LNG for Yukon Energy Power Generation

A Life Cycle Emissions Inventory

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Prepared for

Yukon Energy Corporation

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Table of Contents

List of Figures

List of Tables

About the Pembina Institute and Pembina Corporate Consulting

The Pembina Institute is a national non-profit think tank that advances clean energy solutions through research, education, consulting and advocacy. It promotes environmental, social and economic sustainability in the public interest by developing practical solutions for communities, individuals, governments and businesses. The Pembina Institute provides policy research leadership and education on climate change, energy issues, green economics, energy efficiency and conservation, renewable energy, and environmental governance. For more information about the Pembina Institute, visit www.pembina.org.

Within the Institute, Pembina Corporate Consulting is one of Canada's most-respected and innovative providers of solutions for policy-makers and corporate decision-makers seeking to enhance sustainability and competitiveness, and to support the shift to more sustainable production and consumption. Our consulting teams bring together core competencies in life cycle thinking, rigorous research, multi-stakeholder dialogue and innovative communications, in service of our mission of advancing more-sustainable energy solutions.

The Pembina Institute and its consulting group have had a long history of working with the both the fossil fuel and electricity sectors in Canada, including collaboratively reducing harmful impacts of oil and gas development, advancing renewable energy policy, supporting CCS, and evaluating emerging unconventional fossil fuel and alternative energy technologies using a life cycle approach. The Pembina Institute has been a pioneer in helping multi-stakeholder groups understand the opportunities and challenges of emerging energy developments.

1 Introduction

In an effort to better understand the life cycle environmental impacts of using liquefied natural gas (LNG) for power generation, the Yukon Energy Corporation (YEC) is interested in a life cycle analysis of LNG sourced from Shell's Jumping Pound Gas Complex to generate back-up power instead of using diesel.

LNG for export is growing rapidly, with global demand potentially tripling by 2030. With 11 proposed LNG plants on Canada's west coast alone, much of this LNG demand is being driven by China's "off coal" strategy and Japan's search for nuclear alternatives. As well, LNG facilities using conventional gas are also being developed. One example is Shell's Jumping Pound project, which seeks to supply a "green transportation corridor" between Calgary and Edmonton. Associated with this, Yukon Energy has contracted for LNG supply from Shell for a five-year term in an effort to displace diesel, and seeks to communicate to its stakeholders the life cycle environmental benefits.

While it is generally accepted that switching from diesel to natural gas can contribute to the reduction of several key environmental and human health impacts, the added energy requirements of liquefying, storing and transporting, and re-gasifying for this type of application has not been quantified to date. Indeed, limited data exists given the nascent nature of the technology. The sour gas produced at Jumping Pound also requires additional processing in order to remove hydrogen sulfide prior to liquefaction — creating additional life cycle implications. Completing an LCA on the specific scenario of the Yukon Energy project is the only credible way to assess and externally communicate the potential benefits from converting to from diesel to LNG. The work presented in this report is a first step toward such a life cycle analysis.

1.1 Overview of report structure and LCA approach

This analysis is consistent with ISO 14040:2006 Life Cycle Assessment (LCA) Principles and Framework. This introduction includes an overview of the objectives, audiences considered and the options assessed. Section 2 (Scoping) provides an overview of the issues identified along with a description of the general life cycle activities considered. Results are presented in Section 3, which focus on the quantitative differences in key environmental parameters across options.

High-level context for these issues is commented on where appropriate; however, this analysis did not include an impact assessment whereby the quantitative results were placed into specific regional or local context. As such, this analysis is more focused on developing a Life Cycle Inventory in order to discern quantitative differences between options, as opposed to a more comprehensive LCA with environmental context. Areas for further investigation are highlighted in Section 3.3.

1.2 Study objective

The goal of this analysis is to provide an independent assessment of the range of environmental releases, key variables, assumptions and sources of uncertainty around the net life cycle environmental changes of switching back-up diesel generation to LNG sourced from Shell's Jumping Pound Gas Complex.

