural gas versus diesel fuel, which can adversely affect LNG's competitive ability to yield expected delivered fuel cost savings at mine sites.

Review of **natural gas fuel mine haul truck technologies** confirmed the following potential range of opportunities:

- Existing technologies in Canada are limited mainly to LNG-dual fuel conversions provided by GFS Corp., an after-market supplier, for limited Komatsu and Caterpillar models with about 50% average diesel displacement. This GFS technology was used in the recent Teck FRO coal (B.C.) pilot and the Alpha Natural Resources (Wyoming) pilot studies. Results from these pilots remain confidential and proprietary, beyond public comments about not meeting expected emission reductions. To date, no operation in Canada or Wyoming is known to have implemented ongoing commercial operations with this technology.
- Trolley assist mine truck electrical option is another existing technology suited for mine haul trucks in some open pit mines. At remote site operations where power is generated on site using LNG, this would enable natural gas to displace diesel fuel for mine haul truck use without requiring new vehicle conversions beyond what is needed for commercial trolley assist operation.
- In Canada and abroad various other emerging natural gas technologies in mine haul trucks are being developed or tested including Caterpillar's dual fuel Dynamic Gas Blending (60-70% diesel displacement), Caterpillar and Westport working toward a High Pressure Direct Injection system (90-95% diesel displacement), Australian experimentation with High Density Compressed Natural Gas (more than 80% diesel displacement), and Rolls Royce experimenting with Spark Ignition technology (100% diesel displacement). Due to confidentiality, limited information is known on the commercialization and state of readiness of these options.
- Potential reductions in air emissions from use of LNG to displace diesel fuel have been estimated for GHG (20% to 35%) and specific air pollutants, i.e., NOx (31% to 40%, potentially up to 97%), SOx (74% to 100%), particulate matter (50% to 89%), as well some other emission reductions. Confidentiality restricts access to information on actual field results in pilots or other tests.

Assessment of **potential maximum natural gas use scenarios** for mine haul trucks in Canada indicated the following:

- Annual fuel cost savings (2016$) of $134 to $537 million with 50% diesel displacement, and $255 to $1,021 million with 95% diesel displacement; approximately 50% of these cost savings would be in the oil sands sector, and about 56% of the oil sands savings would be from 308+tonne payload trucks.
- Annual GHG emissions reduction of 0.72 million tonnes [CO_2e] with 50% diesel displacement, and 1.37 million tonnes [CO_2e] with 95% diesel displacement; approximately 50% of these GHG emission reductions would be in the oil sands sector.

Review of **factors affecting actual natural gas use and timing** for mine haul trucks in Canada highlighted the following:

- Actual and projected savings per GJ in delivered fuel prices for LNG versus diesel fuel, i.e., these need to be sufficient to attract mine haul operator commitments;
- Fluctuations in diesel fuel prices that create concerns about sustainable levels of cost savings from use of LNG (this appears to have impacted some situations in recent years);
- Adequate year-round road access for LNG to mine sites;
- Specific issues for converting existing mine operations to use LNG for mine haul trucks, (e.g., disruption of operations, new upfront costs, staff training, etc.) compared with planning for LNG use from the outset at a new mine development;
- Confirmation of reliable mine haul truck unit performance with natural gas fuel, with strong OEM commitment (the lack of OEM supplied and strongly supported natural gas units prevents the higher displacement scenarios from commencing, and likely also severely limits potential adoption of the 50% conversion technologies); and
- Adequate LNG supply chain development in reasonable proximity for mine sector use, with confidence of expanding LNG supplies and secure pricing arrangements.

Overall opportunities for natural gas use to improve economics at some mine sites can enhance mine haul truck opportunities to use this fuel, e.g., mines with opportunities to use LNG rather than diesel for power generation and/or concentrate shipping, heating, or rail shipments. Examples could include large mines in Newfoundland and Labrador, Quebec and in other provinces and territories that currently rely on diesel for electricity generation, or future mine developments in these regions. Those investment decisions will also be impacted by government regulations, such as carbon taxes, government plans, such as roads and other infrastructure developments for rural areas, and investment decisions by other parties, such as NG facility development in near proximity to the mine site or other supply improvements.

The Study provides **recommendations for future research,** including research regarding: mobile methane emissions monitoring, GHG lifecycle emissions analysis, standards for mobile LNG refueling, high performance LNG fuel storage and delivery systems, durability of vacuum insulated LNG on-board tanks in high vibration mine haul truck environments, pilot projects for emerging high performance and high substitution engine technologies, and safety aspects of natural gas handling and use.

The Study also provides **other recommendations** for LNG supply chain development, and a focused and coordinated effort for LNG to displace diesel fuel for mine haul trucks in Alberta's oil sands sector.

Contractor: InterGroup Consultants Ltd.
Address: 500-280 Smith Street
Winnipeg, MB R3C 1K2
Phone: (204) 942-0654
Fax: (204) 943-3922
Website: www.intergroup.ca

Contract award date January 16, 2017.

TABLE OF CONTENTS

ATTACHMENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

InterGroup Consultants Ltd. ("InterGroup") was retained by Natural Resources Canada ("NRCan") in January 2017 to produce a report on natural gas as a fuel for mine haul trucks (the "Study").

Section 1 reviews the Study objectives and scope, the methodology and approach adopted, and the structure of this report.

1.1 STUDY OBJECTIVES AND SCOPE

The Study's overall objective is to summarize the current challenges and opportunities associated with fueling off-road mine haul trucks with natural gas in Canada. The Study relied on readily available information and data sources.

Large off-road mine haul trucks operated with diesel fuel are used throughout different provinces and territories of Canada in a diverse range of open pit operations for oil sands (synthetic crude extraction), coal mining, and a diverse range of other mines (e.g., copper, iron, gold, and other minerals).

The basic opportunity for benefits from displacing diesel fuel with natural gas in this market is lower fuel costs and reduction in greenhouse gases (GHG) and air pollutants (NOx, SOx, PM, HC and CO). The basic challenge is gaining access to reliable and proven technology for natural gas use in mine haul trucks, as well as establishing the entire required related infrastructure to secure and use natural gas at open pit mine sites.

The Study's scope and objectives more specifically cover the following:

1. Assessment of potential market features, focused on the following:
    a. The off road mine haul diesel fuel market in Canada by different regions and economic sectors (e.g., oil sands, coal, other open pit mines), including the number of large off road mine haul trucks, estimated current annual diesel fuel consumption by these trucks, and (ideally) perspectives on future trends in this market over the coming decades.
    b. The broad opportunity for use of natural gas to displace diesel fuel, based on projections of natural gas supplies and the price of natural gas versus crude oil and diesel fuel in the coming decades.
2. Survey of current state of natural gas fueled mine truck technologies (including truck fuel storage tanks, and refueling and on-site fuel supply logistic options) by major suppliers to describe and compare (e.g., advantages/disadvantages, state of readiness, risks and uncertainties) to the extent feasible at this time, the following:
    a. The range of technology options (current and emerging) for large mine haul truck use of natural gas, including survey of pilot projects and/or actual commercial use inside and outside Canada, and state of readiness for these technologies, e.g., currently available for commercial use versus current estimates of when expected to be commercially available in future.

   b. Applicability of specific technology to different mine haul trucks (scale and Original Equipment Manufacturer ["OEM']).

   c. Estimated economic impact factors with use of natural gas with each technology option (modification costs for existing units, costs for new units, impact on diesel fuel displacement [at idle and low RPM use as well as at high RPM use], any other comparative cost impacts for open pit mine operators compared with continued reliance only on diesel fuel, e.g., ability to work a full normal shift without lost time for more frequent refueling, need to maintain both diesel and natural gas fuel supplies on site).

   d. Estimated air emission impact factors with use of natural gas with existing technology option (expected changes in GHG emissions and pollutant emissions).

   e. Overall assessment of these technology options to define a few scenarios that reflect simplified assumptions of different possible natural gas displacement of diesel fuel in mine haul trucks.

3. Assessment of a few defined scenarios for natural gas use to displace diesel fuel for mine haul trucks in Canada, based on the outcomes of each of the market assessment and technology survey, plus consideration of off-site natural gas supply chain issues and requirements that may affect potential use for certain open pit mine locations. The scenarios will assess high level potential business case and air emission impacts from natural gas use, and comment on uncertainties, barriers and risks e.g., identification of economic, technological, regulatory and societal risks, barriers and uncertainties affecting potential use of natural gas for mine haul trucks in Canada.

4. Summary of conclusions and recommendations on future work studies/research to address identified issues and to enhance the opportunities for natural gas displacement of diesel fuel in mine haul truck fleets.

The study did not focus on safety, regulations and maintenance which each could present issues in adopting natural gas in mine haul trucks. It is expected that the vehicle component systems will be adequately designed to meet the applicable standards (CSA B109, SAE J2343/J2645); however, NRCan has noted relevance for modeling of, and risk analysis of, methane explosions. The recommendations section has been expanded accordingly to include research on safety aspects of natural gas handling and use.

1.2 METHODOLOGY AND APPROACH

The approach for the Study focused on preparing a report within the specified timelines that provided an updated overview of what can be determined on natural gas opportunities to displace diesel in the off-road mine haul truck sector based on readily available and public information and data sources.

At the outset, work focused on two separate activities:

1. Assessing the existing off-road mine haul truck sector diesel fuel use market; and

2. Survey of natural gas fuel mine haul truck technologies.

Initial information highlighted reliance in on liquefied natural gas ("LNG") for natural gas use in mine haul trucks, in large part to facilitate storage on the vehicles of adequate fuel for a normal 12 hour shift operation. Ongoing investigations therefore assumed a need for LNG as part of the natural gas supply chain for mine haul truck use of this fuel.

The diversity of the off-road mine haul truck sector in Canada created challenges in securing readily available information and data on current and projected diesel fuel use. There is no overall data set for fuel use by these trucks. In response to this challenge, the approach utilized a range of credible information for estimates of this diesel fuel use based on review of the 2014 National Inventory GHG Emissions Report data for off-road fossil fuel use in transportation, other available information regarding GHG emissions per unit of diesel fuel, a Casino Mine case study,[1] an oil sands case study,[2] and data on existing mine haul truck numbers by size group, sector and jurisdiction as provided by The Parker Bay Company. Additional information on future prospects for natural gas use was derived from the National Energy Board (pricing forecasts and scenarios), the US Energy Information Administration (pricing forecasts and scenarios), and data utilized from Yukon Energy (LNG supply chain development examples).

A focus on technologies for natural gas use in large mine haul trucks led to a specific set of conversion kit options (i.e. Gaseous Fuel Systems Corp.), limited and relevant OEM technologies (e.g., Caterpillar, Komatsu, and related work undertaken by Westport), one recent pilot study in Canada (i.e., Teck Fording River Operations pilot), and a few pilot or other studies outside Canada (e.g., Alpha Natural Resources in Wyoming, and work in Australia on a compressed natural gas option for mine haul trucks). Accordingly, key person interviews and/or other information exchanges (e.g., e-mail) were sought out with representatives of these organizations, and also with representatives of LNG suppliers (FortisBC and Gaz Metro) and interested third parties (e.g., Canadian Natural Gas Vehicle Alliance (CNGVA), National Research Council (NRC), and the Clean Energy Research Committee at UBC). Due to the competitive market and proprietary information constraints, confidentiality often limited the information that could be obtained for the Study, and available studies and publicly available information were therefore also reviewed to provide a solid basis for an updated overview of these technologies.

The scenario analysis on potential future natural gas use in mine haul trucks in Canada was based on the outcomes of the above market and technology reviews, with consideration of off-site natural gas supply chain development issues and requirements that may affect potential use for certain open pit mine locations. The scenarios focused on potential ranges of diesel fuel displacement without attempting to assess in any detail the potential timing for achieving such displacement under different scenarios.

[1] See Appendix 2.1.

[2] Christopher Zuliani, Ebrahim Salehi, Greg Almquist and Sanjiv Save, Hatch Ltd.: "Leveraging LNG, The case for replacing diesel with natural gas for oil sands mining fleets", Oil sands Review, October 2015.

1.3 CONVERSION FACTORS

A wide range of conversion factors and fuel prices are referenced in this study. Factors and prices adopted in referenced sources are generally retained as adopted by each source.

Unless otherwise noted, analysis developed for this study used the following conversion factors:

- Diesel fuel:
    - 0.0368 GJ per litre of diesel fuel, based on NEB Conversion Tables [https://www.neb-one.gc.ca/nrg/tl/cnvrsntbl/cnvrsntbl-eng.html].
    - 3.02155 kg [CO_2e] GHG emissions per litre of diesel fuel (78.12 kg [CO_2e] per GJ) calculated using emissions factors for CO_2, CH_4 and N_2O as reported in Environment Canada National Inventory Report, multiplied by global warming potentials for a 100-year horizon for CH_4 and N_2O as estimated in Table 2.14 in the IPCC 2007 paper "Changes in Atmospheric Constituents and in Radiative Forcing".
- Natural gas fuel:
    - GHG emissions estimated at 72.5% of diesel emissions or 56.66 kg [CO_2e] per GJ (explained in the study).
- General:
    - 1.0551 GJ/MMBtu [https://www.neb-one.gc.ca/nrg/tl/cnvrsntbl/cnvrsntbl-eng.html].

1.4 STRUCTURE OF REPORT

The balance of the report on the Study is as follows:

- **Section 2 - Mine Haul Truck Fuel Requirements in Canada**, reviews available information on the off-road mine haul diesel fuel requirements in Canada, overall and by different regions and economic sectors, and the broad opportunity for use of natural gas and LNG to displace diesel fuel in this market;

- **Section 3 - Review of Natural Gas Fuel Mine Haul Truck Technologies**, reviews available information on the current state of natural gas fuel mine haul truck technologies;

- **Section 4 - Scenario Assessments for Natural Gas Use in Mine Haul Truck Market**, reviews scenarios for potential future natural gas use to displace diesel fuel in mine haul trucks in Canada; and

- **Section 5 - Summary of Conclusions and Recommendations**, includes future work studies/research to address identified issues and to enhance the opportunities for natural gas displacement of diesel fuel in mine haul truck fleets.

A list of references and contacts in this Study is provided in the Attachments at the end of the Report.

2.0 MINE HAUL TRUCK FUEL REQUIREMENTS IN CANADA

2.1 INTRODUCTION

Section 2 reviews available information on the off-road mine haul truck diesel fuel requirements in Canada, overall and by different regions and economic sectors. The size of this market as well as its location and development are key factors affecting the potential future use of natural gas to displace diesel fuel use for mine haul trucks. The lack of clear and consistent data on current (let alone projected) diesel fuel use in this very diverse market creates challenges which are addressed below, starting with review of information on existing mine haul trucks in Canada.

Section 2 also reviews the broad opportunity for natural gas and LNG to displace diesel fuel in Canada, based on projections of natural gas and LNG supplies and prices relative to diesel fuel in the coming decades.

2.2 EXISTING MINE HAUL TRUCKS IN CANADA

Information on existing mine haul trucks in Canada has been obtained from The Parker Bay Company as part of this study. The Parker Bay Company maintains a world-wide confidential mine equipment data base using Original Equipment Manufacturer (OEM) information on mine machine shipments, and are not aware of any material issues regarding their data base of "mining class" trucks (i.e., about 90 metric tonnes and higher of payload) in Canada.[3]

Table 2-1 provides a summary as of late 2016 of the reported existing mine haul trucks in Canada by metric ton payload size ranges and by open pit mining sector. In total, 1,991 units were recorded, of which 695 units (35%) are relatively large (290 to 363 tonnes payload), 814 units (41%) are relatively small (90 to 190 tonnes payload), and the balance (482 units or 24%) are in the 218-255 tonnes payload range. The following allocations by mining sector are shown (in order of scale in the overall mine haul truck market):

- **Oil Sands** - 792 units (40% of total mine haul trucks in Canada), with 472 units (60% of total trucks in Oil Sands) 290 tonnes or more payload, only 225 units (28%) 190 tonnes or less payload, and only 95 units (12%) 218-255 tonnes payload.
- **Coal** - 407 units (20% of total), with 135 units (33%) 290 tonnes or more payload, 149 units (37%) 190 tonnes or less payload, and 123 units (30%) 218-255 tonnes payload.
- **Copper, Gold, Iron** - 405 units (20% of total), with 82 units (20%) 290 tonnes or more payload (with most of these in iron, followed by gold), 111 units (27%) 190 tonnes or less payload (with

[3] The normal data issues are delays in reporting when machines are scrapped, sold, moved, or not clearly allocated among specific mines, sectors or regions ("unknown" reporting for location, sector etc. may occur with contractor or leased machines where it is known that the unit is operating but other details are lacking). Reporting issues tend to be concentrated in smaller mines and/or smaller mine haul truck units.

most of these in gold and copper), and 212 units (52%) 218-255 tonnes payload (accounts for 58-61% of all copper and iron units, 34% of gold units).

- **Others/unknown** - 387 units (19% of total), with only 6 units (2%) 290 tonnes or more payload, 329 units (85%) 190 tonnes or less payload, and 52 units (13%) 218-255 tonnes payload.

Table 2-1: Mine Haul Truck Units in Canada (2016) by Sector & Payload Size (mt)

	Mine Haul Truck Size (tonnes payload)						Total	%
	90-110	127-150	154-190	218-255	290	308-363		
Number of Units (2016)								
Oil Sands	113	77	35	95	141	331	792	40%
Coal	52	19	78	123	119	16	407	20%
Copper	18	-	25	99	19	-	161	8%
Gold	26	27	-	42	-	27	122	6%
Iron	8	1	6	71	23	13	122	6%
Others/unknown	243	59	27	52	2	4	387	19%
Total	**460**	**183**	**171**	**482**	**304**	**391**	**1,991**	**100%**

Source: The Parker Bay Company (as provided for this study).

Table 2-2 provides a more detailed summary of these mine haul truck units by province or region, highlighting that 92% of all units (and 99% of all large mine haul units of 290 or more tonnes or 218-255 tonnes) are concentrated in the following five provinces:[4]

- **Alberta** - 1,205 units (60% of the total) are in this province, concentrated mainly in oil sands (792 units identified) and also including coal (154 units identified).
  - Large mine haul units of 290 or more tonnes payload in Alberta accounted for most of the oil sands units, and for 70% of all such units in Canada (489 units).
  - Mine haul units of 218-255 tonnes payload in Alberta accounted for 37% of all such units in Canada.
- **British Columbia** - 392 units (20% of the total) are in this province, concentrated mainly in coal (226 units identified) and copper (144 units identified), plus some trucks in gold mines (19 units).
  - Large mine haul units of 290 or more tonnes payload accounted for 35% of the province's units (139 units), with most of the units being in the coal sector.
  - Mine haul units of 218-255 tonnes payload in British Columbia units accounted for 39% of all such units in Canada.
- **Quebec** - 95 units (5% of the total) are in this province, concentrated mainly in iron (54 units identified) and gold (27 units identified).

[4] The northern territories (Yukon, NWT and Nunavut) accounted for 84 units (4% of the total), but 98% of these units are 190 tonnes or less in payload. Saskatchewan accounted for 27 units (1% of the total), all of which were in the coal sector and 150 tonnes or less in payload.

    - Large mine haul units of 290 or more tonnes payload accounted for only 14% of the province's units (13 units), with these units being in the iron sector.
    - Mine haul units of 218-255 tonnes payload in Quebec accounted for 13% of all such units in Canada.

- **Ontario** - 74 units (4% of the total) are in this province, concentrated mainly in gold (50 units identified).
    - Large mine haul units of 290 or more tonnes payload accounted for 36% of the province's units, with these units being in the gold sector.
- **Newfoundland & Labrador** - 67 units (3% of the total) are in this province, concentrated mainly in iron (61 units identified).
    - Large mine haul units of 290 or more tonnes payload accounted for 34% of the province's units, with these units being in the iron sector.
    - Mine haul units of 218-255 tonnes payload in Newfoundland and Labrador accounted for 7% of all such units in Canada.

In summary, 94% of the large mine haul units of 290 or more tonnes payload in Canada in 2016 were concentrated in the following provinces and sectors (Canada total: 695 units):

- Alberta oil sands mines (472 units, 68% of Canadian total).
- British Columbia coal mines (120 units, 17% of Canadian total).
- Ontario gold mines (27 units, 4% of Canadian total).
- Newfoundland & Labrador iron mines (23 units, 3% of Canadian total).
- Quebec iron mines (13 units, 2% of Canadian total).

Similarly, 86% of mine haul units with 218-255 tonnes payload in Canada in 2016 were concentrated in the following provinces and sectors (Canada total: 482 units):

- British Columbia copper mines (99 units, 20% of Canadian total).
- Alberta oil sands mines (95 units, 20% of Canadian total).
- British Columbia coal mines (87 units, 18% of Canadian total).
- Alberta coal mines (36 units, 7% of Canadian total).
- Newfoundland & Labrador iron mines (36 units, 7% of Canadian total).
- Quebec iron mines (35 units, 7% of Canadian total).
- Quebec gold mines (27 units, 6% of Canadian total).