This study quantifies the environmental releases of the proposed LNG project and compares to the alternative power generation scenario of new diesel engines. This is in recognition of YEC's plans to replace its entire diesel fleet in the next 15 years, and to increase its capacity. This analysis considers replacing 9 MW of the current 40 MW of diesel.

1.3 Study audience

This analysis was performed for YEC as the primary audience. However, YEC is interested in sharing the report more broadly with its stakeholders, including interested community and environmental groups, regulators, and First Nations. In the development of this analysis, the Yukon Conservation Society was included as an observer and commentator as a means of increasing its understanding of the analysis and providing an opportunity to raise concerns or issues as appropriate.

1.4 Study limitations

The Pembina Institute was engaged by YEC to solely investigate LNG compared to diesel fuel consumed in new engines as back-up power based on a recent short-term contract between YEC and Shell. The inclusion of other energy supply systems for back-up power was outside the scope of this analysis.

While the benefit of this analysis is that it uses actual data informed by specific alternatives YEC has considered, it is important to recognize that the results of this analysis cannot be considered representative of all LNG-related projects. This analysis considers sources of fuel and power generation technologies that are specific to YEC. LNG could be used for different applications such as heat or as a transportation fuel and could displace any number of other fuel types. As such, it is important to consider the results of this analysis only within the context of YEC's decision making process and not more broadly as it relates to LNG applications.

Lastly, the analysis only considers environmental implications and does not consider financial or social impacts. As well, no regional environmental context was considered to compare quantified results against.

2 Scope of analysis

2.1 System description

This study focuses on quantifying key environmental outputs from the two power generation systems, or “pathways”:

1) Power generation using LNG as input fuel
2) Power generation using diesel as input fuel

Figure 1 displays a simplified graphical description of the two competing pathways; detailed maps are included in Appendix A.

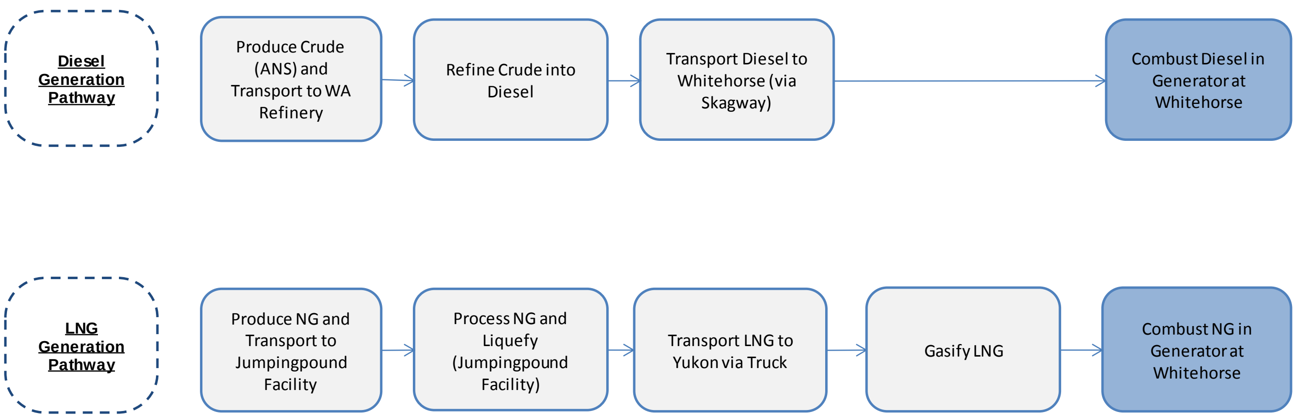

Figure 1. Simplified activity maps for pathway descriptions

The major life cycle stages displayed in Figure 1 are described further in Table 1 below.

Table 1. Description of diesel and LNG pathways by stage

Life Cycle Stage Activity	Diesel Pathway	LNG Pathway
Produce fuel	Crude is extracted from Alaska's North Slope and transported to Puget Sound refinery via ocean freighter	Natural gas is produced from conventional gas fields near Shell's Jumping Pound facility and delivered directly to the facility by pipeline
Process fuel	Crude oil is refined into diesel fuel and other refined petroleum products	LNG is treated to remove sulphur and other impurities and then liquefied
Transport fuel to Whitehorse	Diesel is transported from Puget Sound to Skagway, AK via ocean freighter and from Skagway to Whitehorse via truck transport	LNG is trucked from Jumping Pound to Whitehorse on diesel fueled A-Train with a payload capacity of 95.3 m^3
Combust fuel	Diesel is combusted for power in a CAT Continuous 3300 generator operating at 41.6% efficiency	LNG is vapourized and combusted for power in a GE Jenbacher generator operating at 46.3% efficiency

2.2 Functional unit

When comparing multiple systems it is important that each system must deliver the same level of service or product. This ensures the system comparison is fair and equitable. A functional unit is the base unit of comparison upon which the systems are compared.

The functional unit in this study is defined as 1 MWH of electricity generated at YEC's Whitehorse facility.

2.3 Issues exploration and identification

In order to identify those environmental parameters that would be quantified as part of this analysis, Pembina first completed the life cycle activity maps (above and in Appendix) and then considered the range of possible environmental impacts from any energy system (outside of nuclear). The range of potential impacts considered was drawn from a comprehensive list Pembina has developed over two decades of working on energy systems. In reviewing the discrete activities involved in the life cycle of both options against the range of potential impacts, the parameters for quantification were identified. The following table describes the parameters quantified.

Table 2. Environmental parameters quantified

Parameter	Unit	Description
Greenhouse Gases (GHGs)	kg or t CO_2e	Emissions resulting from human activities are substantially increasing the atmospheric concentrations of several significant greenhouse gases, especially carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These are increasing the greenhouse effect, resulting in an overall average warming of the earth's surface. Health Canada has identified seven significant health concerns associated with climate change including temperature-related morbidity and mortality, extreme weather events, and air pollution-related effects.[1] Current climate science calls for an aggregate reduction in industrialized countries' emissions to 25 to 40% below the 1990 level by 2020 and 85 to 90% below 1990 levels by 2050.[2] CO_2 emissions that originate from biogenic sources are not included in this analysis, as an equivalent amount of CO_2 will be re-sequestered in the growth of the plant material from which it came. Thus, only CO_2 emissions from fossil fuel sources are accounted for, including transportation fuels and the combustion of plastics. The current convention for timeframe associated with the global warming potential of non-CO_2 related GHGs is 100 years. However, the use of a 20-year timeframe is considered important given the current state of the climate. This shorter timeframe would greatly increase the global warming potential of non-CO_2 GHGs. Both are considered in this report, and a further discussion is provided in section 2.3.2.
Acid Deposition	kgNO_x kgSO_x	NO_x and SO_x contribute to acid deposition leading to impacts on soils, lakes, forests, crops and buildings. NO_x has approximately 70% the acidifying potential of SO_2. Acids also combine with non-methane VOCs to form ground-level ozone, which can cause adverse effects on humans, including lowered lung function and the development of chronic respiratory diseases. Ground-level ozone also has significant impact on reducing the productivity of agricultural crops and forests. Equivalency factors are used to relate emissions of various acids and acid-forming compounds. For the purposes of this report SO_x and NO_x have been quantified separately and combined represented in terms of Acid deposition potential.
Particulate Matter (PM)	kg PM	Particulate matter is comprised of tiny pieces of solid and liquid matter small enough to be suspended in the air. The finest of these particulates are primarily soot and exhaust combustion products that may irritate the respiratory tract and contribute to smog formation. Secondary sources of PM result from SO_2, NO_x and non-methane organic compound emissions that combine to form PM in the atmosphere. Of particular concern are PM_{10} and $PM_{2.5}$ — fine particulates smaller than 10 and 2.5 microns in size that can penetrate deep into the lungs. These particulates can have a serious effect on respiratory function and have been linked to cancer, especially

[1] Health Canada, "Understanding the Health Effects of Climate Change." http://www.hc-sc.gc.ca/ewh-semt/climat/impact/index-eng.php