Table 2-2: Mine Haul Truck Units in Canada (2016) by Province/Region

Province/ Region	Mine Haul Truck Size (mt payload) 90-110	127-150	154-190	218-255	290	308-363	Total	%
Alberta	281	144	114	177	152	337	1,205	61%
British Columbia	11	16	36	190	129	10	392	20%
Quebec	12	2	6	62	0	13	95	5%
Ontario	32	0	0	15	0	27	74	4%
Newfoundland & Labrador	7	1	0	36	23	0	67	3%
Yukon, Northwest Territories, Nunavut	60	15	7	2	0	0	84	4%
Saskatchewan	25	2	0	0	0	0	27	1%
Nova Scotia	18	0	0	0	0	0	18	1%
Unknown	14	3	8	0	0	4	29	1%
Grand Total	**460**	**183**	**171**	**482**	**304**	**391**	**1,991**	**100%**

	Mine Haul Truck Units by Mining Sector Oil Sands	Coal	Copper	Gold	Iron	Others	Unknown	Total	%
Alberta	792	154					259	1,205	61%
British Columbia		226	144	19		3		392	20%
Quebec				27	54		14	95	5%
Ontario				50		24		74	4%
Newfoundland & Labrador					61	6		67	3%
Yukon, Northwest Territories, Nunavut			17	26	7	29	5	84	4%
Saskatchewan		27						27	1%
Nova Scotia							18	18	1%
Unknown							29	29	1%
Grand Total	**792**	**407**	**161**	**122**	**122**	**62**	**325**	**1,991**	**100%**

Source: The Parker Bay Company (as provided for this study). "Unknown" reporting for location, sector etc. may occur with contractor or leased machines where it is known that the unit is operating but other details are lacking.
Alberta: includes 6 oil sands projects and 8 coal mines.
British Columbia: Includes 5 metal mines (copper, gold), 6 coal mines, one other (limestone quarry).
Quebec: Includes one gold mine and one iron mine.
Ontario: Includes 3 gold mines, one diamond mine, and various aggregate sites.
Newfoundland & Labrador: one iron mine, one nickel-copper-cobalt mine, one aggregate producer.
Yukon, Northwest Territories, Nunavut: one copper mine, one iron mine, one gold mine, one diamond mine.
Saskatchewan: 3 coal mines.

2.3 MINE HAUL TRUCK DIESEL FUEL REQUIREMENTS

Overall fuel consumption data for the existing mine haul trucks in Canada outlined in Section 2.2 is not readily available for reference in this study.

Annual diesel fuel consumption by mine haul trucks varies in response to a range of factors, including size of the unit (payroll and related horsepower), hours of operation, average payload, grades, speed and acceleration, road surface/grade and tire quality, operator driving style, idle time, outside temperature, weather and adequacy of the maintenance program.[5] Detailed studies are available assessing these factors overall, as well as for different specific open pit mines. One study of nine different gold, iron and oil sands open pit mines in Canada indicated diesel fuel mine haul truck requirements ranging from 220 to 428 litres per kilotonne of material removed, and noted that the larger mines surveyed did not appear to be realizing any savings in energy consumption per kilotonne of material removed compared with the smaller open pit mines in the study.[6]

Annual Canadian mine haul truck diesel fuel requirements are dominated by the larger units (e.g., over 200 tonne payload, and especially 290 mt or more payload) which tend to operate year round with two 12 hour shifts per day. The following two case study examples are noted in this regard:

- **Casino Mine Case Study:**[7] Review of diesel fuel requirements averaging about 37 million litres per year for mine operations (excludes on-site power generation LNG requirements) as projected in this mine's feasibility study indicates about 27 million litres per year (73%) for mine haul and water trucks, with over 90% of this truck fuel use being for the fleet of the largest mine haul units (Caterpillar 797F at 360 mt).[8]
- **Oil Sands Case Study:**[9] Diesel fuel requirements of 318,000 litres (2,000 barrels) per day [116 million litres per year] were estimated in this hypothetical oil sands mining operation case study, assuming 40 heavy haul trucks and five heavy lift shovels. Although the study did not specify the assumed size of these haul trucks, Table 2-2 above confirms the dominance of units in the 308-363 mt payload range for existing oil sands operations. If diesel fuel use per mine haul unit averaged between 1.5 and 2.0 million litres/year,[10] the 40 haul trucks would account for 60 to 80 million litres of diesel per year or 52% to 69% of the overall diesel fuel volume estimated in this

[5] For a review of mine haul truck fuel consumption, see: V. Kecojevic and D. Komijenovic, "Haul truck fuel consumption and CO_2 emission under various engine load conditions" in Mining Engineering, December 2010.

[6] Natural Resources Canada; **Benchmarking the Energy Consumption of Canadian Open-Pit Mines**; 2005. Figures 3.24 and 3.25 at page 39 (study assumed 10.74 kWh equals 1 litre of diesel fuel). The lowest energy consumption per kilotonne of material removed tended to be indicated for the smallest and largest open-pit operations, i.e., higher consumption was indicated for six of the nine operations surveyed that were between the smallest and largest open-pit operations, and the other lowest consumption operation was only slightly larger than the smallest operation.

[7] See Appendix 2.1. This mine project is currently in the environmental review phase for development. The remaining 27% of mine operation diesel fuel use not used for truck haul units and water truck use is for Track Dozers, Wheel Dozers, Wheel Loaders, Motor Graders, Excavators. Most of the LNG use (90%) planned at the mine is for power generation.

[8] At projected average hourly fuel use of 225.5 diesel litres per hour (as estimated for this mine), annual fuel use for this 360 mt unit will approximate 1.5 million litres for each of the Caterpillar 797F units or 76% average annual utilization (with over 20 active units in most operating years). In contrast, the smaller Caterpillar 777F mine trucks (at 90 mt) have projected average hourly fuel use at this mine of 62.8 diesel litres per hour with annual fuel use of about 0.4 million litres for each of three to seven active units (these units not active in all operating years). The water trucks have projected average hourly fuel use at this mine of 90.2 diesel litres per hour with annual fuel use averaging about 0.5 million litres for each of three active units (average annual use about 63%).

[9] Christopher Zuliani, Ebrahim Salehi, Greg Almquist and Sanjiv Save, Hatch Ltd.: "Leveraging LNG, The case for replacing diesel with natural gas for oil sands mining fleets", Oil sands Review, October 2015.

[10] Average annual utilization assumed at 75-80%, assuming large units. By way of example, the Casino Mine case study assumed 76% average annual use with average diesel fuel use per hour of operation assumed at 225 litres per hour for 360 mt unit. The upper end is provided for a possible range, assuming larger units with average diesel fuel use per hour of operation at 280 litres per hour. This analysis assumes that smaller unit fuel use did not have a material impact on the oil sands case study assumed LNG fuel use (as noted in the Casino Mine study, much lower average annual use [e.g., 60-70%] was assumed for the smaller units).

case study. This same case study estimated the potential oil sands demand in the Fort McMurray region at over 3.8 million litres (one million US gallons) of diesel per day (about 1,400 million litres per year) - implying the potential of 700 to 980 million litres per year of diesel for mine haul truck use (assuming mine haul truck use at 50% to 70% of the total diesel fuel requirement).

Table 2-3 provides an estimate of potential annual Canadian diesel fuel requirements in 2016 for the mine haul units estimated in Table 2-1 and Table 2-2. Due to the absence of actual diesel volumes for this range of existing mine haul units, let alone for estimates for each mine sector and/or haul truck size group, these are estimates only of "potential" requirements that may well not be confirmed when and if added information is available. The assumptions adopted for this estimate are noted in the table, including:

- Assumed average unit size for each grouping of mine haul units (there is no specific evidence as to the correct average in each case - assumed around mid-point of range for each grouping from Table 2-1).
- Assumed average diesel fuel use per operating hour (the Casino Mine Case Study averages were assumed per tonne of payload capacity for units at the extremes of the payload range [at 90 and 360 mt payloads], and estimated average diesel fuel use per operating hour were interpolated for the remaining payload capacities). It is noted that average fuel use per operating hour is likely to vary materially for different mines, and that the assumed approach does not address such variations or how such variations may affect overall fuel requirement estimates.
- Assumed average utilization (operating hours) per year (the upper range at 77.5% is adopted for the largest units, based on assumed maximum average possible use per year after consideration of maintenance and all other factors [a range of 75 to 80% was assumed earlier for large units, and 77.5% is adopted as mid-point in this range]; lower average annual utilization levels are assumed for the smaller payload units as shown in Table 2-3)[11].

[11] The Casino Mine study indicated 76% average annual use for large units (a range of 75 to 80% was assumed earlier in review of the oil sands case study, and 77.5% reflects a mid-point of this range]), and a much lower range (60 to 70%) for the small units using LNG. Assumptions were adopted for the smaller units (i.e. below 200 mt) based on what was deemed reasonable in the context of the available information.

Table 2-3: Potential Annual Diesel Fuel Requirements (million litres/year) – Mine Haul Truck Units in Canada (2016) by Sector & Payload Size[12]

	Mine Haul Truck Size (tonnes payload)						Total	%
	90-110	127-150	154-190	218-255	290	308-363		
Number of Units (2016)								
Oil Sands	113	77	35	95	141	331	792	40%
Coal	52	19	78	123	119	16	407	20%
Copper	18	-	25	99	19	-	161	8%
Gold	26	27	-	42	-	27	122	6%
Iron	8	1	6	71	23	13	122	6%
Others/unknown	243	59	27	52	2	4	387	19%
Total	**460**	**183**	**171**	**482**	**304**	**391**	**1,991**	**100%**
Assumed av. truck size (tonnes)	100	140	175	240	290	340		
Assumed av. litres per operating hr.	69.5	95.8	118.2	157.9	187.0	214.8		
Assumed av. % utilization (op hrs/yr)	60%	60%	70%	75%	75%	77.5%		
Potential Diesel Use (million L/yr)								
Oil Sands	41.3	38.8	25.4	98.6	173.2	482.6	859.9	47%
Coal	19.0	9.6	56.5	127.6	146.2	23.3	382.3	21%
Copper	6.6	-	18.1	102.7	23.3	-	150.8	8%
Gold	9.5	13.6	-	43.6	-	39.4	106.1	6%
Iron	2.9	0.5	4.3	73.7	28.3	19.0	128.7	7%
Others/unknown	88.8	29.7	19.6	54.0	2.5	5.8	200.3	11%
Total	**168.1**	**92.2**	**123.9**	**500.2**	**373.5**	**570.1**	**1,828.0**	**100%**

Source for number of units - see Table 2-1.

Table 2-3 estimates total mine haul unit diesel requirements at 1,828 million litres per year, with 944 million litres per year (52% of the total) estimated for units of 290 mt or larger, and a further 500 million litres per year (27% of the total) estimated for units of 218-255 mt payload. i.e., diesel fuel volumes are highly concentrated in the larger sized truck units.

At least 860 million litres per year (47% of the total) is estimated in Table 2-3 to be used in the oil sands (a material portion of "unknown" units would likely also be in oil sands). The annual oil sands estimate is within the upper end of the 700 to 980 million litre/year range reviewed earlier from the oil sands case study. There is no other reference assessment, however, to check estimates for the other mine sectors.

As a possible additional cross check on the Table 2-3 estimates, another potential source for overall diesel requirement estimates has been examined related to Canadian mine operations (including mine haul trucks). Estimates of GHG emissions (in metric tonnes of CO_2 equivalent) in 2014 from mine sector off-road fuel use (for "transportation") in Canada[13] have been reviewed, and related diesel fuel volumes

[12] By the way of example, Table 2-3 estimates that for 240 tonne class truck the average annual fuel consumption is about one million litres. Fortis BC May 23, 2014 LNG Use in Mines presentation [available at http://mineralsnorth.ca/images/uploads/pdf/Fortis.pdf, accessed on February 13, 2017] estimates that a mine haul truck in this size class consumes an average one million litres/year. Personal Communication with Sylvain Langis, Director, Sales Development, Fuel Market for Gaz Metro on January 30, 2017 also confirms about one million litre diesel fuel use on average per year by mine haul trucks.

[13] Canada's Submission to the United Nations Framework Convention on Climate Change; *National Inventory Report 1990-2014: Greenhouse Gas Sources and Sinks in Canada*; Part 3, Annex 10, Table A10-2.

estimated assuming 3.02155 kg GHG [CO_2e] emissions per litre of diesel fuel.[14] Based on this analysis as summarized below by mine sector, mine haul truck diesel fuel use in Canada in 2014 is estimated at about 1,650 million litres per year (which is 90% of the overall estimate for Canada in 2016 as provided in Table 2-3).

- **Oil Sands:** 3.2 Mega tonne [Mt] CO_2e (out of 18 Mt total GHG emissions from all activities for this sector) - implies potential annual off-road diesel fuel use of 1,059 million litres. This is about 76% of the above noted case study estimate of potential oil sands demand in the Fort McMurray region. Mine haul truck use at about 70% of this off-road diesel fuel use would approximate 750 million litres per year (which is within the range noted from the case study, and 87% of the specific estimate in Table 2-3 prior to any allocation of a large share of diesel estimated for "unknown" units in Alberta).
- **Coal Production:** 1.3 Mt CO_2e (out of 4 Mt total GHG emissions from all activities for this sector) - implies potential annual off-road diesel fuel use of 430 million litres. Mine haul truck use at about 70% of this off-road diesel fuel use would approximate 300 million litres per year. This estimate for mine haul diesel requirements in the coal sector is sensitive to the assumed 70% share of all off-road diesel fuel use (this mine haul diesel fuel estimate is 78% of the estimate in Table 2-3 prior to any allocation for "unknown" units).
- **Other Mining:** 2.6 Mt CO_2e (out of 8 Mt total GHG emissions from all activities for this sector) - implies potential annual off-road diesel fuel use of 860 million litres. Mine haul truck use at about 70% of this off-road diesel fuel use would approximate 600 million litres per year. This estimate for mine haul diesel requirements in other mining (including copper, gold and iron) is sensitive to the assumed 70% share of all off-road diesel fuel use (this mine haul diesel fuel estimate is 156% of the estimate in Table 2-3 prior to any allocation for "others/unknown" units, i.e., with "others/unknown" added to this other mining group, the estimate of 600 million litres/year is 102% of the 586 million litres/year in Table 2-3 excluding oil sands and coal production units).

In summary, based on available information and the above assessments, existing mine haul truck diesel fuel requirements in Canada can be estimated at between 1,650 and 1,800 million litres per year, with oil sands mining likely accounting for about 750 to 900 million litres/year or 45% to 50% of the Canadian total requirement. The allocation of the balance between coal and other mining is less clear, with coal mining likely accounting for 300 to 400 million litres per year (18% to 22% of the total), and other mining for the balance (about 500 to 600 million litres per year).

Any initiative for natural gas displacement of mine haul truck diesel fuel use will likely focus on future (rather than recent existing) diesel fuel requirements in this market. This study has not attempted to assess the potential future extension of existing mine haul truck fuel use, or the potential across Canada

---

[14] CO_2 equivalent 3.02155 kg/litre is calculated using emissions factors for CO_2 [2.690 kg/l], CH_4 [0.00015 kg/l] and N_2O [0.0011 kg/l] as reported in Environment Canada National Inventory Report, multiplied by global warming potentials for a 100-year horizon of 25 for CH_4 and 298 for N_2O as estimated in Table 2.14 in the IPCC 2007 paper "Changes in Atmospheric Constituents and in Radiative Forcing" [https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf, accessed on March 29, 2017]. For the purpose of this report 3.02155 kg of CO_2 equivalent (CO_2e) GHG emissions is assumed per litre of diesel fuel.

for major new open pit mine development. It is noted, however, that oil sands mining is expected to continue as a major open pit mining sector for some decades,[15] while various current initiatives to reduce reliance on thermal coal use will at some point reduce future open pit coal mine activities. Potential major new open pit mine developments such as the Casino Mine will, if and when developed, also impact future mine haul diesel fuel requirements relevant to potential natural gas opportunities in this sector (as reviewed in Appendix 2-1, the Casino Mine development assume use of LNG to displace diesel fuel for mine haul trucks).

2.4 NATURAL GAS & LNG COSTS FOR MINE USE

The broad opportunity today for natural gas and LNG to displace diesel fuel in Canada is supported by projected low commodity prices for natural gas relative to crude oil in the coming decades; however, for mine haul truck use in particular, it is also necessary to consider comparative processing and transport costs for these competing fuels, as well as the adequacy of LNG supply in each mining region.

Longer-term price forecasts and scenarios for commodity costs[16] for oil and natural gas, as addressed in recent forecasts to 2040 by the National Energy Board (NEB) of Canada,[17] show a continued major gap per GJ for oil prices compared to natural gas prices with a price range to reflect uncertainty (see Figure 2-1). This price gap reflects the abundance of natural gas supplies.

- **NEB Reference Price Forecasts:** 2015 Brent crude oil price[18] at US$9.15/GJ is US$6.41/GJ higher (3.3 times) than the 2015 Henry Hub natural gas price at US$2.75/GJ; by 2040 the forecast crude oil price is US$13.17/GJ higher (4.0 times) than the natural gas price.[19]
- **NEB Low and High Price forecasts:** The 2040 Brent crude oil price is US$9.7/GJ higher than the Henry Hub natural gas price under the low price forecasts, and US$16.3/GJ higher under the high price forecasts.

---

[15] For example, Figure 5.2 Oil Sands Production, Reference Case in National Energy Board's Canada's Energy Future 2016 shows production growth through 2040 [available at https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2016/index-eng.html, accessed on February 8, 2017].

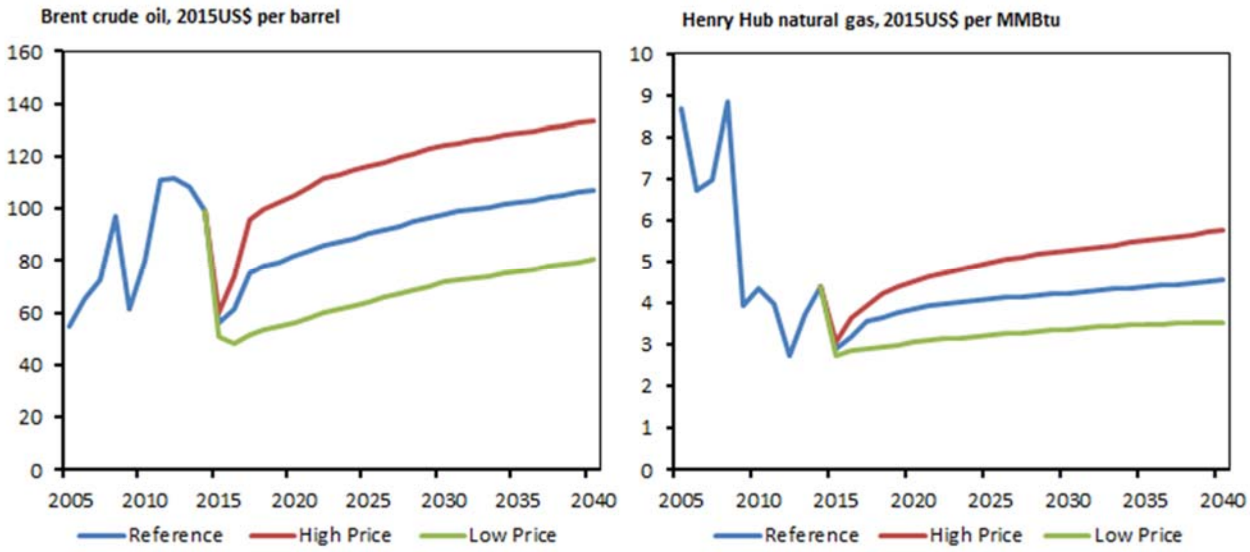
[16] "Commodity costs" as used in this study reference the crude oil prices that refinery companies pay as feedstock and the cost of natural gas as feedstock for LNG liquefaction. Subsequent analysis addresses additional costs that affect mine delivered fuel costs.

[17] National Energy Board of Canada; **Canada's Energy Future 2016: Energy Supply and Demand Projections to 2040 – An Energy Market Assessment – January 2016**; Chapter 3; https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/index-eng.html.

[18] Figure 2-1 shows Brent price average for 2015 at US$56/bbl, increasing to about $80/bbl by 2020 ($13.79/MMBtu) and then increasing more gradually to about $107/bbl for 2040 ($18.45/MMBtu) - a real growth in price (above inflation) averaging 2.6%/year over the 25 year forecast period; equivalent Brent crude oil prices per GJ assume 6.12 GJ per bbl of crude oil (5.8 MMBtu/bbl). The West Texas Intermediate (WTI) price is about $5/bbl less than the Brent price throughout the forecast period, and the Western Canadian Select (WCS) price [benchmark for heavy crude oil in western Canada] averages $17/blb below the WTI price.

[19] Figure 2-1 forecasts a real growth in the Henry Hub natural gas price (above inflation) averaging 1.8%/year over the 25 year forecast period (from US$2.90/MMBtu in 2015 to US$4.55/MMBtu in 2040).

Figure 2-1: NEB Crude Oil and Natural Gas Price Forecasts to 2040 (2015US$)



Source: National Energy Board of Canada; **Canada's Energy Future 2016: Energy Supply and Demand Projections to 2040 – An Energy Market Assessment – January 2016**; Figure 3-1 and Figure 3-2.