[2] *The Case for Deep Reductions: Canada's Role in Preventing Dangerous Climate Change*, (David Suzuki Foundation and the Pembina Institute, 2005). http://www.pembina.org/pub/536

		those particulates from diesel exhaust which contain carcinogenic fuel combustion products.[3]
Carbon Monoxide	g CO	Carbon monoxide is a toxic gas. At low levels it causes fatigue and can cause chest pain for people with heart disease. At higher concentrations it can cause impaired vision and coordination along with headaches, dizziness, confusion and nausea. At very high concentrations CO exposure is fatal. Acute effects include angina, impaired vision and reduced brain function.[4]

These parameters are considered the key air emissions of concern and focus for the pathways included in the analysis.

2.3.1 Parameters not included in this analysis

Land impacts were not quantified nor qualitatively addressed for the following reasons:

- There are no new land related impacts on the diesel system. The diesel pathway is the current pathway for YEC.
- Land use for both pathways uses existing infrastructure.
- The two new facilities required for the LNG system — liquefaction and re-gasification — are on existing industrial sites and would not change the land use or land-related impacts on the site.

While spills, particularly from the diesel pathway, are of high importance, no attempt was made to quantify the probability of spills occurring from this system. However, the probability of spills is of course more than zero and certainly can be a factor in decision-making processes. Similarly, high-volume accidental gas releases can occur and impact safety and environmental health, but quantification of the probability of events and associated level of impact was outside the scope of this analysis.

Water impacts are not quantified for the two systems in question as there are no major water inputs or outputs across the life cycle of the diesel or gas systems. Where there may be some minor water use, these activities do not take place inside any water stressed regions. Areas of consideration are discussed in Section 3.3.

2.3.2 CH_4 global warming potential: 100-year versus 20-year time interval

Each greenhouse gas produces a different amount of radiative forcing, and has a variable lifespan in the atmosphere. Normally a conversion to carbon dioxide equivalent (CO_2e) is done to account for this. The conversion, known as Global Warming Potential (GWP), is imperfect. It is the integral over time of the radiative forcing where the other gases are

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[3] R.F. Webb Corporate Ltd., *The Environmental Effects of Transportation Fuels – Final Report,* (Natural Resources Canada, 1993).

[4] EPA, "An Introduction to Indoor Air Quality: Carbon Monoxide." http://www.epa.gov/iaq/co.html

weighted in relation to CO_2, which is assigned a GWP of 1. Since various GHGs have different lives in the atmosphere — decades for methane (CH_4) and centuries for CO_2 — the value of the GWP depends on the time scale selected.[5] Typically 20, 100, and 500 years have been used.

Methane's comparatively short lifespan in the atmosphere means that it has a much larger GWP in a 20-year time horizon than it does on a longer time scale. The table below shows a range of values for methane's GWP and their source.

Table 3. Global Warming Potentials for methane under different time scales

Source	20-year GWP	100-year GWP	500-year GWP
United Nations Framework Convention on Climate Change (2010)*	56	21	6.5
IPCC Fourth Assessment Report (2007)	72	25	7.6
IPCC Third Assessment Report (2001)	62	23	7

*The United Nations Framework Convention on Climate Change is based on the IPCC Second Assessment Report, published in 1997.

More recent GWPs for CH_4 are higher as newer modelling attempts to take into account the interaction between CH_4 and other aerosols in the atmosphere.[6] While this results in a higher GWP for CH_4, it also increases the uncertainty in the value[7] with error in the range of 23%.[8]

Using a shorter time scale when looking at CH_4 emissions will greatly impact the final results, as the GWP for CH_4 is nearly tripled on a 20-year vs a 100-year timeline. There is increasing discussion in the scientific community on which of these time period is most appropriate when considering fugitive emissions, with reasonable arguments being made on both sides. Most research, assessments, and publications currently use 100 years, which is generally what is used by the IPCC and regulators.[9]