The latest forecast outlook (2017 Annual Outlook) provided by the U.S. Energy Information Administration similarly forecasts a reference price for crude oil through to 2040 more than three times higher than the natural gas price reference price on an energy equivalent basis.[20]

Crude oil and natural gas commodity prices in Canada can be affected by $US/Can exchange rates as well as local market conditions. For crude oil prices, the exchange rate can mute the impact of world market price changes on relevant Canadian crude oil prices to the extent that the exchange rate moves with the world market price for oil. Crude oil and natural gas prices in Alberta can also be depressed relative to US prices by local market conditions and ability to access markets. Overall, however, these factors are not expected to undermine the expectation of natural gas prices being considerably lower than diesel fuel prices within Canadian markets in the coming decades - to the contrary, the price saving per unit of energy for natural gas versus diesel fuel appears to have been widened in markets such as Alberta by local conditions.[21] Similarly, introduction of carbon taxes will likely enhance rather than reduce the projected price advantage for natural gas relative to crude oil products.

---

[20] U.S. Energy Information Administration; Annual Energy Outlook 2017, page 64. http://www.eia.gov/outlooks/aeo/index.cfm

[21] In Alberta the long-run average price ratio between diesel, as measured by Edmonton rack prices, and natural gas (AECO) on an energy basis from 2010 through 2015 was roughly seven. (See E. Salehi, S. Save, C. Zuliani, G. Almquist, Hatch Ltd.: "Fueling Alberta oil sands fleets with natural gas" in Hydrocarbon Processing, January 2016, Figure 2. The paper argues that this was one of the largest price differentials in the world between diesel and natural gas. It notes that the province has relatively expensive diesel, with a well-established price premium averaging about $10/bbl in Alberta relative to the Gulf Coast, versus an abundance of natural gas that can be purchased at a discount relative to the NA market).

Looking beyond basic commodity costs for natural gas and crude oil, mine haul truck fuel costs per GJ for each open pit operation will ultimately be set by the cost of delivered fuel products required for these trucks (e.g., diesel fuel or LNG).

As reviewed in Section 3 and noted earlier in the Casino and oil sands case studies, natural gas use to displace diesel fuel in mine haul trucks is likely to require that the natural gas be supplied as LNG (to enhance range of supply chain access beyond current natural gas pipeline locations, and to enable mine haul truck ability to operate for a full 12 hour shift without reloading). Accordingly, the following discussion focuses on LNG as the fuel product likely to be required for natural gas use in mine haul trucks (Section 3 also reviews a Compressed Natural Gas technology option).

Delivered costs for LNG and diesel fuel products will be significantly affected by several factors beyond the basic commodity price for crude oil or natural gas and any related carbon taxes, e.g., refining costs and market pricing for diesel fuel (see earlier comment about premium diesel fuel prices in Alberta), liquefaction processing costs for LNG, and transportation costs to each mine site. The commodity cost for crude oil or natural gas ultimately accounts for only a portion of the final delivered cost for these fuels - and LNG requires added supply chain development, with added processing and transport costs, that may affect its delivered cost competitiveness with diesel fuel.

Delivered costs for diesel and LNG to Yukon Energy's thermal plant at Whitehorse provide an example of the relative importance of commodity prices versus processing and transportation costs for diesel fuel and LNG, and how ongoing factor adjustments may affect the cost savings offered by LNG for a relatively low volume LNG user. Figure 2-2 summarizes related information from March 2014 forecasts (at the time of regulatory reviews prior to installation of the new Whitehorse LNG facilities and gas generators) and September 2016 actuals.

Figure 2-2 highlights general factors affecting LNG opportunities and costs relative to diesel fuel over the 2014-2017 time period throughout all regions in Canada, including:

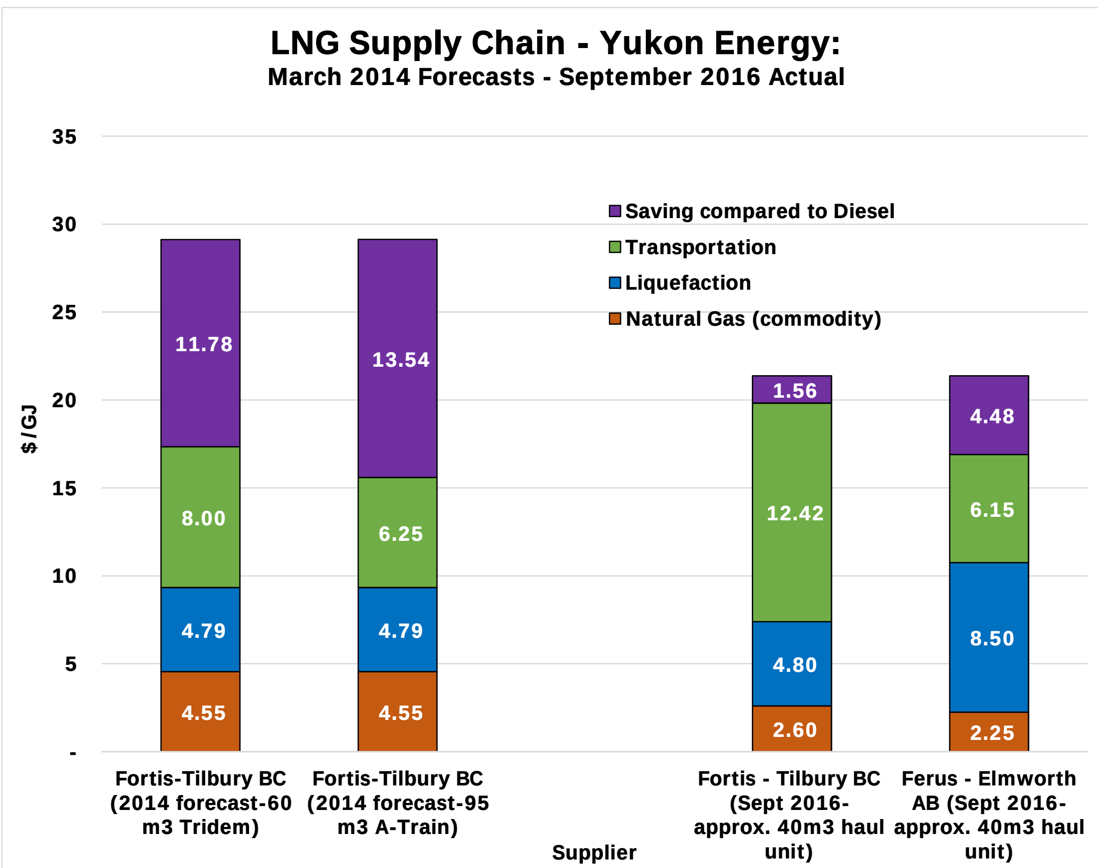
- Diesel delivered prices were higher in 2014 than in 2016, and the drop in these prices reduced potential cost savings from use of LNG to the extent that LNG delivered costs did not fall by similar amounts by 2016.
- On a per GJ basis, the drop in natural gas commodity prices in Figure 2-2 from 2014 forecasts to 2016 actual was much less than the decline in diesel fuel delivered prices.
- Delivered costs for LNG are highly affected by liquefaction and transportation costs.
- LNG liquefaction costs can be dependent on currently available facilities:
    - Fortis' existing Tilbury facilities have a regulated charge that only changed for inflation, and is expected to decline when larger scale facilities are established.
    - Ferus' existing Elmworth facilities have a higher cost process and thus a higher charge, which could decline when new facilities are established.

- LNG transportation costs are highly dependent on both distance and assumed haul options:
  - o Tilbury is about 2,720 km from Whitehorse while Elmworth is about 1,570 km from Whitehorse - the shorter distance from Elmworth yields a material saving (about 50%, and over $6/GJ, in Figure 2-2) in transportation costs.
  - o Cost savings per GJ can also occur with adoption of larger LNG payloads per haul unit, e.g., the 2014 estimates in Figure 2-2 show a potential cost saving of $1.75/GJ from adoption of a larger haul unit [95 m^3 versus 60 m^3 payload], and the actual transportation costs in 2016 reflect the adverse impact in all cases of shipment by smaller haul units [only about 40 m^3].

As shown in Figure 2-2, the cumulative impacts of these various factors can have very material impacts on potential net cost savings offered by use of LNG to displace diesel.

For this reason, aggressive ongoing pursuit of lower LNG liquefaction and transportation costs per GJ can be of critical importance for sustained and material cost savings relative to diesel fuel. Figure 2-2 highlights one such change adopted in 2016 to improve cost savings. Other similar improvements are continuing to be pursued by Yukon Energy.

Figure 2-2: Yukon Energy LNG Supply Chain Examples



Source re: LNG costs: Yukon Energy filings in March 2014 at Yukon Utilities Board hearing on Part 3 Application for Whitehorse Diesel-Natural Gas Conversion Project, Exhibit B-12. Michael Brandt, VP Yukon Energy, "LNG Supply Chain Development Factoring in the Upside Potential", presentation to Yukon Geoscience Forum, November 19, 2016.

A more detailed review of Figure 2-2 LNG and diesel costs as well as other available information enables consideration of the following factors affecting diesel versus LNG delivered costs:

- **Diesel** - Depending on factors affecting oil prices, commodity costs can represent from about one-third to about two-thirds of delivered diesel fuel costs to Whitehorse (excluding any fuel taxes), i.e., the balance of the cost is for refining, market factors that impact charges for refined product, and transportation which costs (compared to crude oil prices) are somewhat more stable.[22] Additional factors may affect diesel cost in northern areas.[23]
- **LNG** - Commodity natural gas costs for Yukon Energy at Whitehorse as shown in Figure 2-2 for September 2016 approximated 13% of delivered LNG fuel costs from either Fortis at Tilbury, B.C. ($19.8/GJ delivered cost, commodity cost of $2.60/GJ) or Ferus at Elmworth, AB ($16.9/GJ delivered cost, commodity cost of $2.25/GJ), with the balance being liquefaction and transportation costs.[24] Earlier, in March 2014, Yukon Energy's forecast costs for this LNG supply from Fortis at Tilbury, B.C. as shown in Figure 2-2 assumed a natural gas commodity cost at $4.55/GJ that ranged from 26% to 29% of forecast total delivered LNG costs (from $15.59 to $17.34/GJ, depending on whether A-Train or Tridem haul units were assumed).[25]
- **LNG Cost Saving** - In early 2014, LNG cost savings per GJ for product delivered to Yukon Energy at Whitehorse were forecast at 40% to 47% of the price of diesel (when diesel was assumed at about $29.12/GJ or $1.1265/litre). In September 2016, LNG cost savings per GJ for the lowest cost supply (from Elmworth, AB) approximated 21% of the price of diesel (at about $21.4/GJ or $0.83/litre). To highlight the importance of transportation costs, LNG cost savings in September 2016 for supply from Tilbury (which had higher actual costs than from Elmworth) would have approximated 36% of the price of diesel if the earlier (March 2014) A-Train haul option and costs has been realized;[26] this assessment reflects the lower natural gas commodity

---

[22] Assessments depend on specific crude oil price adopted and CAN$/US$ exchange rate. This assessment reflects WTI price per barrel (US$) and the period from the start of 2010 to about mid-2016. On average over this period, commodity price as valued on this basis (after conversion to CAN$) was slightly above 50% of the total delivered diesel cost in Whitehorse, excluding any fuel taxes. However, at low oil prices this percentage may tend to the lower end of the observed range.

[23] See Don Dean (Prolog Canada), presentation to Yukon Geoscience Forum, November 19, 2016, which noted that security of supply is now an issue for diesel supplies to northern Canadian territories, reflecting that refineries are being mothballed (no new refineries for 35 years), and that remaining refineries are at full capacity and distribute to markets easy to access (i.e., northern areas difficult to access are not a priority).

[24] Michael Brandt, VP Yukon Energy, "LNG Supply Chain Development Factoring in the Upside Potential", presentation to Yukon Geoscience Forum, November 19, 2016. The Yukon Energy example indicates a 15% cost reduction from ability to secure closer supplies (Elmworth, Alberta vs. Delta, B.C.), notwithstanding a higher current liquefaction charge at the Elmworth facility. Additional potential future cost savings are noted with adoption of larger haul units (e.g., King B Train at 2,000 GJ payload would increase haul payload by 91% over existing Tandem units or equivalent unit payloads currently experienced), as well as potential local future market developments to support additional and closer LNG supply facilities.

[25] Yukon Energy filings in March 2014 at Yukon Utilities Board hearing on Part 3 Application for Whitehorse Diesel-Natural Gas Conversion Project, Exhibit B-12. The larger A-Train haul unit (payload at 95.3 $m^{3)}$ had a lower estimated haul cost per GJ than the Tridem haul unit (payload assumed at 60 m^3).

[26] The A-Train option was initially developed for LNG haul to Yukon locations through the Alaska Highway from locations such as Fort Nelson, B.C. and potentially from locations in Alberta. It was found not to be acceptable to regulators for LNG haul from Delta, B.C. More recently, regulatory approvals in BC have been secured for the King B LNG unit trailers (>85 m^3 payload), and route review is currently proceeding for at least Alaska Highway LNG facility locations.

InterGroup CONSULTANTS

cost in 2016 versus what was assumed in the early 2014 estimates, and the continued importance of transport haul unit improvements.

The Casino Mine Case Study (see Appendix 2.1) provides a separate supply chain cost example for a prospective high volume and long-term LNG user located in Yukon north west of Whitehorse, where 90% of the LNG requirement is for power generation.

- The CMC LNG delivered cost estimate (2012$Q4) of approximately $11.2/GJ was about 42% of the assumed delivered cost of diesel fuel (about $26.9/GJ); the gas commodity cost component of about $4.3/GJ was 38% of the estimated delivered LNG cost; the LNG cost estimates assumed liquefaction by others at new facilities to be developed at Fort Nelson B.C., and LNG haul to the mine (about 1,300 km one way) using LNG-fueled tractors and A-Train units with 95 m^3 of LNG payload.
- Since preparing the 2012 feasibility cost estimate, CMC has signed an MOU with Ferus regarding the Fort Nelson LNG facilities, and the B-Train tanker design (>85 m^3 of LNG payload) has been approved by BC Highways (compliant with Bulk Haul requirements without needing a pilot car). With its planned LNG supply chain, LNG's cost advantage relative to diesel remains strong today under current commodity price conditions (i.e., delivered diesel price reduction from the 2012 feasibility study is about $3.9/GJ, which is at least partially offset by lower natural gas commodity costs).

The LNG supply chain developed and planned to date in this northern region is now supporting its first new mine. In northern British Columbia, just south of the Yukon border with access from the Alaska Highway, the Silvertip silver-lead-zinc mine is currently coming into operation with LNG fueled on-site power generation.

In Quebec, an LNG supply chain has been developed in 2016 from Gas Metro's LNG facility in Montreal to supply power and heat to Stornoway's new Renard mine located about 800 km north of Montreal. Commodity cost for the natural gas accounts for 21% of delivered cost, and in this case another 19% of the final cost is apparently accounted for by pipeline and distribution transport of the natural gas to the liquefaction facility. Liquefaction accounts for 32% of the delivered cost, and transport of the LNG for 28% using year round road access.[27]

In summary, at the current stage of LNG supply chain development in Canada, costs for mine haul truck LNG use may vary considerably depending on site location and the level of LNG supply chain development in that region today.

---

[27] Yves Perron, VP, Stornoway; presentation November 23, 2016 "Build Quebec's First Diamond Mine", page 13. Shows allocation of LNG cost that accounts for $0.155/kW.h fuel cost for the power generation at the mine. Assuming power generation conversion efficiency of 40% (based on assumed efficiency for new engines – no information on this in the presentation), the delivered LNG cost would approximate $17.2 per GJ. Delivered diesel fuel costs appear to exceed $30/GJ for this mine.

On a broad basis, the following summary observations are noted with regard to delivered costs of diesel and LNG based on the examples reviewed:[28]

- Delivered fuel costs by highway to northern locations can see commodity costs accounting for only 50% or less of final diesel fuel prices and less than 20% of delivered LNG prices in at least some western Canada locations. LNG commodity costs, including related pipeline and distribution costs, in many cases can also represent 25 to 40% of final delivered costs for LNG.
- Whereas diesel fuel supply chains are long established and well developed, LNG supply chains are only recently being established and are still developing. This can make LNG procurement more difficult, but it can also offer (in relative terms) greater opportunities for future cost reductions than would apply for diesel fuel.
- Year-round road access is generally required for LNG use at any mine site, since long-term LNG storage is costly.
- Haul distance is a key factor affecting delivered LNG costs at any mine site;[29] however, costs per GJ delivered can also be materially affected by haul unit options, liquefaction options (technologies, locations, scale of facilities, and pricing approach adopted), and trade-offs addressed in the location of new LNG supply facilities.
- While commodity prices for crude oil and natural gas are expected to escalate materially faster than inflation over the next 25 years (as forecast in the reference NEB price forecasts), escalation of delivered prices for diesel fuel and LNG will be affected by changes in processing and transportation costs, i.e., delivered price escalation would be expected to be less than the commodity price escalation, especially for LNG, which will tend to enhance the relative cost advantage of LNG.

2.5 LNG SUPPLIES FOR MINE USE IN CANADA

The lack of new small-scale liquefaction infrastructure in Canada has been one of the major challenges to domestic customers switching to LNG. This specific factor is therefore reviewed in more detail below.

A limited level of LNG production capability existed in Quebec, Ontario and British Columbia prior to the last decade, often to facilitate efficient operation of natural gas utility systems with varying seasonal loads. Considerable attention began to be directed after about 2010 towards consideration of potential

[28] Some of these points are also referenced in ICF International report to Canadian Gas Association, "Economic and GHG Emissions Benefits of LNG for Remote Markets in Canada", May 2016, at page 6 which also references Standing Senate Committee on Energy, the Environment and Natural Resources, Power Canada's Territories, 2014.

[29] Plum Energy has highlighted how delivered LNG cost increases with haul distance, estimating that delivered cost per MMBtu increases by $0.01 per added mile haul distance (equivalent to delivered cost per GJ increasing by $5.88 per 100 km of added haul distance). [Plum Energy, LNG Economics 201: Effects of Distance on Price, April 11, 2014. http://www.plumenergy.com/lng-economics-201-effects-distance-price/] Plum noted that this cost in practice may vary considerably depending on customer site location, required equipment, and other items that greatly impact costs.

new large LNG export facilities without much attention to potential domestic uses for LNG to displace diesel fuel. However, this situation has been changing dramatically over the past few years.

The following reviews LNG supply facilities and currently known plans in B.C., Alberta, Quebec and Ontario as well as facilities in North Dakota close to the Canadian border:[30]

- **British Columbia** -
  - Fortis has had LNG facilities since 1971 at Tilbury Island in Delta, B.C. (about 5,000 GJ/day or about 55,000 USG/day), and since 2011 at Mt. Hayes, B.C. (about 8,800 GJ/day) on Vancouver Island.
  - The Fortis LNG facility at Tilbury is currently being expanded, adding 34,000 GJ/day liquefaction capacity and 1.1 million GJ of storage as well as marine shipping capability. This expansion is currently planned to begin operation in 2017, reducing liquefaction charges per GJ and materially expanding the overall LNG supply available for use in B.C., Yukon and other potential markets in this region.
  - In addition, AltaGas in early 2017 will start operating a new 27,000 USG/day liquefaction facility at Dawson Creek, B.C., greatly reducing haul distances for LNG supplied to customers in this region and at points to the north in Yukon and NWT.
- **Alberta** -
  - Encana established a facility at Strathmore, AB in 2013 with a capacity of about 480 GJ/day.
  - Ferus Natural Gas Fuels in 2014 established a 50,000 USG/day facility at Elmworth, AB (about 65 kilometers southwest of Grande Prairie).
  - Ferus has cancelled its earlier plans to establish a 100,000 USG/day facility near Edmonton, AB in 2016; however, this expansion may now occur in 2017 at the Elmworth, AB facility.
  - Sonoma Resources received regulatory approval in October 2016 for its Talbot Lake LNG Plant project, with an initial capacity of 80,000 USG/day to be located on a brownfield site about 100 km north of Red Earth Creek, AB (about 400 km north by road from Edmonton 700 km west by road from Fort McMurray). Potential development for in service is being planned for early 2018.[31]

---

[30] This review does not consider the existing Canport LNG import facility in St. John, New Brunswick or the status or potential implications of potential new LNG facilities for export in B.C., Nova Scotia and Newfoundland and Labrador.

[31] Nikiforuk, C.F. CRNG Energy Inc. and Miller, R.E., Sonoma Resources Ltd.; "Reducing Energy Costs for Remote Mines and Communities Through Improved Liquefaction Technology for LNG", paper presented at Yellowknife Geoscience Forum November 17, 2016 (modified November 29).

- **Quebec** -
    - Gaz Métro has had a plant for 45 years in Montreal East able to produce over 100,000 USG/day of LNG.
    - Gas Métro is currently tripling the capacity if its LNG facility.
    - Stolt, LNGaz has received approval of the Government of Quebec to construct an LNG facility at Bécancour, Quebec. The facility, which is to be completed in 2018, will have a capacity of 2,800 tonnes/day of LNG (about 145,000 GJ/day).
- **Ontario** -
    - Union Gas has an existing LNG facility at Hagar with a capacity of slightly under 4,000 GJ/day.
    - Northwest Midstream states that is has received local and provincial permits to start construction of an LNG facility in Thorold, ON at a capacity of about 35,000 GJ/day.
- **North Dakota** -
    - North Dakota LNG has a recently established a facility outside Tioga, North Dakota with a capacity of 76,000 USG/day.

In summary, most (but not all) regions of Canada currently have access to LNG for domestic uses such as displacing diesel fuel for mine haul trucks. Furthermore, recent experience demonstrates a wide range of LNG plant scales that can be developed relatively quickly in response to market opportunities (subject to having access to natural gas supplies). Finally, the example of LNG supplies from Delta, B.C. being transported approximately 3,750 km by truck to Inuvik, NWT highlights the potential for supply chain development in the short term (where market conditions so justify) pending development of new LNG supply facilities closer to a market. LNG transport, storage and boil off gas issues when storage is prolonged will tend to constrain its potential use at locations that are only road accessible for brief time periods (e.g., by winter roads).

Appendix 2.1 - Casino Mine Case Study – LNG Option for Mine Haul Trucks

Overview of Casino Mine Project[32]

The Casino Mine project being developed by Casino Mining Corp. (CMC) involves a copper, gold, molybdenum and silver deposit located about 300 km northwest of Whitehorse, in west-central Yukon. The project, which is currently in the environmental assessment review phase, ranks among the largest copper-gold deposits in the world. The proposed development is an open pit, truck and shovel operation processing about 190,000 tonnes per day of ore and waste. The mill at the mine site is expected to process about 120,000 tonnes of ore per day and the heap leach (to recover the gold) 25,000 tonnes per day over a 22-year mine life (excludes inferred resources that exceed the established ore reserves).

The Casino Mine project will have a 200 MW on-site combined cycle power plant relying on LNG transported to the mine site (using LNG-fueled tractors and B-Train tankers) from an LNG facility to be built by others in the Fort Nelson area of northeastern B.C., approximately 1,300 km by all-year road from the mine site. The typical power running load of 130 MW will operate 24 hours per day for 365 days per year, using 900 m^3/day (237,000 US gal/day) of LNG. Electric power will represent about 30% of the cost to process the ore.

The LNG supply chain development for the on-site power generation provides the basis for other planned uses of LNG related to this mine project, including:

- Options for large fleet of 340 MT mine haul trucks (LNG options to diesel are noted to include high pressure direct injection [HPDI] technology under development by Caterpillar, gas-diesel mixture technology currently available for smaller capacity haulage units, and conventional diesel-electric haulage units operating on a regenerative trolley assist network. Mining operation LNG fuel use estimated at 90 m^3 (24,000 US gal) per day (equal in energy to about 14,400 US gal per day of diesel).[33]
- LNG will be the primary fuel for heating and ventilating purposes throughout the project facilities. LNG fuel use for such other on-site uses estimated at 10 m^3/day.
- LNG fueled over-the-highways tractors to haul: 1,100 tonnes/day of copper concentrates, 400 tonnes per day of lime and grinding media, and 140,000 tonnes per day of diesel. LNG for these off-site uses estimated at 20 m^3 (5,300 gal) per day.

CMC estimates that the planned use of LNG for this project relative to diesel will reduce carbon dioxide emissions by about 28% or about 140,000 mt/year and also significantly reduce annual operating costs.

---

[32] Cameron Brown, VP Engineering, Casino Mining Corp.; "LNG Fuels Casino Mining & Processing Operations", presentation to Yukon Geoscience Forum, November 19, 2016. Supplemented with information from Casino Mining Corp. web site: *http://casinomining.com/project/.*

[33] Assumed diesel energy content (HHV) approximates 0.1464 GJ/US gal and assumed LNG energy content (HHV) approximates 0.0870 GJ/US gal [about 23 GJ per m^3]. Energy content in practice can vary from these assumptions.

Mine Haul Trucks Case Study

CMC had specific assessments developed (as part of its feasibility studies concluded in 2012 and early 2013) of potential LNG versus diesel fuel use for the following on-site mine trucks:[34]

- Caterpillar 797F truck (360 mt) - 28 units (with 8 rebuilds), with numbers varying over the mine life (appears to peak at about 24 active units); unit average fuel use 225.5 diesel litres/hour.
- Caterpillar 777F truck (90 mt) - 10 units, with numbers varying over the mine life (appears to peak at 7 active units); unit average fuel use 62.8 diesel litres/hour.
- Water truck (30,000 gal) - 6 units, with numbers varying over the mine life (appears to peak at 3 active units); unit average fuel use 90.2 diesel litres/hour.

Table A2.1-1 summarizes the feasibility study estimates of diesel fuel requirements over the Casino Mine life without LNG, breaking out fuel volumes for potential LNG use (per the above units).

Table A2.1-1: Projected Casino Mine Diesel Volume Requirements over Mine Life (000 litres)

	Pre-Operation 3 yrs	Operation Yrs 1-2	Operation Yrs 3-15	Operation Yrs 16-17	Operation Yrs 18-19	Operation Yrs 20-22	Total Operation Yrs 1-22	Total All Years
Diesel Option (000 litres)								
Potential LNG option units*	23,052	54,561	425,547	49,633	37,239	21,123	588,103	611,155
Other mining fuel uses**	11,485	21,408	157,369	20,148	12,330	8,148	219,403	230,888
Total Diesel Volumes	34,537	75,969	582,916	69,781	49,569	29,271	807,506	842,043
*CAT 797F, CAT 777F, Water Truck								
** Track Dozers, Wheel Dozers, Motor Graders, Excavators, Wheel Loaders								
Av per year-Potential for LNG	7,684	27,281	32,734	24,816	18,619	7,041	26,732	24,446
Av per year - Other fuel uses	3,828	10,704	12,105	10,074	6,165	2,716	9,973	9,236
Av per year - Total Diesel	11,512	37,985	44,840	34,890	24,784	9,757	36,705	33,682
Share for Potential LNG option	67%	72%	73%	71%	75%	72%	73%	73%

Table A2.1-1 indicates that the three mine truck units assumed for potential LNG use account for 73% of overall mine operation diesel fuel use, with average diesel volumes for these units of 32,734 thousand litres per year (about 23,700 US gal/day) for most operating years (e.g., years 3 to 15). The large mine haul units (Caterpillar 797F at 360 mt) account for the vast majority (e.g., about 90%) of the diesel volumes assumed for potential LNG use.

LNG displacement of diesel within the Table A2.1-1 potential mine haul fuel volumes for this project will vary depending on the mine haul truck LNG technology assumed to be available:

---

[34] Independent Mining Consultants, Inc.; **Casino Copper-Gold Project Yukon Territory, Canada - Feasibility Study Mining,** December 2, 2012 (assuming diesel fuel); and **Casino Copper-Gold Project Yukon Territory, Canada - Feasibility Study Mining - LNG Truck Haulage**, January 14, 2013.

1. **Natural gas-diesel mixture option** - LNG conversion kit options (with dual fuel capability) are assumed to offer potential to displace 50% to 70% of the diesel fuel use with minimal time or cost required for unit conversions, e.g., implies in most operation years for the Casino Mine, displace between about 11,900 to 16,600 US gal/day of diesel fuel use for the mine trucks. [The CMC estimates noted earlier of 24,000 US gal/day LNG use for mining operations is equal to about 14,400 US gal/day of diesel fuel displacement, and appears to reflect this level of minimum displacement with respect to mine trucks].

2. **High pressure direct injection [HPDI] option** - This LNG use technology is under development by Caterpillar for high horsepower applications within the range relevant to the Casino Mine, and is estimated to displace about 95% of diesel fuel use. CMC had a feasibility assessment completed[35] assuming that this option would be available by the time that the Casino Mine is developed for the selected mine haul truck units (per Table A2.1-1). Key results from this assessment (2012$, assumed parity of CAN$ and US$):

    - Capital cost increase impact for LNG trucks: $15.5 million, or 3.7% increase to this specific major mining equipment cost otherwise estimated at $423.1 million with all diesel fuel use (includes impact of $11.5 million of pre-production fuel cost savings from LNG fuel displacement of diesel fuel prior to full in-service of the mine capital development).[36]

    - Operating fuel cost saving impact from LNG fuel displacement of diesel fuel in the selected mine haul units: $329.9 million over 22 year mine operation, or 39% saving in total mining operation fuel cost otherwise estimated at $840.6 million with all diesel fuel use.[37] Diesel fuel use without LNG accounts for 60% of estimated mine operation costs over the 22 year life. Under the assumptions adopted for the feasibility study, the fuel cost savings in the first year of operation will offset the net added capital costs assumed with the LNG option that occur prior to start of operations.

    - The CMC Feasibility Study estimates a Net Present Value cost saving after tax from LNG use for mine haul trucks over the mine life of over $60 million at an 8% discount rate per year.

---

[35] Independent Mining Consultants, Inc.; **Casino Copper-Gold Project Yukon Territory, Canada - Feasibility Study Mining - LNG Truck Haulage**, January 14, 2013.

[36] Total mine capital cost without LNG is $648.9 million, including $172.4 million "sustaining capital" incurred after start of mine operations. CMC assumed added capital cost with LNG option at $600 per unit for Cat 797F, $200 per unit for Cat 777F, and $300 per unit for the water truck. A material portion of the added mine capital cost with LNG ($11.7 million) occurs after the start of operations and is a sustaining capital cost impact. The net added capital cost with LNG as at start of operations is only $3.8 million in this feasibility assessment.

[37] The IMC feasibility study assumed mine site diesel cost at $1.041 per litre and LNG cost at $0.480 per diesel equivalent litre, based on information provided by CMC. The fuel cost saving estimate of $329.9 million reflects the assumed saving of $0.561 per litre and the estimated 588,103 thousand litres of diesel fuel displaced by LNG/diesel fuel mix (see Table A2.1-1). Adjusted fuel cost saving estimates can be provided using alternative fuel cost savings per litre and/or different diesel displacement percentages. The LNG cost assumed for the referenced IMC feasibility study was conservative relative to CMC's LNG cost estimates, in part to recognize that 5-10% of the HPDI fuel will be diesel. [CMC's LNG cost estimate in 2012 Q4 approximated $11.2/GJ or about $0.43 per diesel equivalent litre].

3. **Conventional diesel-electric haulage units operating on a regenerative trolley assist network** - CMC continues to consider this option, which would require added LNG use for power generation (at energy conversion efficiencies that exceed 50% with combined cycle generation) to fully displace diesel or LNG use in mine haul units (with lower energy conversion efficiencies) where trolley assist is adopted, e.g., potentially on steep uphill mine haul segments as well as in the extensive downhill haul segment at the Casino Mine where regenerative power can be provided. Technology for trolley assist options is reasonably well established,[38] and in the case of the Casino Mine can offer an option for LNG use to displace diesel fuel use in mine haul trucks.

The CMC Case Study for mine haul truck diesel fuel displacement with natural gas is premised on the CMC plan to use LNG for on-site power generation. LNG requirements for on-site power generation account for 90% of the overall LNG supply to be delivered to the Casino Mine, and establish the basis for developing a secure and cost-efficient LNG supply chain as part of the mine development plan (including plans for adequate new LNG supply to be developed by Ferus at a desired northern location [Fort Nelson], with deliveries of LNG to the Casino site by LNG-fueled tractors and B-Train tankers with capacity to deliver 2,000 GJ [over 85 m^3] per unit). The Casino Feasibility Study referenced above for the HPDI mine haul truck LNG option assumed an LNG cost delivered to the mine site of approximately $0.48 per diesel equivalent litre (about $12 per GJ); the CMC LNG cost estimate in Q4-2012$ assumed a gas commodity cost of about $4.3/GJ,[39] implying that the assumed liquefaction cost, haul cost (1,300 km) and contingency totaled about $7.7/GJ.

Absent the on-site power generation requirements for LNG, the economic feasibility of mine haul truck use LNG opportunities at this mine site would likely be severely constrained until an equivalent secure and cost effective LNG supply chain was established by others.

[38] Based on information provided by CMC, Siemens has been working with several OEMs to produce truck drive systems for 240t to 400t. Trucks would run on diesel power in the pit and around the crusher, but over 80% of the fuel that would otherwise consumed on grade is displaced. Operating mines with Siemens trolley systems and trolley trucks with Siemens drives have been commissioned since 2000 at various mines in Zambia and South Africa.

[39] Personal communication with Cameron Brown, VP of Engineering, CMC.

3.0 REVIEW OF NATURAL GAS FUEL MINE HAUL TRUCK TECHNOLOGIES

3.1 INTRODUCTION

Section 3 reviews available information on the current state of natural gas fueled mine truck technologies, including truck fleet storage tanks, and refueling and on-site fuel supply logistic options.

The review first addresses existing technologies (i.e., options currently available for commercial application), and then addresses emerging technologies.

Natural gas use in mine haul trucks can potentially involve either liquefied natural gas (LNG)[40] or some form of compressed natural gas (CNG), with LNG typically being favoured in order to enhance on-truck fuel storage. If LNG is used, it must be vaporized on the truck prior to its use, i.e., natural gas at normal temperature remains the fuel used for the engine. Options for natural gas use include conversions of existing diesel fueled units (by either a separate conversion kit supplier or by the OEM) where there will be continued dual fuel use of diesel and natural gas (including use of only diesel if needed), as well as newly designed units that operate either entirely on natural gas or retain some use of diesel fuel and potential dual fuel use. In open-pit mine cases where on-site power generation with LNG is adopted, there may also be the option to displace diesel with natural gas by use of trolley assist technology to displace diesel fuel using electricity generated with LNG fuel.

For each technology, the review describes to the extent feasible the key features of the technology, its applicability to different mine haul trucks (scale and OEM), its state of readiness, estimated economic impact (high level business case summary), estimates of impacts on GHG and pollutant air emissions, and any pilot studies in Canada and (to a limited extent) elsewhere.

As reviewed in Section 2, mine haul trucks are gigantic and operate in extreme and demanding environments. There are several Original Equipment Manufacturers (OEMs) and a range of different truck sizes (metric tonnes payload) - given a focus on saving of fuel costs and adverse air emissions, the review tends to focus on the larger size units where fuel change can have the biggest impacts. High level and reliable use throughout each day (24 hours, with two 12 hour shifts) and all months of the year is needed - a factor which to date, when looking at natural gas fuel options, has favoured use of LNG to enhance on-vehicle storage of natural gas sufficient for at least one full shift. To be successful, a natural gas option also cannot compromise the haul trucks' required high torque and horsepower - and must yield, with sufficient certainty, cost and air emission reductions that will justify adoption of this option to displace reliance on well established diesel fuel technologies.

[40] LNG is natural gas that is cooled to -162 degrees C, reducing its volume 600:1. LNG is a colourless, odorless, non-toxic liquid that is less than half the weight of water. It is stored and transported at low pressure in double walled vacuum jacket trailers.

Table 3-1 summarizes various estimated potential reductions in air emissions from use of LNG to displace diesel fuel, indicating potential reductions for GHG (20% to 35%),[41] NOx (31% to 40%, potentially up to 97%), SOx (74% to 100%), particulate matter (50% to 89%), as well some other emissions.[42] Aside from potential issues regarding natural gas life cycle GHG emissions (which relate mainly to fuel production stage leakages), the outstanding question is the extent such emission reductions are secured in practice under each of the various technology options.

Table 3-1: Potential GHG and Air Pollutant Reductions: LNG Vs Diesel in Mine Haul Trucks

Contaminant	FortisBC. 2014[43]	Caterpillar 2012 Study[44]	Hatch Presentation[45]	CMI[46]
GHG	-29.9%			-20 to - 35%
NOx	-30.9%	-40%	Up to -97%	
SOx	-73.7%		-100%	
Particulate Matter	-50.2%	-60%	-89%	
CO2		-20%	-50%	
CO			-91%	
Volatile Organic Hydrocarbon (VOCs)			-50%	

[41] Lower GHG emission benefits have been estimated for life cycle emission impacts (20 and 100 year life), taking into account GHG emissions during production phase fuel leakage (see ESDOE, Alternative Fuels Data Center, "Natural Gas Vehicle Emissions", May 2016. Concerns have also been noted about methane leakage with CNG in particular (and natural gas in general) displacing diesel fuel for vehicles (see O. Delgado, R. Muncrief; "Assessment of Heavy Duty Natural Gas Vehicle Emissions; Implications and Policy Recommendations"; July 2015).

[42] Details have not been provided or pursued as to the source of these reported variances. NRCan comments on the Draft Report suggested that the reported reductions in GHG and air pollutants may vary in these references due to different technology options, varying diesel substitution rates (emissions may be higher at low substitution rates due to unburnt methane in the exhaust coupled with mostly diesel-based GHG emissions) and other factors such as differing assumptions about lifecycle emissions of methane (and increasing attention to fugitive emissions from natural gas extraction and transportation.

[43] Jason McIvor, FortisBC: Presentation "FortisBC: LNG Use in Mines", May 23, 2014 (stated source: GH Genius Model).

[44] Caterpillar, LNG Mining Truck – Launch Review, May CIM Conference Edmonton, May 2012.

[45] Hatch, Presentation "LNG for Mining Operations", May 2016 (stated source: US Department of Energy). Don Dean, Prolog Canada referenced the same estimates and source in presentation to Yukon Geoscience Forum, November 19, 2016. A brief report on Natural gas Vehicles by US Senate Democratic Policy Committee (re: Clean Energy Jobs and Oil Accountability Act) states that the EPA has found that when natural gas is used in vehicles to displace diesel fuel: reduce particulate matter by 50%, significantly reduce CO emissions, reduce NOx and VOC emissions by 50% or more, potentially reduce CO_2 emissions 25% depending on the source of the natural gas, and drastically reduce toxic and carcinogenic pollutants.

[46] Canadian Mining Institute, March-April 2016 Edition, Alexandra Lopez-Pacheco. "Conversion Story" https://magazine.cim.org/en/2016/March/technology/Conversion-story.aspx.

The following review has relied on publicly available studies/surveys, articles and other publications combined with interviews/exchanges where feasible with key persons involved with these technologies. In many instances, direct discussions revealed that new information was confidential and proprietary and thus would not be available for this review. As a result, this study has not been able to address some of the potentially important differences that may occur in regard to technologies reviewed below.[47]

3.2 EXISTING TECHNOLOGIES

Existing technologies for natural gas use in mine haul trucks available for use in Canada have been limited to LNG-diesel dual fuel conversion systems as provided by Gaseous Fuel Systems (GFS) Corp., an after-market supplier. The trolley assist electrical "natural gas" option also exists for open-pit mine cases where on-site power generation with LNG is adopted. None of the OEM options are commercially available or eligible as an existing technology option.

3.2.1 GFS LNG-Diesel Dual Fuel After-Market Conversion

Gaseous Fuel Systems (GFS) Corp., an after-market supplier based out of Florida, has been specializing in LNG-diesel conversion since 1988. GFS has engineered the GFS EVO-MT System introduced in 2013 which can be installed onto Komatsu 830 DC/AC and 930E haul trucks and Caterpillar 793B, C, D models and Caterpillar 777B and C models. In 2015, GFS released a new system designed for Caterpillar's 793D haul truck (Figure 3-1).[48]

[47] NRCan comments on the Draft Report noted that there is a large body of literature published by the SAE and ASME on CNG emissions by some of the manufacturers mentioned in the report which essentially show that important differentiations must be made in regards to technology. NRCan noted that LNG vaporizer systems may operate closer to stoichiometry (ideal fuel air ratio) than direct injection systems and this will affect the thermal efficiency and thus achievable energy consumption estimates. Conversely, NRCan noted that the closer direct injection systems approach diesel fuel/air ratios (leaner), the more they behave like diesels in terms of higher thermal efficiency but also in terms of engine emissions - and, in some cases, they may begin to emit particulates like diesels.

[48] The GFS EVO-MT System has been used on Caterpillar trucks successfully throughout the U.S.A. In Canada, where Caterpillar in Canada has been pursuing its own dual fuel system, the GFS EVO-MT System has only been installed on Komatsu trucks. GFS has established dealers throughout Canada. See GFS Corp., Manufacturer of Natural Gas Conversions for High Horsepower Diesel Engines Names Two New Distributors in Canada for its EVO-MT System. January 7, 2016. https://globenewswire.com/news-release/2016/01/07/800092/10158967/en/GFS-Corp-Manufacturer-of-Natural-Gas-Conversions-for-High-Horsepower-Diesel-Engines-Names-Two-New-Distributors-in-Canada-for-its-EVO-MT-Systems.html?culture=en-us.

Figure 3-1: GFS Corp EVO-MT System

Source: GFS Corp., EVO-MT 7930 LNG Conversion for Caterpillar 793 Mine Haul Trucks. Accessed: http://www.gfs-corp.com/industry.php/mining/products/1.

Option Description and High Level Economics

The GFS conversion retains the OEM diesel fuel system in its entirety, with the capability to operate solely on diesel fuel when required. LNG stored on the truck is converted to natural gas (vaporized) prior to use, i.e., natural gas at normal temperature remains the fuel used for the engine when displacing diesel fuel. Once the LNG is converted to a vapor phase, it is delivered to the engine air-intake system at a point upstream of the turbo-compressor using low restriction air-gas mixing technology.