Arguments for using 20 years generally center around a concern that we will reach a climate tipping point in the near term, or that reducing shorter-lived components (methane as well as carbon black and other aerosols) will buy additional time in dealing with the longer-term effects of CO_2.[10]

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[5] E J Moniz, H D Jacoby and A J M Meggs, "Life-Cycle Climate Impacts from Fossil Fuel Use," Appendix 1A in *The Future of Natural Gas* (MIT, 2011) http://mitei.mit.edu/publications/reports-studies/future-natural-gas

[6] D T Shindell, G Faluvegi, D M Koch, G A Schmidt, N Unger and S E Bauer, "Improved attribution of climate forcing to emissions," *Science* 326 (2009). Available at http://www.see.ed.ac.uk/~shs/Climate%20change/Data%20sources/Shindell%20methane.pdf

[7] Moniz et al., "Life-Cycle Climate Impacts from Fossil Fuel Use."

[8] Shindell et al., "Improved attribution of climate forcing to emission."

[9] Wikipedia, "Global Warming Potential." http://en.wikipedia.org/wiki/Global-warming_potential

[10] Raymond T. Pierrehumbert, "Losing time, not buying time," *RealClimate*, December 6, 2010. http://www.realclimate.org/index.php/archives/2010/12/losing-time-not-buying-time

Arguments for using 100 years, other than that it is the conventional approach, are usually focused on the importance of the longer-lived GHGs in the atmosphere. CH_4 oxidizes to CO_2 in 10 to 12 years, so the amount of CH_4 in the atmosphere is related to the average emissions of CH_4 over the previous decade. The amount of CO_2 in the atmosphere is directly linked to the cumulative emissions of CO_2 since the Industrial Revolution, and the warming impact of CO_2 will persist for hundreds to thousands of years beyond when it was emitted.[11] Studies have shown that cumulative emissions over a century have a much greater impact than the immediate rate of emissions.[12] Thus, reducing methane emissions over the next 20 years would only delay a temperature rise by a few years and have a much smaller impact than reducing cumulative GHG emissions.

Another contributing factors to the use of a 100-year timeframe is that countries such as Canada have made GHG reduction commitments under Kyoto and those commitments are based on the GWPs used in the second assessment report. In order to maintain a consistent comparison year-over-year, Canada and other countries still continue to use the 100-year GWP.[13]

The implications of using shorter or longer timeframes for assessing climate impacts is explored in the GWP sensitivity analysis, section 3.2.1.

2.4 Data quality

2.4.1 Data selection

Selecting the appropriate data for a life cycle study is a critically important step that is based on the life cycle practitioner's expertise, experience and best practice guidance. The data can have a large impact on the final results. This report uses the following two categories of data:

1) The level of activity for each major life cycle stage (termed "activity data" in this report). Examples of activity data are kilometres traveled or m^3 of natural gas produced.

2) The level of emissions arising from each activity (termed "emission factors"). These factors estimate the environmental releases from each stage of the life cycle.

[11] Ibid.

[12] H. Damon Matthews, Nathan P. Gillett, Peter A. Stott & Kirsten Zickfeld, "The proportionality of global warming to cumulative carbon emissions," Nature (Letters) 459 (2009). Available at http://www.cccma.ec.gc.ca/papers/ngillett/PDFS/nature08047.pdf

[13] Canada's 2013 submission to the UNFCCC applied a 100-year GWP, noting, "Consistent with Decision 2/CP.3, the 100-year GWPs, provided by the IPCC in its Second Assessment Report (Table 1–1) and required for inventory reporting under the UNFCCC, are used in this report." http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php

For some activities numerous sources of data may be available, in which case the life cycle practitioner must use their judgement and experience to select that which is most appropriate. For some activities, there may be only one source of information and it may not be ideal. In such cases, these must be noted as a source of uncertainty.

Data in this study has been selected using the following considerations:

- Vintage: The data has been produced in the recent past, or time is irrelevant.
- Geography: The data is chosen for the most pertinent geographical regions.
- Technology: The data represents the specific technology being assessed.
- Performance data: The data is from operational facilities or is based on engineering estimates.
- Source: The source of data is reliable and published by a reputable entity (e.g. a national government organization, academic institution or industry association). Shell data was used for upstream gas activity, as it is specific to their operations and LNG facility design.