The dual fuel system after conversion runs on 100% diesel at idle and very low speeds; as speed increases, a computer algorithm begins to displace the diesel with gas, allowing up to 70% diesel substitution. Averages of 40-50% diesel displacement can be expected using dual fuel engines, based on pilot projects and commercialized products in North American coal mining fleets.[49] The GFS EVO-MT System is designed to allow mine haul trucks to reach these displacements of diesel fuel while retaining OEM, diesel only performance in such critical areas as power, response, and efficiency.

The GFS conversion kit is pre-fabricated "pod" that is installed externally of the engine and includes double-walled vacuum insulated cryogenic tanks (to store the LNG), LNG vaporizer, cryogenic safety controls, high and low pressure gas regulators, gas flow meter and sensors. LNG storage on each truck with the conversion is normally sufficient to allow for a 12-hour refueling cycle for a typical 12 hour shift. A conversion kit is shipped to the mine site completely assembled and tested, designed for specific haul

[49] The description in this paragraph of diesel and natural gas use with the LNG conversion is generally from E. Salehi, S. Save, C. Zuliani, and G. Almquist, Hatch Ltd., Calgary, Alberta, Canada. "Fueling Alberta Oil Sands Fleets with Natural Gas". Hydrocarbon Processing, January 2016. Personal Communication with Guo Hongsheng, Senior Research Officer, National Research Council, January 31, 2017 confirms that these dual fuel conversions can reach diesel displacements of up to 70% under ideal conditions. An average 50% diesel displacement for these conversions was also assumed in Jason McIvor, FortisBC: Presentation "FortisBC: LNG Use in Mines", May 23, 2014.

truck configurations and duty cycles.[50] The converter can typically be installed at the mine site by a technician in a 6 to 8 hour period.[51]

The cost of the EVO-MT System is between $150,000 and $300,000 for each conversion, including install.[52] The cost range is dependent on the truck model.

George Aguilera, of GFS Corp. estimates that in 2014 payback of a conversion system was approximately 2 years with the cost of diesel at that time, and that the current payback is approximately 4 years due to the lower cost of diesel.[53] Assuming the upper limit conversion cost of $300,000 per truck and diesel use per truck (before conversion) averaging about 125 litres/hour (1 million litres/year),[54] 50% average annual diesel displacement with LNG and a two year payback implies a cost saving of approximately $0.30 per litre of diesel displaced (about $7.76/GJ); a four year payback implies a cost saving of approximately $0.15 per litre of diesel displaced (about $3.88/GJ).

A case study assessment of an equivalent dual fuel conversion option for 40 mine heavy-haul trucks and five heavy-lift shovels at a hypothetical oil sands site assumed 2,000 bpd (318,000 litres per day) of diesel, averaging about 294 litres per hour per unit, that could be 50% displaced by LNG. Assuming a natural gas price at about $3.13/GJ, and a diesel price at about $21.86/GJ, the case study indicated a three year payback of an estimated $70 million capital cost that included all costs for an on-site micro-LNG plant, refueling stations and engine conversions. Approximately $49 million (70%) of the capital cost estimate was for designing and building the LNG facility, indicating assumed costs for conversions and on-site refueling averaging about $468,000 per truck and heavy duty shovel. The case study analysis showed that economics for the LNG route were robust to changes in the diesel to natural gas price in Alberta, potential cost increases in implementing the project, and lower diesel substitution rates.[55]

GFS Corp. has been involved in pilot LNG mine haul truck projects in Canada and the United States (see below), and have been talking to companies in Quebec, Ontario, the northern territories, B.C., and Alberta. However, due to confidentially GFS Corp. could not divest which OEMs, mines, and LNG suppliers are all involved in current discussions. GFS Corp. has also stated that the most interest is coming from

---

[50] The description presented in this paragraph is generally a summary from Russell A. Carter, Waiting for Ignition, Engineering and Mining Journal, February 5, 2016. http://www.e-mj.com/features/5942-waiting-for-ignition.html#.WJ3bbGczWUk. See also GFS Corp., Manufacturer of Natural Gas Conversions for High Horsepower Diesel Engines Names Two New Distributors in Canada for its EVO-MT System. January 7, 2016. https://globenewswire.com/news-release/2016/01/07/800092/10158967/en/GFS-Corp-Manufacturer-of-Natural-Gas-Conversions-for-High-Horsepower-Diesel-Engines-Names-Two-New-Distributors-in-Canada-for-its-EVO-MT-Systems.html?culture=en-us.

[51] Personal Communication with George Aguilera, Executive Vice President, GFS Corp., February 7, 2017.

[52] Canadian Mining Institute, March-April 2016 Edition, Alexandra Lopez-Pacheco. "Conversion Story". https://magazine.cim.org/en/2016/March/technology/Conversion-story.aspx A conversion cost of $300,000 per truck was assumed in Jason McIvor, FortisBC: Presentation "FortisBC: LNG Use in Mines", May 23, 2014.

[53] Personal Communication with George Aguilera, Executive Vice President, GFS Corp. February 7, 2017.

[54] This was assumed when assessing business case for open pit mining assuming 830 Komatsu/793 CAT in Jason McIvor, FortisBC: Presentation "FortisBC: LNG Use in Mines", May 23, 2014.

[55] See E. Salehi, S. Save, C. Zuliani, and G. Almquist, Hatch Ltd., Calgary, Alberta, Canada. "Fueling Alberta Oil Sands Fleets with Natural Gas". Hydrocarbon Processing, January 2016; and "Leveraging LNG" in Oilsands Review, October 2015.

outside of Canada, particularly in Eastern Europe and Russia where diesel is still controlled by government and taxed, making LNG fuel source a much cheaper option.[56]

Fording River Coal Pilot Project in Southeast B.C.

The GFS EVO-MT System was used in the only public LNG mine haul truck use pilot to date in Canada, at the Teck Fording River Operations (FRO) coal pilot project in southeastern B.C. Teck estimated that if they were to expand the dual LNG-diesel fuel across their steelmaking coal operations there is the potential to eliminate approximately 35,000 tonnes of CO2 emissions annually and reduce fuel costs by more than $20 million annually.[57]

The pilot project began in 2015 and ended December 2016. The pilot had several parties involved including:

- Teck Resources Limited – the mine truck operators and miners. Teck is a Canadian metals and mining company.
- FortisBC Inc. – the LNG supplier (shipped by road 1,100 km from Tilbury LNG plant at Delta, B.C.),[58] and also financial contributor to the project.
- GFS Corp. – supplier and engineer of the EVO-MT dual-fuel conversion retrofit.
- Chart Industries – mobile unit and self contained mobile fueling station that includes a patented liquid-submersed pump and an integrated meter system that allows operators faster start-ups and single hose, zero-loss filling with auto shut-off.[59]
- Komatsu - the OEM.

Teck installed 6 GFS EVO-MT System retrofit converters onto four Komatsu 830E mine haul trucks and two 930E mine haul trucks. Teck worked closely with the OEM and retrofit GFS to ensure proper installation, maintenance, and use.

The pilot project allowed Teck to gain important knowledge, experience, and data to evaluate LNG use, while reducing operating costs and emissions.[60] Since the end of the FRO pilot Teck has indicated that they did not meet their emission reduction targets, that the project has indicated that LNG can be used safely in their operations, and that it will continue to look at using LNG as a fuel source alternative for haul trucks.[61] Teck has not to date released publicly any added information on its realized operating cost

[56] Personal Communication with George Aguilera, Executive Vice President, GFS Corp. February 7, 2017.
[57] Teck, Behind the Pilot, June 22, 2016. http://www.teck.com/news/stories/2016/behind-the-pilot--lng-truck-conversion-at-fording-river-operations.
[58] For description of Fortis LNG facilities, see: FortisBC, Liquefied Natural Gas, 2017. https://www.fortisbc.com/NaturalGas/Business/Pages/Liquefied-Natural-Gas.aspx.
[59] Russell A. Carter, Waiting for Ignition, Engineering and Mining Journal, February 5, 2016. http://www.e-mj.com/features/5942-waiting-for-ignition.html#.WJ3bbGczWUk.
[60] Teck, Behind the Pilot, June 22, 2016. http://www.teck.com/news/stories/2016/behind-the-pilot--lng-truck-conversion-at-fording-river-operations.
[61] Report by Josh Hoffman, B-104 News Centre blog, based on release and comments by Nic Milligan of Teck, December 15, 2016.

savings or emissions reductions.[62] The following perspectives can be offered based on available information, including comments provided by George Aguilera of GFS Corp. with respect to this pilot:[63]

- LNG supply – as FRO was a pilot project and was set for only a total of 6 Komatsu mine haul trucks, it was not feasible to look into building a permanent LNG storage or supply facility on-site. The distance (1,100 km) needed for shipping LNG to the site adds considerably to the LNG costs at the site.
- Price of diesel - diesel price today is much lower than it was when the FO pilot was planned in 2014, increasing the payback time needed on LNG retrofit kits.
- Current option of GFS Corp. as a retrofit and not an OEM means the EVO-MT System is technically not supported by the OEM and may invalidate warranties. GFS Corp. does provide a one year warranty on its product.
- Emissions testing is still limited and, from GFS Corp.'s perspective, not entirely reliable as the current instrumentation does not install well on current mine haul trucks (Caterpillar and Komatsu models), and emissions testing is often completed with the truck standing still. These factors can, from GFS Corp.'s perspective, affect emissions testing on a dual fuel system in several ways, e.g., as testing may not represent the mine haul truck as it is moving, diesel displacement may not be accurately reflected, and/or diesel may kick back in as the engine is standing still.[64]

Teck apparently continues after the end of FRO pilot project to be in regular contact with FortisBC and GFS Corp. regarding LNG updates. It is understood that the 6 retrofit kits used in the FRO pilot project are sitting in Teck storage and current discussions on its use are ongoing, however any timing for reinstallation at the moment is unknown.[65]

GFS LNG Mine Haul Truck Pilots in Wyoming

GFS Corp. has been involved with the following LNG-diesel dual fuel conversion kit option pilots in Wyoming:[66]

- Alpha Natural Resources, a major mine operator in Wyoming's Powder River Basin, started mine truck testing in 2012 at its Belle Ayr Mine.[67]
- After 18 months of daily operation at the Belle Ayr Mine, Alpha Coal West converted its 16 Caterpillar 793 haul units (see Figure 3-2 below) to LNG at the nearby Eagle Butte Mine - and

---

[62] Personal communications were had with Larry Davey and Jeff Sutherland of Teck to seek out updated information, and questions have been provided to them for possible response before this review concludes.

[63] Personal Communication with George Aguilera, Executive Vice President, GFS Corp. February 7, 2017.

[64] Personal Communication with George Aguilera, Executive Vice President, GFS Corp. February 7, 2017.

[65] Personal Communication with George Aguilera, Executive Vice President, GFS Corp. February 7, 2017.

[66] Russell A. Carter, Waiting for Ignition, Engineering and Mining Journal, February 5, 2016. http://www.e-mj.com/features/5942-waiting-for-ignition.html#.WJ3bbGczWUk.

[67] GFS Corp., GFS Corp Plans to Install LNG Conversions Alpha Coal West Mine Trucks, August 21, 2011. http://www.gfs-corp.com/news.php/yr/2011/art/1/yr/2011.

contracted with Plum Energy to build an LNG plant at the Eagle Butte Mine, sized to 28,500 gallons of LNG a day (of which Alpha Coal West was expected to use about 6,400 gallons/day of LNG to fuel its trucks).[68]

- In 2015, GFS had an order to have 10 of its EVO-MT 9300 LNG conversion systems installed on Komatsu 930E haul units at Arch Coal's Black Thunder Mine in Wright, Wyoming as part of Arch Coal's ongoing program to assess the benefits of using LNG its mining operations (fleet of LNG-powered 830E units had been in operation at Black Thunder since January 2014).[69]

Figure 3-2: Caterpillar 793B Retrofitted with a GFS Corp EVO-MT System (EVO-MT 7930)

Source: GFS Corp., GFS Corp Names Power Train Technologies, LLC as Distributor in Chile for its LNG Mine Truck Conversion Systems, May 27, 2015. Accessed: https://globenewswire.com/news-release/2015/05/27/739353/10136098/en/GFS-Corp-names-Power-Train-Technologies-LLC-as-Distributor-in-Chile-for-its-LNG-Mine-Truck-Conversion-Systems.html.

Despite the apparent push forward in 2014/15 at Alpha Coal's Belle Ayr and Eagle Butte mines based on the extended GFS LNG conversion kit pilots, including announcement of the Plum Energy LNG facility, there is no apparent evidence today that these initiatives have continued. The Alpha Eagle Butte Mine apparently subsequently went bankrupt and was purchased by Centura Mine Group. Discussion with Holly Pierce of Alpha Natural Resources revealed that the LNG pilot project has concluded at the Eagle Butte Mine and the technology and conversion kits from that pilot project are sitting in storage. Holly Pierce further stated that Alpha was finding that the LNG pilot project at the Eagle Butte Mine was not cost

[68] GFS Corp., Plum Energy to Build LNG Plant at Alpha Coal's Eagle Butte Mine, September 20, 2014. http://www.gfs-corp.com/news.php/yr/2014/art/19/yr/2014.

[69] GFS Corp., New Order for the Supply of LNG Haul Truck Conversion Systems to Arch Coal's Black Thunder Mine, March 12, 2015. http://www.gfs-corp.com/news.php/yr/2015/art/23/yr/2015.

effective and did not achieve emissions reductions forecasts, but could not get into details due to confidentiality.[70]

At this time no new information has been obtained regarding the Arch Coal Black Thunder Mine LNG pilot, including whether it in fact proceeded and/or any results to date regarding cost or emissions reductions.

3.2.2 Trolley Assist Mine Truck Electrical Option

As reviewed in Appendix 2.1, Casino Mining Corporation (CMC) continues to examine the mine haul truck option of diesel-electric haulage units operating on a regenerative trolley assist network.

Under the Casino Mine development, where on-site power generation will use LNG, this option would require added LNG use for power generation (at energy conversion efficiencies that exceed 50% with combined cycle generation) to fully displace diesel or LNG use in mine haul units (with lower energy conversion efficiencies) where trolley assist is adopted, e.g., potentially on steep uphill mine haul segments as well as in the extensive downhill haul segment at the Casino Mine where regenerative power can be provided.

Technology for trolley assist options is reasonably well established,[71] and in the case of mines relying for power from on-site LNG fueled generators, can offer an option for LNG use to displace diesel fuel use in mine haul trucks.

3.3 EMERGING TECHNOLOGIES

Emerging technologies for natural gas use in mine haul trucks include dual fuel conversions (Caterpillar OEM with LNG in various tests, and high density compressed natural gas dual fuel conversion with Caterpillar unit in Australia), and technologies that rely on natural gas for normal engine performance (high pressure direct injection option and spark ignition gas engine option).

3.3.1 Caterpillar Dynamic Gas Blending LNG-Diesel Dual Fuel Conversion (DGB)

In Canada, Caterpillar is currently the only known OEM pursuing a LNG-diesel dual fuel conversion system for mine haul trucks.

---

[70] Personal Communication with Holly Pierce, Alpha Natural Resources, February 2, 2017.

[71] Based on information provided by CMC, Siemens has been working with several OEMs to produce truck drive systems for 240t to 400t. Trucks would run on diesel power in the pit and around the crusher, but over 80% of the fuel that would otherwise consumed on grade is displaced. Operating mines with Siemens trolley systems and trolley trucks with Siemens drives have been commissioned since 2000 at various mines in Zambia and South Africa.

Caterpillar has been actively examining for many years LNG-diesel dual fuel options for oil and gas applications as well as mine haul trucks, and has in recent years explained that it is working on two types of these systems:[72]

- Dynamic Gas Blending (DGB), which mixes natural gas with air and combines with diesel for combustion and diesel displacement of up to 60-70% (with ability to retain operation only on diesel if and when required). The first DGB conversion retrofit kits (for oil and gas applications) were introduced to the market in 2013. In 2015, it was announced that Cat had been running a DGB-equipped large mine haul truck at a test site near Tucson, Arizona, and that results indicated that customers operating DGB mine haul trucks could potentially save more than $1 million to as much as $4 million per unit over a 10 year period after the incremental cost of the installation is repaid. In 2016, it was noted that Cat 785C DGB truck (150 tonne) had been running successfully on LNG-diesel at three sites in North America since early 2015.[73]
- High Pressure Direct Injection (HPDI), which injects natural gas directly into the engine, using only a small amount of diesel as an ignition source, and which can provide greater than 90% diesel substitution (this is addressed below in Section 3.3.3).

Caterpillar in 2012 outlined that its LNG program objectives will include decreased emissions and GHG, evaluation of alternative fuel systems (i.e. fumigation), equivalent engine performance, same or lower sound levels, similar reliability when compared to diesel, and minimum 12 hour LNG fuel storage on-board.[74] Cat described an objective of a phase 1 study, plans to target 793, 795, and 797 models and a phase 2 study to additionally target 785 and 789 models. Caterpillar's Steve Igoe indicates that OEM performance reliability is better than an aftermarket conversion kit as the OEM can properly engineer and maintain the technology.[75]

Due to confidentiality, not much more is known about Caterpillar's current DGB technology aside from it being installed on the Cat DGB 785C truck (150 tonne) where it has been piloted in conjunction with the Shell Oil Sands Mining Initiative on three of its sites since 2015.[76] Commercialization of Caterpillar's dual fuel DGB system has been estimated at 12-18 months.[77]

3.3.2 High Density Compressed Natural Gas (HDCNG)

Compressed natural gas (CNG) is a type of storage system that can be used for dual fuel systems, similar to the GFS LNG dual fuel system, where the only material difference relates to the gas storage mode on

[72] Most of this summary comes from Russell A. Carter, Waiting for Ignition, Engineering and Mining Journal, February 5, 2016. http://www.e-mj.com/features/5942-waiting-for-ignition.html#.WJ3bbGczWUk. The referenced article included information from presentation by Jeff Castleman (strategy manager for Cat's large mining truck business) to the HH Summit in Dallas, Texas in 2015.

[73] Steve Igoe, Commercial Manager, LPSD Gas Engine Business, Peoria IL; "Cat Dual Fuel DGB Mining Truck Update, Delivering Customer Value", October 13, 2016, presentation at HH Summit in Chicago.

[74] Caterpillar, LNG Mining Truck – Launch Review, May CIM Conference Edmonton, May 2012.

[75] Personal Communication with Steve Igoe, Commercial Manager, Caterpillar, February 7, 2017.

[76] Personal Communication with Bruce Winchester, Executive Director, Canadian Natural Gas Vehicle Alliance, January 27, 2017.

[77] Personal Communication with Bruce Winchester, Executive Director, Canadian Natural Gas Vehicle Alliance, January 27, 2017.

the truck, i.e., the gas is stored in a compressed state as opposed to a liquid state with LNG. CNG works by being fed into the engine area via high pressure tubes where a pressure regulator accepts the CNG and reduces the pressure to the appropriate manifold intake pressure, the natural gas solenoid valve lets the gas flow from the regulator into the fuel injector and mixes with air as it enters the engine's combustion chambers.[78] Absent the CNG fuel, the engine can simply convert back to diesel.

Guo Hengsheng of the National Research Council of Canada indicates that CNG has not been experimented at all with mine haul trucks in Canada, and has been limited in Canada to experimentation with smaller vehicles (passenger vehicles, buses, semi-trucks).[79] CNG has been typically seen as a good option for smaller vehicles while LNG is seen as a good option for longer driving range requirements, particularly with 8.9 to 12 litre engines hauling large loads up to 80,000 lbs.[80] LNG has also been seen as more attractive than CNG for vehicles that are in constant operation with quick refill (i.e. mine haul trucks), specifically as LNG needs to be used within 5 days to avoid tank venting.[81]

Advancement in CNG mine haul trucks is occurring, however, in Australia where Mine Energy Solutions (MES), Sime Darby, and IntelliGas are working together to advance High Density Compressed Natural Gas (HDCNG) for mine haul trucks.[82] MES has been experimenting with HDCNG on the Caterpillar 789C mine haul truck, and reports the following attributes and results:

- HDCNG is compressed, stored and dispensed at more than 350 bar (5,076 psi), which is about twice the energy density of conventional CNG and about 65% of the energy density of LNG.
- HDCNG has less space and weight demands than normal CNG, and none of the handling issues from the cryogenic nature of LNG.
- MES has found diesel displacement of more than 80% achieved over full range drive cycle conditions without loss of torque or power.
- Other benefits found during testing include reduced noise and vibration.
- MES also claims the conversion technology can be retrofittable to any type of manned or automated mining vehicle and can easily be reversed.
- HDCNG fuel packs are mounted on the truck in four fuel cassettes, each containing two lightweight composite cylinders, which are designed to be robotically exchanged at the fueling

---

[78] CNG United, How Does CNG Work, 2017. https://www.cngunited.com/how-does-cng-conversion-work/.

[79] Personal Communication with Guo Hengsheng, National Research Council, January 31, 2017.

[80] Westport, CNG and LNG: What's Best for Your Fleet, June 20, 2013. http://www.westport.com/file_library/files/webinar/2013-06-19_CNGandLNG.pdf.

[81] Westport, CNG and LNG: What's Best for Your Fleet, June 20, 2013. http://www.westport.com/file_library/files/webinar/2013-06-19_CNGandLNG.pdf.

[82] The following information on the Australian HDCNG option is sourced to Russell A. Carter, Waiting for Ignition, Engineering and Mining Journal, February 5, 2016. http://www.e-mj.com/features/5942-waiting-for-ignition.html#.WJ3bbGczWUk. MES is the engineer of the CNG conversion technology, Sime Darby is a multinational conglomerate who have joint ventured with MES and own a Caterpillar dealership in Queensland where tests are occurring, and IntelliGas have developed the components and processes for the production, storage, dispensing, and utilization of HDCNG.

station in less than five minutes and on both sides of the vehicle simultaneously (see Figure 3-3). In-pit mobile refueling can also be provided as an option.

Additional updated information on HDCNG costs, emissions, operation efficiencies (e.g., fuel loading time impacts over a shift), state of readiness and other factors have not been uncovered to date.

Figure 3-3: HDCNG Storage Tanks on a Mine Haul Truck

The High Density Compressed Natural Gas (HDCNG) conversion system on this truck uses fuel cassettes that are robotically replaced at the refueling station.

Source: Engineering and Mining Journal, Russell A. Carter, Waiting for Ignition, February 5, 2017. http://www.e-mj.com/features/5942-waiting-for-ignition.html#.WJ3bbGczWUk.

3.3.3 High Pressure Direct Injection (HPDI)

Westport Inc. is the leader on High Pressure Direct Injection (HPDI), which was developed out of University of British Columbia research in the early 1980s and has been pursued in partnerships with Caterpillar and Cummins. HPDI is a technology where natural gas is injected directly into the combustion chamber at high pressure (thus it is called high pressure direct injection). HPDI cannot run on 100% diesel, provides power and torque similar to a diesel engine, and can replace 95% of the diesel use.[83]

[83] Hatch, LNG for Mining Operations, May 2016.

Westport Inc. claims a diesel displacement of 90% while still delivering on performance and fuel economy equivalent to that of high performance diesel fueled engines.[84] Westport HPDI 2.0 uses natural gas as the primary fuel along with a small amount of diesel as an ignition source. The two fuels are not pre-mixed with the intake air before they enter the combustion chamber so there is no risk of engine knock and therefore no need to lower the compression ratio and peak torque output. As compared to diesel fuel, directly injected natural gas burns with a lower adiabatic flame temperature and has a low propensity to the formation of carbon particles and therefore offers inherent NOx and PM emissions benefits that provide more product engineering flexibility. Westport HPDI 2.0 claims a natural gas storage and delivery system with proprietary fuel tank, fuel pump, and system controls that match the vehicle range, performance, and driveability of diesel in mine haul trucks. Westport HPDI 2.0 system is also engineered to be compatible with both LNG and CNG storage methods.

Westport currently has two joint ventures which include Cummins Westport in North American and Weichai Westport Inc. (WWI) in China. Both ventures focus on medium to heavy duty markets. Cummins Westport Inc. designs, engineers, and markets 6 to 12 litre spark-ignited automotive natural gas engines for commercial transportation applications such as truck and buses.[85] WWI current engines are widely used in city buses, coaches, and heavy duty truck applications in China or exported to other regions globally.

In terms of mine haul trucks, Westport has been working closely with Caterpillar on a Direct Inject Gas similar to HPDI.[86] Testing of the HPDI system back in 2012 revealed that the technology was a very good fit for Caterpillar. No pilot projects on the technology are currently running, but a pilot project is expected to become operational in 2017 or 2018.

Caterpillar has confirmed its interest in HPDI.[87] However, due to confidentiality there is no publicly available or sourced current information on the status of this initiative with Caterpillar. As a result, it is unknown if the Caterpillar/Westport Direct Inject Gas project has been successful, what reliability and performance are like, where it stands on state of readiness, costs involved, and where emissions testing stands.

The HPDI LNG option was included in a case study assessment for 40 mine heavy-haul trucks and five heavy-lift shovels at a hypothetical oil sands site assumed 2,000 bpd (318,000 litres per day) of diesel, averaging about 294 litres per hour per unit, that could be 95% displaced by LNG if an HPDI engine were commercialized. Assuming a natural gas price at about $3.13/GJ, and a diesel price at about $21.86/GJ, the case study indicated net present value benefits with HPDI over two times that of the Base Case with

[84] This paragraph's information is sourced to Westport, Westport HPDI 2.0, 2017. http://www.westport.com/is/core-technologies/hpdi-2. Notwithstanding the reference here to 90% diesel displacement, 95% diesel displacement has been assumed in case studies for Casino Mine and the oil sands, and is assumed in the Scenario 2 assessments in Section 4 of this study.

[85] Westport, Cummins Westport, 2017. http://www.westport.com/is/partners/joint-ventures.

[86] This paragraph's information is sourced to personal communication with David Mumford, Senior Director, HPDI Product Portfolio, Westport, January 30, 2017.

[87] See Russell A. Carter, Waiting for Ignition, Engineering and Mining Journal, February 5, 2016. http://www.e-mj.com/features/5942-waiting-for-ignition.html#.WJ3bbGczWUk. Also, see Canadian Mining Institute, Alexandra Lopez-Pacheco, "Conversion Story", March-April 2016 Edition. https://magazine.cim.org/en/2016/March/technology/Conversion-story.aspx.

GFS option 50% displacement, and an IRR of 45%, with the estimated $70 million capital cost that included all costs for an on-site micro-LNG plant, refueling stations and engine conversions.[88]

3.3.4 Spark Ignition (SI) Gas Engine

A spark ignition (SI) engine is an internal combustion engine where the combustion process is ignited by a spark plug (via a spark). The SI engines are often used interchangeably with gasoline engines in a typical gasoline powered vehicle. Apart from a required spark plug, an SI engine works in similar way as can be compared to a compression ignition engine where heat from compression and injection of a fuel initiate the combustion process without the need of a spark. This is what occurs in a diesel engine and dual fuel systems in mine haul trucks. Several companies and technologies are experimenting with and have commercialized the use of natural gas as the fuel source in SI engines, where natural gas and air provide the right amount of ignition to create combustion.

Westport has created a commercialized spark-ignited natural gas engine in conjunction with Cummins that is used in commercial vehicles, such as trucks and buses, but has not experimented with SI in larger off-road vehicles such as mine haul trucks.

Rolls Royce Power Engines has been experimenting with the use of SI in large off-road vehicles, notably mine haul trucks and marine. Due to confidentiality and a lack of publicly available information the advancement and progression of Rolls Royce in SI and mine haul trucks is not known, beyond the fact that MTU, a subsidiary of Rolls Royce, is leading development. However, marine engines have been commercialized under Bergen gas engines and have provided natural gas SI engines that are much more fuel efficient, produce less emissions, deliver on power and response, and provide a much cleaner work environment when compared to a marine diesel engine.

Ran Archer, MTU's senior manager of Global Mining, has stated that MTU is pursuing SI with 100% natural gas displacement of diesel over dual fuel technology as MTU does not believe current dual fuel engine technologies can provide enough natural gas substitution, given today's low oil prices, to justify the cost of a retrofit and offset the added refueling complexity.[89] Thus, MTU is pursuing SI natural gas engines that run on 100% natural gas with no need of diesel displacement, as opposed to dual fuel engines that require continuing reliance on diesel.

Additional updated information on SI costs, emissions, operation efficiencies, state of readiness, potential timing for commercial use, and other factors have not been uncovered to date.

---

[88] See E. Salehi, S. Save, C. Zuliani, and G. Almquist, Hatch Ltd., Calgary, Alberta, Canada. "Fueling Alberta Oil Sands Fleets with Natural Gas". Hydrocarbon Processing, January 2016; and "Leveraging LNG" in Oilsands Review, October 2015.

[89] Canadian Mining Institute, Alexandra Lopez-Pacheco, "Conversion Story", March-April 2016 Edition. https://magazine.cim.org/en/2016/March/technology/Conversion-story.aspx.

4.0 SCENARIO ASSESSMENTS FOR NATURAL GAS USE IN MINE HAUL TRUCK MARKET

4.1 INTRODUCTION

Section 4 reviews scenarios for potential future natural gas use to displace diesel fuel in off-road mine haul trucks in Canada, and related potential reductions in fuel costs and Greenhouse Gas (GHG) emissions in this sector.

The analysis initially focuses on snap shot assessments of two potential scenarios for maximum natural gas displacement of diesel fuel use for mine haul trucks in Canada. Subsequent analysis discusses factors that may affect actual levels of natural gas use and the timing for achieving such diesel fuel displacement.

4.2 DEFINING POTENTIAL MAXIMUM USE SCENARIOS

Section 2.3 estimated existing mine haul truck diesel fuel requirements in Canada at between 1,650 and 1,800 million litres per year, with oil sands accounting for about 750 to 900 million litres per year, i.e., about 45% to 50% of the Canadian total. This study has not attempted to forecast future diesel fuel requirements in the mine haul sector. Scenarios examined in Section 4 utilize the diesel fuel annual requirements as estimated in Table 2-3 (total of 1,828 million litres per year, with break outs for oil sands and other mining sectors) as a Base Case for assessing potential impacts of natural gas use to displace diesel fuel in this sector.

- Potential opportunities for natural gas use are only likely where there is adequate year-round road access for delivery of LNG. To reflect this factor, the potential market opportunity for natural gas is assumed to equal 95% of the total mine haul diesel fuel requirement in Canada.[90]
- Due to its overall dominant position in the mine haul market sector, oil sands mine haul truck diesel fuel requirements are also addressed specifically in the scenarios examined (and it is assumed that 100% of the oil sands mine haul truck diesel fuel use has adequate year-round road access).

Section 3 identified various existing and emerging technologies for natural gas use in mine haul trucks. Existing opportunities are limited mainly to LNG-diesel dual fuel conversion systems where 50% diesel displacement tends to reflect a reasonable average displacement estimate. Emerging opportunities include a broader range of potential technologies for both dual fuel conversions and options that would rely on natural gas for normal engine operation (including potential for 100% diesel displacement in

[90] The estimate is intended to flag the fact of this limitation rather than provide a precise estimate of the mine haul market that lacks adequate year round road access. It can be noted that mine haul trucks in Yukon, Northwest Territories and Nunavut account for about 4% of total existing mine haul trucks in Canada; however, not all mines in these territories lack adequate year round road access. The estimate allows for some mines located in remote locations in other provinces.

spark ignition gas engines). In order to provide a useful and representative range for potential future natural gas use in mine haul trucks in Canada, the following two scenarios are examined for natural gas and LNG technology use to displace diesel fuel:

- Scenario 1: 50% Natural Gas Use (reflects current conversion options).
- Scenario 2: 95% Natural Gas Use (reflects potential future high pressure direct injection option).

Sections 2 and 3 have highlighted the extent to which cost savings for mine operators from natural gas use in mine haul trucks depend on the gap in delivered price per GJ at the mine site for natural gas (LNG) versus diesel fuel. For example, a $300,000 conversion cost for a mine haul unit with 50% dual fuel natural gas use in a unit using 1 million litres/year would be recovered in two years with a fuel cost saving (natural gas saving versus diesel fuel) of $7.8/GJ and in four years with a fuel cost saving of $3.9/GJ.[91] Potential delivered fuel cost savings for LNG versus diesel fuel for a wide range of current and forecast cases examined in Section 2.4 ranged from about $4/GJ to over $15/GJ, depending on LNG transportation and liquefaction costs for specific applications as well as factors affecting overall diesel fuel prices versus natural gas commodity costs.[92]

Based on the above information, the scenario analysis estimates annual fuel cost savings from natural gas use in mine haul trucks over a range of savings in delivered price per GJ at the mine site (natural gas saving versus diesel fuel) ranging from $4/GJ to $16/GJ (2016$), with delivered diesel fuel prices ranging from $0.75 to $1.15 per litre (excluding taxes). Information for February 2017 in Alberta and B.C. (i.e., the region accounting for the dominant share of mine haul truck activity) suggests a current delivered price gap of about $8 to $10/GJ for many locations with delivered diesel fuel prices averaging about $0.77 per litre.[93]

For the scenario analysis, GHG emissions for diesel fuel are estimated at 78.12 kg GHG [CO2e] per GJ[94] and GHG emissions for natural gas are estimated at 72.5% of the diesel emissions or 56.66 kg GHG [CO2e] per GJ.[95] Although not estimated in this scenario analysis, it is noted that natural gas use to

---

[91] See discussion in Section 3.2. Similar timing would apply for a HPDI option with 95% diesel fuel displacement at an added capital cost per unit approaching $600,000.

[92] Section 2.4 describes the extent to which delivered LNG prices (relative to diesel fuel prices) are driven by liquefaction and transportation costs. Long term forecasts as reviewed in Section 2.4 suggest that a tendency for the gap to widened as crude oil and natural gas prices escalate faster than inflation.

[93] Review of diesel fuel prices in Alberta and B.C. as reported by Natural Resources Canada for late February 2017 excluding taxes (which are not applied for off-road mine haul truck use) indicates an average price of about $0.77 per litre or $19.9/GJ. In contrast, LNG supplied by Fortis from Tilbury during this same time period cost less than $8/GJ at the plant gate and a $2/GJ charge for transportation would likely allow for delivery for up to about 500 km radius.

[94] NEB conversion rate of 0.03868 GJ per litre of diesel fuel. GHG emissions at 3.02155 kg GHG [CO_2e] per litre of diesel fuel is calculated using emissions factors for CO_2 [2.690 kg/l], CH_4 [0.00015 kg/l] and N_2O [0.0011 kg/l] as reported in Environment Canada National Inventory Report, multiplied by global warming potentials for a 100-year horizon of 25 for CH_4 and 298 for N_2O as estimated in Table 2.14 in the IPCC 2007 paper "Changes in Atmospheric Constituents and in Radiative Forcing" [https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf, accessed on March 29, 2017].

[95] Based on estimate of 117 lb/MMBBtu of CO_2 for natural gas versus 161.3 lb/MMBtu of CO_2 for diesel fuel, as per US Energy Information Administration, https://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11 [accessed on February 15, 2017]. This is also the mid-point of CMI GHG emission reduction estimate of 20 to 35% for use of LNG vs. diesel in mine haul trucks (see Table 3-1).

displace diesel fuel will also materially reduce a range of air emission pollutants (e.g., NOx, Sox, Particulate Matter) as reviewed in Table 3-1.

4.3 SCENARIO ANALYSIS – MAXIMUM POTENTIALS

4.3.1 Scenario 1: 50% Natural Gas Use

Fuel Cost Savings

Under Scenario 1 with 50% natural gas use, one mine haul truck with Base Case diesel fuel use of 1 million litres per year will secure the following annual fuel cost savings (2016$) over the range of delivered fuel price savings examined for natural gas versus diesel fuel:

- At $4 per GJ saving for natural gas vs. diesel fuel:
    - $77,000 savings per year
    - 7% to 10% fuel cost saving at delivered diesel prices ranging from $0.75 to $1.15 per litre.
- At $8 per GJ saving for natural gas vs. diesel fuel:
    - $155,000 savings per year.
    - 13% to 21% fuel cost saving at delivered diesel prices ranging from $0.75 to $1.15 per litre.
- At $12 per GJ saving for natural gas vs. diesel fuel:
    - $232,000 savings per year.
    - 20% to 31% fuel cost saving at delivered diesel prices ranging from $0.75 to $1.15 per litre.
- At $16 per GJ saving for natural gas vs. diesel fuel:
    - $309,000 savings per year.
    - 27% to 41% fuel cost saving at delivered diesel prices ranging from $0.75 to $1.15 per litre.

Annual fuel cost savings per mine haul truck will vary from the above to the extent that Base Case annual diesel fuel use varies from the assumed one million litres per year (for some large units, annual fuel diesel fuel use may range from 1.5 to over 2 million litres per year).

Table 4-1 provides summary of potential fuel cost savings under Scenario 1. Under this scenario [assumes 50% Natural Gas Blends with Diesel] it is estimated that the mining sector could save between $134 and $537 million per year (2016$) from switching to LNG use for mine haul trucks, including between $66 to $266 million per year in the Oil Sands sector in Alberta:

- About 79% of total savings (all mine sectors) are from 218+ tonne payload trucks.
- About 50% of total savings (all mine sectors) are estimated to be in Oil Sands.

- About 56% of total Oil Sand potential savings are from 308+ tonne payload trucks, and about 88% are from 218+ tonne payload trucks.

Table 4-1: Potential Annual Fuel Cost Savings by Mine Haul Truck Payload Size: Scenario 1[96]

	Mine Haul Truck Size (tonnes payload)						Total
	90-110	127-150	154-190	218-255	290	308-363	
Total Number of Units (2016)	**460**	**183**	**171**	**482**	**304**	**391**	**1,991**
Oil Sands (units)	113	77	35	95	141	331	792
Base Case							
All Mining Sectors							
Potential Diesel Use (TJ/yr)	**6,501**	**3,566**	**4,793**	**19,347**	**14,448**	**22,052**	**70,707**
Potential Diesel to Displace (TJ/yr) at 95%	**6,176**	**3,387**	**4,554**	**18,380**	**13,726**	**20,949**	**67,171**
Oil Sands							
Potential Diesel Use (TJ/yr)	1,597	1,500	981	3,813	6,701	18,668	33,261
Scenario 1 - 50% Natural Gas Blends with Diesel							
All Mining Sectors							
Potential Diesel Use (TJ/yr)	3,413	1,872	2,516	10,157	7,585	11,577	37,121
Potential Natural Gas Use (TJ/yr)	3,088	1,694	2,277	9,190	6,863	10,475	33,586
Total Potential Fuel Cost Savings ($ million)							
At $4/GJ saving for natural gas vs. diesel fuel	**12**	**7**	**9**	**37**	**27**	**42**	**134**
At $8/GJ saving for natural gas vs. diesel fuel	**25**	**14**	**18**	**74**	**55**	**84**	**269**
At $12/GJ saving for natural gas vs. diesel fuel	**37**	**20**	**27**	**110**	**82**	**126**	**403**
At $16/GJ saving for natural gas vs. diesel fuel	**49**	**27**	**36**	**147**	**110**	**168**	**537**
Oil Sands							
Potential Diesel Use (TJ/yr)	798	750	491	1,907	3,351	9,334	16,630
Potential Natural Gas Use (TJ/yr)	798	750	491	1,907	3,351	9,334	16,630
Total Potential Fuel Cost Savings ($ million)							
At $4/GJ saving for natural gas vs. diesel fuel	**3**	**3**	**2**	**8**	**13**	**37**	**67**
At $8/GJ saving for natural gas vs. diesel fuel	**6**	**6**	**4**	**15**	**27**	**75**	**133**
At $12/GJ saving for natural gas vs. diesel fuel	**10**	**9**	**6**	**23**	**40**	**112**	**200**
At $16/GJ saving for natural gas vs. diesel fuel	**13**	**12**	**8**	**31**	**54**	**149**	**266**

Potential GHG Reductions

Table 4-2 provides summary of potential GHG reductions under Scenario 1. Under this scenario it is estimated that the mine sector could reduce its annual GHG emissions by approximately 721,000 tonnes [CO_2e] per year (by about 13%) from switching to LNG use for mine haul trucks, including by about 357,000 tonnes per year in the Oil Sands sector in Alberta.

Allocation of these GHG emission reductions among different payload truck sizes, and different economic sectors (e.g., Oil Sands), is the same as the allocations reviewed about for fuel cost savings from the use of natural gas.

It should be noted that the potential reductions in GHG emissions and air pollutants estimated in this study are theoretical and based on assumptions that do not include impact of conditions such as methane

[96] Litre of diesel fuel converted to TJ using a conversion rate of 1 m3 = 38.68 GJ [0.0368 GJ per litre]. Source: NEB Conversion Tables. 1TJ = 1,000 GJ.

slips from exhaust and engine crankcases, and other factors. Unburned hydrocarbon emissions from LNG engines such as methane could adversely impact GHG emission reduction as they tend to have a higher global warming potential compared to CO_2.