2.4.2 Data sources and assumptions

The data inputs used in this study for both the diesel and natural gas pathways are outlined in Table 4 and Table 5 below.

Table 4. Diesel pathway data sources and assumptions

Life Cycle Stage Activity	Activity Data	Emission Factors
Transport generator to site	Peoria, Illinois manufacturing location and transport method assumed	NREL LCI Database
Produce diesel	Crude is extracted from Alaskan North Slope, transported to Puget Sound and refined	GHGenius v4.03
Transport diesel	Distances of ocean transport to Skagway (1734 km one-way) and truck transport to Whitehorse (354 km round-trip) obtained through Gmaps Pedometer tool	NREL LCI Database
Combust diesel for power	Amount of input diesel fuel combusted was calculated from total power generation forecast (810.5 GWH) and generator efficiency (41.6%)	GHGs: Environment Canada National Inventory Report CACs: CAT continuous technical specification (maximum allowable) SO_2: Existing diesel emission factors

Table 5. LNG pathway data sources and assumptions

Life Cycle Stage Activity	Activity Data	Emission Factors
Transport generator to site	Manufacturing location of Jenbach and transport methods determined by YEC	NREL LCI Database
Produce LNG	Natural gas production, transport, treatment and liquefaction is at Shell's Jumping Pound facility in SW Alberta	Shell Canada CACs (gas treatment): NPRI AB grid electricity: Environment Canada NIR and NPRI
Transport LNG	Transport mode and distance to Whitehorse provided by PROLOG (4654 km round-trip).	NREL LCI Database
Combust natural gas for power	Amount of input LNG required was calculated from total power generation forecast (810.5 GWH) and Jenbacher generator spec efficiency (46.3%)	GHGs: EC CEPEI for lean-burn engine CACs: Jenbacher technical specification (max allowable) SO_2: Assumed 0 in LNG product

Other important assumptions and considerations for either system:

- This report used emission performance data for the diesel power generation based on factory-supplied information. The data provided was the upper range of emissions performance and is therefore conservative. Actually performance would be likely lower, based on operator behavior, possibly even for existing diesel generators. Pembina requested actual operational average data from the manufacturer but received no response.
- The CAT diesel engines are assumed to be manufactured in Peoria, Illinois and transported by truck to Whitehorse. Actual location was not ascertainable.
- The GE Jenbacher natural gas generator is operated using a "lean" fuel mixture meaning excess air is supplied compared to the exact stoichiometric combustion conditions for complete combustion. Operating in this fashion does increase overall efficiency; however, it produces more NO_x emissions due to higher temperatures and also has a material effect on exhaust methane emissions compared to a rich burn engine. The analysis in this report uses emissions data supplied from GE and does not attempt to model operator behavior.
- Trucks transporting diesel and LNG are "A-train" transport trucks with two trailing units. As a conservative estimate, transport of LNG and diesel fuel includes travel to Whitehorse and back again.
- Sulphur is not present in LNG as it is almost entirely removed prior to the liquefaction process.

- Global warming potentials for greenhouse gases are taken from IPCC's Fourth Assessment Report where methane and nitrous oxide have GWPs of 25 and 298, respectively, over a 100-year timeframe. A 20-year timeframe was investigated in the sensitivity case below.

2.4.3 Uncertainty

Data uncertainty is inherent to a life cycle study for numerous reasons as it is impossible to precisely measure or estimate the environmental releases of every species at every life cycle stage. For example, transportation tailpipe emissions are never actually estimated during regular operation. Instead, tests are performed attempting to replicate the myriad of operating conditions that impact performance such as road conditions, wind, road temperature, surface friction and payload. These tests lead to emission factors that are used to estimate environmental releases of GHGs and CACs during actual operation.