Table 4-2: Potential Annual GHG Reductions by Payload Size under Scenario 1[97]

	Mine Haul Truck Size (tonnes payload)						Total
	90-110	127-150	154-190	218-255	290	308-363	
Total Number of Units (2016)	**460**	**183**	**171**	**482**	**304**	**391**	**1,991**
Oil Sands (units)	113	77	35	95	141	331	792
Scenario 1 Potential GHG Reductions							
Estimated GHG with Diesel (000 tonnes CO2e)							
All Mining Sectors	508	279	374	1,511	1,129	1,723	5,523
Oil Sands	125	117	77	298	523	1,458	2,598
Estimated GHG with NG under Scenario 1 (000 tonnes CO2e)							
All Mining Sectors	442	242	326	1,314	981	1,498	4,803
Oil Sands	108	101	66	257	452	1,258	2,241
Estimated GHG Reduction with NG under Scenario 1 (000 tonnes CO2e)							
All Mining Sectors	-66	-36	-49	-197	-147	-225	-721
Percentage of reduction	-13%	-13%	-13%	-13%	-13%	-13%	-13%
Oil Sands	-17	-16	-11	-41	-72	-200	-357
Percentage of reduction	-14%	-14%	-14%	-14%	-14%	-14%	-14%

4.3.2 Scenario 2: 95% Natural Gas Use

Fuel Cost Savings

Under Scenario 2 with 95% natural gas use[98], one mine haul truck with Base Case diesel fuel use of 1 million litres per year will secure the following annual fuel cost savings (2016$) over the range of delivered fuel price savings examined for natural gas versus diesel fuel:

- At $4 per GJ saving for natural gas vs. diesel fuel:
  - $147,000 savings per year.
  - 13% to 20% fuel cost saving at delivered diesel prices ranging from $0.75 to $1.15 per litre).
- At $8 per GJ saving for natural gas vs. diesel fuel:
  - $294,000 savings per year.

[97] The impact of GHG reductions are estimated using estimated at 78.12 kg/GJ [CO2e] [equal to 3.02155 kg per litre]. GHG emissions are estimated at 72.5% of diesel emissions or 56.66 kg/GJ [CO2e] (based on estimate of 117 lb/MMBtu for natural gas versus 161.3 lb/MMBtu for diesel fuel for CO2, as per US Energy Information Administration), https://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11 [accessed on February 15, 2017].

[98] Assumed 95% natural gas use with HPDI has been assumed in case studies referenced earlier for Casino Mine and oil sands. In contrast, as noted earlier, Westport Inc. claims a diesel displacement of 90% while still delivering on performance and fuel economy equivalent to that of high performance diesel fueled engines with HPDI.

    - 26% to 39% fuel cost saving at delivered diesel prices ranging from $0.75 to $1.15 per litre.

- At $12 per GJ saving for natural gas vs. diesel fuel:
    - $441,000 savings per year.
    - 38% to 59% fuel cost saving at delivered diesel prices ranging from $0.75 to $1.15 per litre.
- At $16 per GJ saving for natural gas vs. diesel fuel:
    - $588,000 savings per year.
    - 51% to 78% fuel cost saving at delivered diesel prices ranging from $0.75 to $1.15 per litre.

Annual fuel cost savings per mine haul truck will vary from the above to the extent that Base Case annual diesel fuel use varies from the assumed one million litres per year (for some large units, annual fuel diesel fuel use may range from 1.5 to over 2 million litres per year).

Table 4-3 provides a summary of potential fuel cost savings under Scenario 2. Under this scenario [assumes 95% Natural Gas Blends with Diesel] it is estimated that the mine sector could save between $255 and $1,021 million per year (2016$) from switching to LNG use for mine haul trucks, including between $126 to $506 million per year in the Oil Sands sector in Alberta:

- About 79% of total savings (all mine sectors) are from 218+ tonne payload trucks.
- About 50% of total savings (all mine sectors) are estimated to be in Oil Sands.
- About 56% of total Oil Sand potential savings are from 308+ tonne payload trucks, and about 88% are from 218+ tonne payload trucks.

Table 4-3: Potential Annual Fuel Cost Savings by Payload Size under Scenario 2[99]

	Mine Haul Truck Size (tonnes payload)						Total
	90-110	127-150	154-190	218-255	290	308-363	
Total Number of Units (2016)	**460**	**183**	**171**	**482**	**304**	**391**	**1,991**
Oil Sands (units)	113	77	35	95	141	331	792
Base Case							
All Mining Sectors							
Potential Diesel Use (TJ/yr)	**6,501**	**3,566**	**4,793**	**19,347**	**14,448**	**22,052**	**70,707**
Potential Diesel to Displace (TJ/yr) at 95%	**6,176**	**3,387**	**4,554**	**18,380**	**13,726**	**20,949**	**67,171**
Oil Sands							
Potential Diesel Use (TJ/yr)	1,597	1,500	981	3,813	6,701	18,668	33,261
Scenario 2 - 95% Natural Gas Use							
All Mining Sectors							
Potential Diesel Use (TJ/yr)	634	348	467	1,886	1,409	2,150	6,894
Potential Natural Gas Use (TJ/yr)	5,867	3,218	4,326	17,461	13,040	19,902	63,813
Total Potential Fuel Cost Savings ($ million)							
At $4/GJ saving for natural gas vs. diesel fuel	**23**	**13**	**17**	**70**	**52**	**80**	**255**
At $8/GJ saving for natural gas vs. diesel fuel	**47**	**26**	**35**	**140**	**104**	**159**	**511**
At $12/GJ saving for natural gas vs. diesel fuel	**70**	**39**	**52**	**210**	**156**	**239**	**766**
At $16/GJ saving for natural gas vs. diesel fuel	**94**	**51**	**69**	**279**	**209**	**318**	**1,021**
Oil Sands							
Potential Diesel Use (TJ/yr)	80	75	49	191	335	933	1,663
Potential Natural Gas Use (TJ/yr)	1,517	1,425	932	3,623	6,366	17,734	31,598
Total Potential Fuel Cost Savings ($ million)							
At $4/GJ saving for natural gas vs. diesel fuel	**6**	**6**	**4**	**14**	**25**	**71**	**126**
At $8/GJ saving for natural gas vs. diesel fuel	**12**	**11**	**7**	**29**	**51**	**142**	**253**
At $12/GJ saving for natural gas vs. diesel fuel	**18**	**17**	**11**	**43**	**76**	**213**	**379**
At $16/GJ saving for natural gas vs. diesel fuel	**24**	**23**	**15**	**58**	**102**	**284**	**506**

Potential GHG Reductions

Table 4-4 provides a summary of potential GHG reductions under Scenario 2. Under this scenario it is estimated that the mine sector could reduce its annual GHG emissions by approximately 1,369,000 tonnes [CO_2e] per year (by about 25%) from switching to LNG use for mine haul trucks, including by about 678,000 tonnes per year in the Oil Sands sector in Alberta.[100]

Allocation of these GHG emission reductions among different payload truck sizes, and different economic sectors (e.g., Oil Sands), is the same as the allocations reviewed for fuel cost savings from the use of natural gas.

[99] Litre of diesel fuel converted to TJ using a conversion rate of 1 m3 = 38.68 GJ [0.0368 GJ per litre]. Source: NEB Conversion Tables. 1TJ = 1,000 GJ.

[100] By the way of example of other estimates for similar 95% natural gas use scenarios, **FortisBC [**Jason McIvor, FortisBC: Presentation "FortisBC: LNG Use in Mines", May 23, 2014 (stated source: GH Genius Model)] estimated at 29.9% reduction; Canadian Mining Institute [March-April 2016 Edition, Alexandra Lopez-Pacheco. "Conversion Story". https://magazine.cim.org/en/2016/March/technology/Conversion-story.aspx] estimated at 20% to 35% GHG reductions.

Table 4-4: Potential Annual GHG Reductions by Payload Size under Scenario 2[101]

	Mine Haul Truck Size (tonnes payload)						Total
	90-110	127-150	154-190	218-255	290	308-363	
Total Number of Units (2016)	**460**	**183**	**171**	**482**	**304**	**391**	**1,991**
Oil Sands (units)	113	77	35	95	141	331	792
Scenario 2 Potential GHG Reductions							
Estimated GHG with Diesel (000 tonnes CO2e)							
All Mining Sectors	508	279	374	1,511	1,129	1,723	5,523
Oil Sands	125	117	77	298	523	1,458	2,598
Estimated GHG with NG under Scenario 2 (000 tonnes CO2e)							
All Mining Sectors	382	209	282	1,137	849	1,296	4,154
Oil Sands	92	87	57	220	387	1,078	1,920
Estimated GHG Reduction with NG under Scenario 2 (000 tonnes CO2e)							
All Mining Sectors	-126	-69	-93	-375	-280	-427	-1369
Percentage of reduction	-25%	-25%	-25%	-25%	-25%	-25%	-25%
Oil Sands	-33	-31	-20	-78	-137	-380	-678
Percentage of reduction	-26%	-26%	-26%	-26%	-26%	-26%	-26%

4.4 FACTORS AFFECTING ACTUAL NATURAL GAS USE & TIMING

The above analysis in Section 4.3 focused on snap shot assessments of two potential scenarios for maximum natural gas displacement of diesel fuel use for mine haul trucks in Canada. The following analysis discusses factors that may affect actual levels of natural gas use and the timing for achieving such diesel fuel displacement.

As highlighted in Sections 2 and 3, there are many factors that can impact the decision making process for open pit mining companies to switch from diesel to natural gas for mine haul trucks.

As reviewed in Sections 4.2 and 4.3, differences in basic fuel prices and any related carbon taxes for delivered diesel and natural gas (LNG) fuels, and the need for adequate year-round road access, are two important factors. Issues with converting an established open pit operation may also be relevant (e.g., disruption of operations, new upfront costs, training for staff, etc.) compared with planning for LNG use from the outset at a new mine development. Fluctuations in diesel fuel prices may also create concern as to the sustainability of expected fuel cost savings, e.g., the recent drop in oil prices resulted in operators seeing a material reduction in potential fuel cost savings from use of natural gas.

Two other key factors are highlighted below:

- **Reliable mine haul unit performance:** Uncertainty as to potential adverse impacts to overall mine operation if change from “reliable” diesel to a new "natural gas" option can deter or delay use of natural gas, notwithstanding clear opportunities for material fuel cost savings. Mine haul

[101] The impact of GHG reductions are estimated using estimated at 78.12 kg/GJ [CO2e] [equal to 3.02155 kg per litre]. GHG emissions are estimated at 72.5% of diesel emissions or 56.66 kg/GJ [CO2e] (based on estimate of 117 lb/MMBtu for natural gas versus 161.3 lb/MMBtu for diesel fuel for CO2, as per US Energy Information Administration), https://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11 [accessed on February 15, 2017].

trucks operate in extreme and demanding environments, and are critical to effective and efficient operation of the overall mine facility. Displacing diesel fuel with natural gas only becomes an option when mine operators are confident that the new fuel will not compromise reliable and efficient mine haul truck performance. Strong OEM commitment, with demonstrated reliable performance, is a key prerequisite for Scenario 2 development, and may also be needed even for widespread adoption of Scenario 1 development.

- **LNG supply chain development:** Inadequate LNG supply chain development can also inhibit interest in using natural gas for mine haul trucks. Diesel fuel supply chains are long established and well developed. In contrast, LNG supply chains are only very recently being established in Canada and are still developing. The lack of new small-scale liquefaction infrastructure in Canada focused on domestic markets, and providing confidence of adequate expanding LNG supplies with secure pricing arrangements, has been one of the major challenges to domestic customers switching to LNG. Coordinated planning of various parties may be needed to address this in specific situations, unless utilities are able to develop LNG supply facilities in advance of the domestic market being established. LNG transportation costs are an added consideration that is highly dependent on both distance and assumed haul options, and concerted attention at securing least cost and reliable LNG transportation is critical for mine operation located at long distances from LNG supply facilities. The cumulative impacts of these various LNG supply chain development factors can have very material impacts on mine operator interest, as well as on potential net cost savings offered by use of LNG to displace diesel. Regional variations in supply chain development and costs may also affect the timing and extent to which either Scenario 1 or 2 development can proceed in specific regions of Canada.

Overall, the above factors to date have inhibited and/or delayed development of LNG use to displace diesel use in mine haul trucks in Canada.

This report has highlighted that about 50% of existing diesel fuel use in Canada for mine haul trucks is concentrated in the Alberta oil sands sector - a sector with adequate year round road access, an expected economic life stretching forward into the future, and with proximity to natural gas and potential purpose built LNG supply facilities. The extent to which either Scenario 1 or Scenario 2 actually develops in Canada between now and 2030, and the timing for such development during this period, is likely to depend on what occurs in the oil sands sector, i.e., rapid deployment of LNG use in this major sector would provide a solid basis for active interest in other open pit mine operations throughout Canada.

5.0 SUMMARY CONCLUSIONS AND RECOMMENDATIONS

Section 5 provides a summary of conclusions from the Study and recommendations on future work to address identified issues and to enhance opportunities for natural gas displacement of diesel fuel in mine haul truck fleets.

5.1 SUMMARY CONCLUSIONS

The basic opportunity for benefits from displacing diesel fuel with natural gas in the mine haul truck market is lower fuel costs and reduction in pollutants (GHG, NOx, SOx, PM). The basic challenge is gaining access to reliable and proven technology for natural gas use in mine haul trucks, as well as establishing the entire required related infrastructure to secure and use natural gas at open pit mine sites.

Mine Haul Truck Market in Canada

Large off-road mine haul trucks operated with diesel fuel are used throughout different provinces and territories of Canada in a diverse range of open pit operations for oil sands (synthetic crude extraction), coal mining, and a diverse range of other mines (e.g., copper, iron, gold, and other minerals).

In 2016, the 1,991 mine haul trucks of 90 tonnes or more payload in Canada were heavily concentrated in Alberta and British Columbia in oil sands and coal mining:

- Over 90% of all units were located in five provinces: Alberta (60%), British Columbia (20%), Quebec (5%), Ontario (4%) and Newfoundland and Labrador (3%).
- Oil sands mining accounted for 40% of the units, coal for 20%, copper for 8%, gold for 6%, and iron mining for 6% (the balance of 19% is other sectors or unknown).
- Almost 60% of units were relatively large: 35% at 290 to 363 tonnes payload, 24% at 218-255 tonnes payload with the balance (41%) in smaller range from 90 to 190 tonnes payload.
- The 695 units of 290 or more tonnes payload were concentrated (94%) in the following five provinces and sectors:
    - Alberta oil sands mines (472 units, 68% of Canadian total).
    - British Columbia coal mines (120 units, 17% of Canadian total).
    - Ontario gold mines (27 units).
    - Newfoundland & Labrador iron mines (23 units).
    - Quebec iron mines (13 units).

Annual Canadian mine haul truck diesel fuel requirements are dominated by the larger units (e.g., over 200 tonne payload, and especially 290 mt or more payload) which tend to operate year-round with two 12 hour shifts per day. Canadian diesel fuel requirements are estimated for 2016 at between 1,650 and 1,800 million litres per year, with oil sands accounting for about 750 to 900 million litres per year, i.e., about 45% to 50% of the Canadian total. About 52% of the Canadian total was for units 290 tonnes or more payload and a further 27% estimated for units of 218-255 tonnes payload. No material use of natural gas currently exists in the mine haul truck market in Canada.

No attempt was made in the Study to forecast future mine haul truck volumes or diesel fuel use.

Market Opportunity for Natural Gas Use

Mine haul truck fuel costs per GJ for each open pit operation will ultimately be set by the cost of delivered fuel products required for these trucks. Mine haul truck use of natural gas is likely to require that it be in the form of liquefied natural gas (LNG) in order to enable adequate mine haul truck fuel storage over at least a full 12-hour shift, and that the LNG supply can be provided to the mine site by adequate year-round road access.

The broad opportunity today for natural gas and LNG to displace diesel fuel in Canada is supported by projected low commodity prices for natural gas relative to crude oil in the coming decades. NEB forecasts are reviewed in Section 2.4 that show crude oil price per GJ at 3.3 times the natural gas commodity price per GJ in 2015, with this gap growing by 2040 to crude oil price being 4.0 times higher than the natural gas price. This relative cost advantage for natural gas will be enhanced if a carbon tax for GHG emissions is introduced.

Savings per GJ for natural gas displacement of diesel fuel for mine haul truck use are determined by the delivered costs for diesel and LNG, and can vary widely by location and time period.

In addition to the commodity costs, delivered costs include refining costs and market pricing for diesel fuel, liquefaction processing costs for LNG, and transportation costs to each mine site. Delivered fuel costs by highway to northern locations can see commodity costs accounting for only 50% or less of final diesel fuel prices and less than 20% of delivered LNG prices in at least some western Canada locations. At the current stage of LNG supply chain development, costs for mine haul truck LNG use may vary considerably depending on site location and the level of LNG supply chain development in that region today.

Current and projected LNG supply facility development highlights the extent to which this has been improving dramatically throughout most regions in recent years.

Natural Gas Fuel Mine Haul Truck Technologies

A range of existing and emerging technologies for natural gas use in mine haul trucks exists today.

Existing opportunities are limited mainly to LNG-diesel dual fuel EVO-MT System conversion provided by GFS Corp., an after-market supplier, for a range of Komatsu and Caterpillar models where 50% diesel displacement tends to reflect a reasonable average estimate. Payback of the dual fuel system conversion cost of up to $300,000 per unit is affected by current diesel prices and in 2014 the payback in some US markets was estimated at 2 years, where current payback is approximately 4 years due to lower cost of diesel. The GFS conversion technology has been used in recent mine haul truck pilot studies in Wyoming and at Teck's Fording River Operation in British Columbia (the only known natural gas use pilot to date in Canada for mine haul trucks). Results from these pilots remain confidential and proprietary, beyond public comments about not meeting expected emission reductions. To date, no operation in Canada or Wyoming is known to have implemented ongoing commercial operations with this technology.

The trolley assist mine truck electrical option is another existing technology suited for mine haul trucks at some open pit sites. At remote site operations where power is generated on site using LNG, this would enable natural gas to displace diesel fuel for mine haul truck use without requiring new vehicle conversions beyond what is needed for commercial trolley assist operation.

Emerging opportunities include a broader range of potential technologies for both dual fuel conversions and options that would rely on natural gas for normal engine operation (including potential for 100% diesel displacement in spark ignition gas engines). Due to confidentiality, limited information is known on the commercialization and state of readiness of these options, which include the following:

- Caterpillar is working on a LNG-diesel dual fuel conversion systems (Dynamic Gas Blending with reported diesel displacements of up to 60%-70%) and a High Pressure Direct Injection System (HPDI) to displace 90 to 95% diesel use.
- Westport Inc. has been the leader in HPDI, working with Caterpillar and Cummins – a pilot is expected to become operational in 2017 or 2018.
- A High Density Compressed Natural Gas (HDCNG) option has been developed in Australia for mine haul trucks through Mine Energy Solutions (MES), Sime Darby, and IntelliGas, with reported diesel displacement of more than 80%.
- Rolls Royce Power Engines has been experimenting with the use of Spark Ignition (SI) in large off-road vehicles, notably mine haul trucks and marine, with MTU (Rolls Royce subsidiary) leading development. MTU states that SI obtains 100% natural gas displacement of diesel over dual fuel technology. However, due to confidentiality not much is known on MTU's progress of SI and LNG.

Potential reductions in air emissions from use of LNG to displace diesel fuel has been examined at a broad level, as various technologies, OEMs, and pilot studies have kept emissions testing results confidential. Various estimated potential reductions in air emissions from use of LNG to displace diesel fuel indicate potential reductions for GHG (20% to 35%), NOx (31% to 40%, potentially up to 97%), SOx (74% to 100%), particulate matter (50% to 89%), as well some other emission reductions.

Potential Maximum Use Natural Gas Scenarios

In order to provide a useful and representative range for potential maximum future natural gas use in mine haul trucks in Canada, two scenarios were examined for natural gas and LNG technology use to displace diesel fuel based on an assumed national market with approximately 1,800 million litres per year of diesel fuel requirements (with 95% assumed at sites accessible by adequate year-round road access):

- Scenario 1: 50% Natural Gas Use (reflects current conversion options).
- Scenario 2: 95% Natural Gas Use (reflects potential future high pressure direct injection option).

The scenario analysis estimated annual fuel cost savings from natural gas use in mine haul trucks assuming savings in delivered price per GJ at the mine site (natural gas saving versus diesel fuel) ranging from $4/GJ to $16/GJ (2016$), and with delivered diesel fuel prices ranging from $0.75 to $1.15 per litre (excluding taxes as applicable for off-road mine haul truck use).

The scenario analysis indicated that one mine haul truck with Base Case diesel fuel use of 1 million litres per year will secure the following annual fuel cost savings (2016$) over the range of delivered fuel price savings examined for natural gas versus diesel fuel:

- Scenario 1 with 50% natural gas use: annual savings range from $77,000 to $309,000, depending on the assumed fuel cost saving per GJ (equals 7% to 41% saving in fuel costs, depending on the assumed delivered diesel fuel price).
- Scenario 2 with 95% natural gas use: annual savings range from $147,000 to $588,000, depending on the assumed fuel cost saving per GJ (equals 13% to 78% saving in fuel costs, depending on the assumed delivered diesel fuel price).

Under Scenario 1 implemented for all units in all mine operations with year-round road access, it is estimated that the mine sector in Canada could save between $134 and $537 million per year (2016$) from switching to LNG use for mine haul trucks, including between $66 to $266 million per year in the Oil Sands sector in Alberta:

- About 79% of total savings (all mine sectors) are from 218+ tonne payload trucks.
- About 50% of total savings (all mine sectors) are estimated to be in Oil Sands.
- About 56% of total Oil Sand potential savings are from 308+ tonne payload trucks, and about 88% are from 218+ tonne payload trucks.

Under Scenario 2 implemented in all units in all mine operations with year-round road access, it is estimated that the mine sector in Canada could save between $255 and $1,201 million per year (2016$) from switching to LNG use for mine haul trucks, including between $126 to $506 million per year in the Oil Sands sector in Alberta:

- About 79% of total savings (all mine sectors) are from 218+ tonne payload trucks.
- About 50% of total savings (all mine sectors) are estimated to be in Oil Sands.
- About 56% of total Oil Sand potential savings are from 308+ tonne payload trucks, and about 88% are from 218+ tonne payload trucks.

Under Scenario 1, it is estimated that the mine sector could reduce its annual GHG emissions by approximately 721,000 tonnes [CO_2e] per year (by about 13%) from switching to LNG use for mine haul trucks, including by about 357,000 tonnes per year in the Oil Sands sector in Alberta. Under Scenario 2, annual GHG emissions would be reduced by approximately 1,369,000 tonnes [CO_2e] per year (by about 25%) from switching to LNG use for mine haul trucks, including by about 678,000 tonnes per year in the Oil Sands sector in Alberta.

Factors Affecting Actual Natural Gas Use and Timing

There are many factors that can impact the decision making process for open pit mining companies to switch from diesel to natural gas for mine haul trucks.

Differences in basic fuel prices and any related carbon taxes for delivered diesel and natural gas (LNG) fuels, and the need for adequate year-round road access, are two important factors. Issues with converting an established open pit operation may also be relevant (e.g., disruption of operations, new upfront costs, training for staff, etc.) compared with planning for LNG use from the outset at a new mine development. Fluctuations in diesel fuel prices may also create concern as to the sustainability of expected fuel cost savings, e.g., the recent drop in oil prices resulted in operators seeing a material reduction in potential fuel cost savings from use of natural gas.

Two other key factors are highlighted below:

- **Reliable mine haul unit performance:** Uncertainty as to potential adverse impacts to overall mine operation if change from “reliable” diesel to a new "natural gas" option can deter or delay use of natural gas, notwithstanding clear opportunities for material fuel cost savings. Mine haul trucks operate in extreme and demanding environments, and are critical to effective and efficient operation of the overall mine facility. Displacing diesel fuel with natural gas only becomes an option when mine operators are confident that the new fuel will not compromise reliable and efficient mine haul truck performance. Strong OEM commitment, with demonstrated reliable performance, is a key prerequisite for Scenario 2 development, and may also be needed even for widespread adoption of Scenario 1 development.
- **LNG supply chain development:** Inadequate LNG supply chain development can also inhibit interest in using natural gas for mine haul trucks. Diesel fuel supply chains are long established and well developed. In contrast, LNG supply chains are only very recently being established in Canada and are still developing. The lack of new small-scale liquefaction infrastructure in Canada focused on domestic markets, and providing confidence of adequate expanding LNG supplies with secure pricing arrangements, has been one of the major challenges to domestic customers switching to LNG. Coordinated planning of various parties may be needed to address this in specific situations, unless utilities are able to develop LNG supply facilities in advance of the domestic market being established. LNG transportation costs are an added consideration that is highly dependent on both distance and assumed haul options, and concerted attention at securing least cost and reliable LNG transportation is critical for mine operation located at long distances from LNG supply facilities. The cumulative impacts of these various LNG supply chain development factors can have very material impacts on mine operator interest, as well as on potential net cost savings offered by use of LNG to displace diesel. Regional variations in supply chain development and costs may also affect the timing and extent to which either Scenario 1 or 2 development can proceed in specific regions of Canada.

Overall, the above factors to date have inhibited and/or delayed development of LNG use to displace diesel use in mine haul trucks in Canada.

This report has highlighted that about 50% of existing diesel fuel use in Canada for mine haul trucks is concentrated in the Alberta oil sands sector - a sector with adequate year-round road access, an expected economic life stretching forward into the future, and with proximity to natural gas and potential purpose built LNG supply facilities. The extent to which either Scenario 1 or Scenario 2 actually develops in Canada between now and 2030, and the timing for such development during this period, is likely to depend on what occurs in the oil sands sector, i.e., rapid deployment of LNG use in this major sector would provide a solid basis for active interest in other open pit mine operations throughout Canada.

5.2 RECOMMENDATIONS FOR FUTURE WORK

Recommendations for future research are provided based on issues, opportunities, and comments from those surveyed during research of the assessment of potential market features and the survey of natural gas fuel mine haul truck technologies. A total of seven recommendations for future research have been revealed based on the research and study above and recommendations provided by Paul Blomerus.[102]

George Augilera of GFS Corp. discussed how emissions testing is still limited and not entirely reliable as current instrumentation does not install well on current mine haul trucks and emissions testing is often completed with the truck standing still.[103] This presents an opportunity to re-engineer the emissions testing process to create a reliable system with accurate results. Overall, two recommendations for future research are provided with regard to emissions monitoring and assessment:

1. Mobile methane emissions monitoring – Current emissions measurement systems for large haul trucks are not mobile making it impossible to determine which modes of engine[104] and vehicle operation are leading to the largest methane emissions, thereby enabling their reduction and elimination through engine tuning. Through a more accurate testing system this would be possible. Improved measurement equipment and test protocols are needed.
2. Lifecycle GHG emissions - Once an accurate emission testing system is in place, a study on lifecycle greenhouse gas emissions study is needed of natural gas fueled mine haul trucks under various scenarios to understand the benefits of natural gas. The progress of engine technology and fuel supply chain options (e.g., where liquefaction takes place) would be factored into this study.

As observed from the Teck FRO pilot study and the distances travelled from the FortisBC Tillbury facility to the Teck mine site (and lack of an LNG storage facility) to fill the converted mine haul trucks with LNG, mobile refueling and storage facilities need to be studied.

3. Mobile refueling technologies and standards - Many studies have taken place on establishing international standards for refueling on-road trucks at stationary dispensers; however, similar research has not gone into mobile refueling systems and particularly with off-road vehicles. Refueling technologies, standards, and safety protocols need to be studied and analyzed. Rough road conditions, rapid refuel transfer, gas boil off minimization, and fugitive emissions minimization are just a few of the areas that need protocols and safety standards established as

[102] Personal communication with Paul Blomerus, CERC, UBC, February 14, 2017, who identified the six areas of priority research.

[103] Personal Communication with George Aguilera, Executive Vice President, GFS Corp. February 7, 2017.

[104] NRCan comments on the draft report for this study noted that several organizations have performed in-use emission verification on mine haul trucks, and that it is possible to verify vehicle emissions in the field, However, this recommendation emerged from discussions and comments provided by others during this study - it has been retained to ensure that the matter receives ongoing attention.

this technology grows. The lack of codes and standards may also result in different requirements in different jurisdictions with the result that potential equipment design applied in one province may not be accepted in another province.

4. High performance LNG fuel storage and delivery systems - A study associated to LNG storage facility needs to occur as engine performance and substitution increases put further demands on the fuel delivery system (with increases in pressure and flow rates). This research is paramount to keep up with the demands of the next generation of high-performance engines while eliminating methane venting.

Caterpillar, as discussed in their 2012 Edmonton CIM conference,[105] and MES of Australia have both expressed the need to reduce noise and vibration as a benefit to their technologies. This is a particularly important feature with a need to study how vibration affects on-truck LNG tank storage.

5. Durability of vacuum insulated LNG tanks in high vibration environments - A study into the durability of insulated LNG tanks in high vibration environments needs to occur and the safety challenges along with it. Currently, LNG tanks developed for heavy duty trucks and other applications have not been proven for vibration and further research is needed into the consequences of failure and long term durability of tanks of various sizes and orientations under severe environmental loading.

A lack of pilot studies throughout Canada has lead to a lack of information in terms of emissions testing, performance, state of readiness, and market penetration. However, results from pilots to date of third party conversions do not appear to have encouraged commercial adoption. Additional research and pilot testing is needed as soon as possible on emerging technologies that will enable OEM supported high substitution of natural gas for diesel with high performance and clear environmental benefits. In order to further understand dual fuel technologies and other existing and emerging technologies further pilot studies need to be observed.

6. Pilots for emerging high performance, high substitution engine technologies - Further research and study in pilot projects is particularly important as technology is changing fast (i.e. Westport is onto a second generation of HPDI systems called HPDI 2.0). Further pilot studies would allow observation and data into the changing technologies as diesel substitution percentages increase, methane exhaust changes, fuel consumption changes, and emissions testing methods improve (including mobile emission monitoring). This gives better insight into payback periods, performance standards, and environmental benefits. Additional funding and studies will help to incentivize OEMs responsible to accelerate the technology development and orientate its deployment towards Canada.

As diesel substitution by natural gas progresses there would be a need to address the safety aspects of natural gas handling and use, including both on board the hauling trucks and at the mine site.[106]

[105] Caterpillar, LNG Mining Truck – Launch Review, May CIM Conference Edmonton, May 2012.

[106] This recommendation arises from NRCan comments on the draft report.

7. Further research and studies required for atmospheric modeling of open pit mine air stratification to identify inversions that might lead to gas accumulation. The review could also include operation of vehicles in or in proximity to tunnels, tunnel entrances, and ventilation fan intakes; analysis of on-board vehicle gas detection and shut off systems as well as ambient methane sensors installed in areas modeled to be at high risk for accumulation; review of rock debris impact and crash durability of LNG storage tanks; both on-board and bulk facilities.

In addition to the seven specific research items, it is also recommended that strategic attention be directed at two additional items: LNG supply chain development and a focused and coordinated effort for LNG displacement of diesel fuel use in the oil sands sector of Alberta.

On LNG supply chain development, the Casino Mine case study highlights the extent to which mine haul truck use of LNG can constitute a small share of LNG use (less than 10%) at a mine site with LNG power generation. Absent the large power generation LNG load to support LNG supply chain development, it is unlikely that the Casino project would have considered LNG use in mine haul trucks. The Casino project interest in LNG, however, has stimulated actual LNG supply chain development in the northern BC and Yukon region such that at least one new mine in this area is now implementing LNG power generation at its site.

On a focused and coordinated effort for LNG displacement of diesel fuel use in the oil sands sector of Alberta, Canada has a unique opportunity here to develop a large scale and accelerated game plan to implement advanced leading technology for high level natural gas use in mine haul trucks. As noted earlier, the timing and extent that natural gas use in mine haul trucks actually develops in Canada between now and 2030 is likely to depend on what occurs in the oil sands sector, i.e., rapid deployment of LNG use in this major sector would provide a solid basis for active interest in other open pit mine operations throughout Canada, and would also enable Canada to be a leader internationally in this sector.

ATTACHMENT A:

Reference List

REFERENCES

Aguilera, G. Executive Vice President, GFS Corp. Personal communication, February 7, 2017.

Blomerus, Paul, Clean Energy Research Center, U.B.C. Personal communication, February 14, 2017.

Brown, C., VP Engineering, Casino Mining Corp. (November 19, 2016). "LNG Fuels Casino Mining & Processing Operations", presentation to Yukon Geoscience Forum. Supplemented with information from Casino Mining Corp. web site: http://casinomining.com/project/.

Canada's Submission to the United Nations Framework Convention on Climate Change. National Inventory Report 1990-2014: Greenhouse Gas Sources and Sinks in Canada, Part 3, Annex 10, Table A10-2.

Carter, R.A. (February 5, 2016). Waiting for Ignition, Engineering and Mining Journal. Retrieved from http://www.e-mj.com/features/5942-waiting-for-ignition.html#.WJ3bbGczWUk.

Castleman, J. (2015). Strategy manager for Caterpillar's large mining truck business. HH Summit in Dallas, Texas.

Caterpillar. (May 2012). CIM Conference Edmonton. LNG Mining Truck – Launch Review.

CNG United. (2017). How Does CNG Work. Retrieved from https://www.cngunited.com/how-does-cng-conversion-work/.

Delgado, O. & Muncrief, R. (July 2015). Assessment of Heavy Duty Natural Gas Vehicle Emissions; Implications and Policy Recommendations.

ESDOE. (May 2016). Alternative Fuels Data Center, "Natural Gas Vehicle Emissions".

FortisBC. (May 23, 2014). LNG Use in Mines presentation. Retrieved from http://mineralsnorth.ca/images/uploads/pdf/Fortis.pdf [accessed February 13, 2017].

FortisBC. (2017). Liquefied Natural Gas. Retrieved from https://www.fortisbc.com/NaturalGas/Business/Pages/Liquefied-Natural-Gas.aspx.

GFS Corp. (August 21, 2011) GFS Corp Plans to Install LNG Conversions Alpha Coal West Mine Trucks. Retrieved from http://www.gfs-corp.com/news.php/yr/2011/art/1/yr/2011.

GFS Corp. (January 7, 2016). Manufacturer of Natural Gas Conversions for High Horsepower Diesel Engines Names Two New Distributors in Canada for its EVO-MT System. Retrieved from https://globenewswire.com/news-release/2016/01/07/800092/10158967/en/GFS-Corp-Manufacturer-of-Natural-Gas-Conversions-for-High-Horsepower-Diesel-Engines-Names-Two-New-Distributors-in-Canada-for-its-EVO-MT-Systems.html?culture=en-us.

GFS Corp. (March 12, 2015). New Order for the Supply of LNG Haul Truck Conversion Systems to Arch Coal's Black Thunder Mine. Retrieved from http://www.gfs-corp.com/news.php/yr/2015/art/23/yr/2015.

GFS Corp. (September 20, 2014). Plum Energy to Build LNG Plant at Alpha Coal's Eagle Butte Mine. Retrieved from http://www.gfs-corp.com/news.php/yr/2014/art/19/yr/2014.

Hatch Ltd. (May 2016). LNG for Mining Operations.

Hoffman, J. (December 15, 2016). B-104 News Centre blog, based on release and comments by Nic Milligan of Teck.

Hongsheng, G. National Research Council. Personal communication, January 31, 2017.

ICF International report to Canadian Gas Association. (May 2016). Economic and GHG Emissions Benefits of LNG for Remote Markets in Canada, page 6. Further reference to Standing Senate Committee on Energy, the Environment and Natural Resources, Power Canada's Territories (2014).

Igoe, S. Commercial Manager, Caterpillar. Personal communication, February 7, 2017.

Igoe, S., Commercial Manager, LPSD Gas Engine Business. (October 13, 2016). Cat Dual Fuel DGB Mining Truck Update, Delivering Customer Value, presentation at HH Summit in Chicago.

Independent Mining Consultants, Inc. (December 2, 2012). Casino Copper-Gold Project Yukon Territory, Canada - Feasibility Study Mining (assuming diesel fuel).

Independent Mining Consultants, Inc. (January 14, 2013). Casino Copper-Gold Project Yukon Territory, Canada - Feasibility Study Mining - LNG Truck Haulage.

Kecojevic, V. & Komijenovic, D. (December 2010). Haul Truck Fuel Consumption and CO_2 Emission Under Various Engine Load Conditions, Mining Engineering.

Lopez-Pacheco, A. (March-April 2016 Edition). Canadian Mining Institute. "Conversion Story". Retrieved from https://magazine.cim.org/en/2016/March/technology/Conversion-story.aspx.

McIvor, J. (May 23, 2014). FortisBC: LNG Use in Mines (stated source: GH Genius Model).

Mumford, D. Senior Director - HPDI Product Portfolio, Westport. Personal communication, January 30, 2017.

National Energy Board of Canada. (January 2016). Canada's Energy Future 2016: Energy Supply and Demand Projections to 2040 – An Energy Market Assessment; Chapter 3. Retrieved from https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/index-eng.html [accessed February 8, 2017].

Natural Resources Canada. (2005). Benchmarking the Energy Consumption of Canadian Open-Pit Mines.

Nikiforuk, C.F. CRNG Energy Inc. & Miller, R.E., Sonoma Resources Ltd. (November 17, 2016). Reducing Energy Costs for Remote Mines and Communities Through Improved Liquefaction Technology for LNG. Paper presented at Yellowknife Geoscience Forum (modified November 29, 2016).

Perron, Y., VP, Stornoway (November 23, 2016). Presentation: Build Quebec's First Diamond Mine.

Pierce, H. Alpha Natural Resources. Personal communication, February 2, 2017.

Plum Energy. (April 11, 2014). LNG Economics 201: Effects of Distance on Price. Retrieved from http://www.plumenergy.com/lng-economics-201-effects-distance-price/.

Rail Association of Canada. (2015). Locomotive Emissions Monitoring Program 2013. Retrieved from www.railcan.ca.

Teck. (June 22, 2016). Behind the Pilot. Retrieved from http://www.teck.com/news/stories/2016/behind-the-pilot--lng-truck-conversion-at-fording-river-operations.

U.S. Energy Information Administration. (January 5, 2017). Annual Energy Outlook 2017. Retrieved from http://www.eia.gov/outlooks/aeo/index.cfm.

Westport. (June 20, 2013). CNG and LNG: What's Best for Your Fleet. Retrieved from http://www.westport.com/file_library/files/webinar/2013-06-19_CNGandLNG.pdf.

Westport. (2017). Cummins Westport and Weichai Westport. Retrieved from http://www.westport.com/is/partners/joint-ventures.

Westport. (2017). Westport HPDI 2.0. Retrieved from http://www.westport.com/is/core-technologies/hpdi-2.

Winchester, B. Executive Director, Canadian Natural Gas Vehicle Alliance. Personal communication, January 27, 2017.

Zuliani, C., Salehi, E., Almquist, G. & Save, S. (October 2015). Hatch Ltd. "Leveraging LNG, The case for replacing diesel with natural gas for oilsands mining fleets", Oilsands Review.

Zuliani, C., Salehi, E., Almquist, G. & Save, S. (January 2016). Hatch Ltd. "Fueling Alberta Oil Sands Fleets with Natural Gas". Hydrocarbon Processing.

ATTACHMENT B:

Contacts

Parties Contacted Who Provided Information	
Company	**Contact**
Alpha Natural Resources	Holly Pierce, 1-307-687-3300
Canadian Natural Gas Vehicle Alliance (CNGVA)	Bruce Winchester, Executive Director, 1-613-564-0181, bruce.winchester@cngva.org
Caterpillar Engines	Steven Igoe, Commercial Manager, 1-309-578-8321, igoe_steven_a@cat.com
Clean Energy Research Committee at UBC	Paul Blomerus, 1-604-813-1830, paul.blomerus@cerc.ubc.ca
FortisBC	Sarah Smith, Director, NGT and Regional LNG, 1-604-323-6682, sarah.smith2@fortisbc.com
Gaz Metro	Patrick Bolduc, Senior Advisor, Development of Affairs, 1-514-598-3423, pbolduc@gazmetro.com
Gaz Metro	Sylvain Langis, Sales Director, 1-514-598-3169, slangis@gazmetro.com
GFS Corporation	George Aguilera, Executive Vice President, 1-954-693-9421, gaguilera@gfs-corp.com
Hatch	Chris Zuliani, Process Engineer/ Oil and Gas, 1-403-920-4026, chris.zuliani@hatch.ca
National Research Council	Hongsheng Guo, Senior Research Officer, 1-613-991-0869, hongsheng.guo@nrc-cnrc.gc.ca
Westport	David Mumford, Senior Director, HPDI Product Portfolio, 1-604-718-2053, david.mumford@wfsinc.com

Other Parties Contacted Who Not Able to Provide Information*	
Company	**Contact**
Finning Cat	James Black, Product Manager, LMT, Mining Market, 1-780-509-2567, james.black@finning.com
Gaz Metro	David Vincent, Director of Business Development and Renewable Energy, 1-514-598-3671,
GFS Corporation	Kerry Hackney, Chief Marketing and Communications Officer, 1-954-693-9657
Gladstein Neandros and Associates	Erik Neandros, CEO, 1-310-573-8553, erik@gladstein.org
Hatch**	Dan McEvoy, dmcevoy@hatch.ca; Ivan Mullany, ivan.mullany@hatch.ca;Martin Meintjes, martin.meintjes@hatch.ca; Jim Kwak, jkwak@hatch.ca; John Pearson, jpearson@hatch.ca; Robert Franki, rfrancki@hatch.ca
IntelliGas (Australia)	Jim McDonald, Chairman, jim@igasenergy.com [No Response]
IntelliGas (Australia)	Paul Whiteman,Managing Director, paul@igasenergy.com
Mine Energy Solutions (Australia)	Sebastian Banks, CEO, sebastian.banls@mesol.com.au. [No Response]
Mining Association of Canada	Danielle Poitras, receptionist, dpoitras@mining.ca
Shell Oil Sands Mining Initiative	Shawn Murphy, Shell International Exploration and Production, shawn.murphy@shell.com [No Response]
Teck Resources Limited	Jeff Sutherland, Energy Lead, Jeff.Sutherland@teck.com
Teck Resources Limited	Larry Davey, Vice President, Planning and Development, Coal, 1-250-425-8200, Larry.Davey@teck.com
Teck Resources Limited	Stephanie Cole, Project Lead FRO, 1-604-699-4000
Westport	Renae Roth, admin assistant, rroth@westport.com

*In many cases, contact was by e-mail and no response was received (see "No Response"). In several other cases, the party needed to talk with others before responding and/or could not provide information due to confidentiality.

** Chris Zuliani from Hatch provided information. Others are noted here with whom some exchange occurred. Several others from Hatch were contacted and had no response, e.g., Jim Sarvinis; Michael Carrea; Nils Voermann; Sanjiv Save.