When multiple data sources exist, it is the life cycle practitioner's duty is to select data that is most applicable to the study system. When sufficient data does not exist, it is incumbent upon the practitioner to be transparent. For this study, several areas were identified where some uncertainty exists.

NG and diesel combustion for power generation

Ideally, the combustion of natural gas and diesel at Whitehorse would be modeled using operating data from an existing facility using the same combustion technologies. This data, however, was not available at the time of the study. In substitution, the combustion emissions were estimated using the GE Jenbacher and CAT Continuous 3300 technical specification documents for the LNG pathway and the diesel pathway respectively which predict emission performance.

Some of the figures listed in the technical documents from CAT are emission limits rather than emissions performance itself. In some instances, the difference between the two (limit vs performance) is not clear.

Both the diesel and natural gas combustion activities are modeled using these technical specification documents. This is noted as a limitation of this study. If actual operating data becomes available, it is recommended to update this study with that data.

LNG production at Shell's Jumping Pound facility

Shell's Jumping Pound facility has been producing natural gas and gas products since 1951. Shell now plans to build an LNG facility at Jumping Pound to supply a number of clients, one of which is YEC.

Ideally energy use and emission data used in this study would be from Jumping Pound operational data; however, this facility does not yet exist. LNG data used in this study is derived from Shell's internal design estimates scoping out all required equipment and technology. Shell has experience deploying modules of the proposed Jumping Pound LNG facility elsewhere and believes that their calculations are very close to how the facility would actually operate. Shell's design calculations are highly confidential and were never intended to be disclosed to any external party. Prior to providing results Shell indicated to Pembina that the data used were conservative in order to provide a "worse case scenario" to inform internal decision making at Shell.

Using operational data from another LNG facility is problematic for the following reasons:

- The gas fields surrounding Jumping Pound are unique in that they are high in sulphur (i.e. sour gas). At the processing plant, this will result in relatively higher on-site SO_2 emissions. Therefore using another LNG facility's data will not produce accurate results because they are treating a natural gas with a different sulphur content and likely different equipment.
- Shell carries internal policies, such as "zero venting", that other operators would not necessarily have nor adhere to.

Particulate matter emissions size range inconsistently reported

While a high degree of confidence exists in the final Particulate Matter results, there is less certainty around the proportion of these particles that are in the 2.5 micron range versus the 10 microns range. While the health impacts of the two different size categories may be similar in nature, there is increased severity with smaller-sized particles. Although some of the environmental performance data used distinguished between these two sizes, many sources did not. As such, particulate matter results are presented as a total of both size ranges.

CAT diesel generator manufacturing location

The manufacturing of the CAT diesel generators is unknown. The study team's multiple inquiries to multiple CAT contacts went unanswered. A web search revealed that CATs largest manufacturing facility is located in Peoria, Illinois. It is therefore assumed that the CAT diesel generators are manufactured here.

3 Results

3.1 Quantitative results

The results of the study are summarized in Table 6 through Table 8 below. They are broken down into four general life cycle stages:

1. Transport generator – from manufacturing location to Whitehorse
2. Produce fuel – includes treatment, refining and transport to facilities
3. Transport fuel –diesel/LNG to Whitehorse
4. Combust fuel – power generation

These tables provide the specific quantitative results for each system, by stage, for each parameter assessed.

Table 6. Diesel pathway results by life cycle stage

	GHGs ($kgCO_2e/MWH$)	NO_x (kg/MWH)	SO_2 (kg/MWH)	PM (kg/MWH)	CO (kg/MWH)
Transport diesel generator	0.06	0.0	0.0	0.0	0.0
Produce diesel	254	0.4	0.4	0.3	0.3
Transport diesel	11	0.2	0.0	0.0	0.0
Combust diesel	619	14.1	0.0	0.8	1.0
TOTAL	884	14.7	0.4	1.2	1.3

Table 7. LNG pathway results by life cycle stage

	GHGs ($kgCO_2e/MWH$)	NO_x (kg/MWH)	SO_2 (kg/MWH)	PM (kg/MWH)	CO (kg/MWH)
Transport natural gas generator	0.05	0.0	0.0	0.00	0.0
Produce LNG	176	0.2	1.5	0.01	0.1
Transport LNG	24	0.3	0.0	0.01	0.0
Combust natural gas	488	0.1	0.0	0.01	0.2
TOTAL	688	0.6	1.5	0.03	0.3

Table 8. Contribution of emissions by life cycle stage

	GHGs (%)		NO_x (%)		SO_2 (%)		PM (%)		CO (%)	
	Diesel	LNG	Diesel	LNG	Diesel	LNG	Diesel	LNG	Diesel	LNG
Transport Generator	0	0	0	0	0	0	0	0	0	0
Produce Fuel	29	26	3	31	93	100	27	42	23	23
Transport Fuel	1	3	2	52	4	0	0	29	2	11
Combust Fuel	70	71	96	16	3	0	72	29	75	66
TOTAL	100	100	100	100	100	100	100	100	100	100

Note that the liquefaction process of the LNG system is included as part of the "Produce Fuel" activity. Due to confidentiality requirements, environmental performance associated with liquefaction is not able to be separated out.

The following sections provide a graphic summary comparing the environmental performance of the options assessed per parameter, broken down by activity.

3.1.1 Greenhouse gas (GHG) emissions

GHGs are emitted at each stage of the diesel and LNG pathways. The LNG pathway produces less GHG emissions (688 kgCO_2e/GWH) than the diesel pathway (884 kgCO_2e/GWH), with the majority of life cycle emissions released at combustion stage (70% for diesel, 71% for LNG) as seen in Figure 2 below.

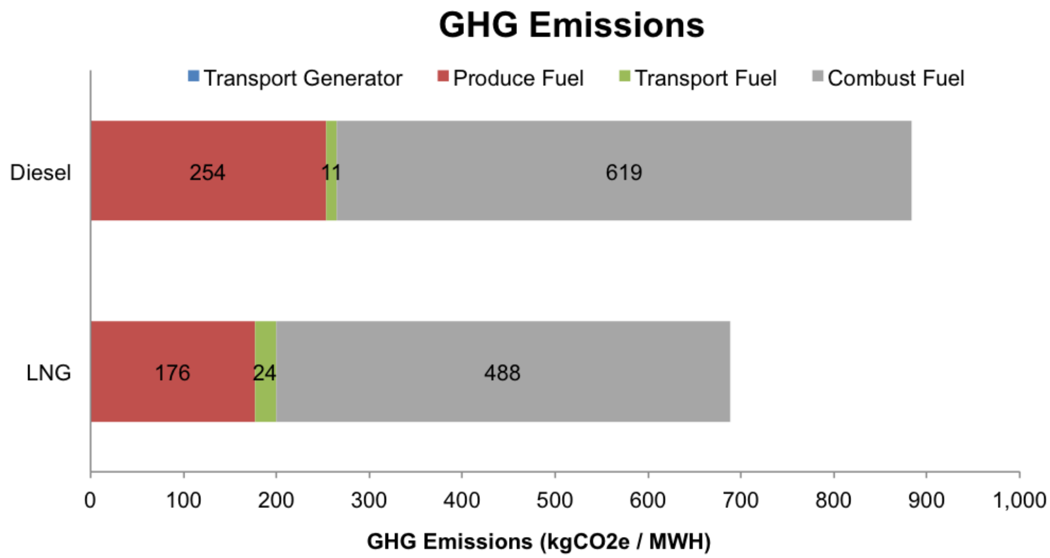


Figure 2. GHG emissions by stage

Fuel production had relatively comparable contributions to the life cycle emissions at 29% and 26% for diesel and LNG respectively as seen in Table 8 above.

Transportation of LNG had higher GHG emissions by gross emissions and by per cent life cycle than the diesel pathway owing to the 100% use of truck transport for transportation. Diesel had lower transport GHG emissions due to its use of ocean freighter for much of the distance which is much more efficient per unit weight of fuel transported.

3.1.2 Nitrogen oxides (NO_x) emissions

Total NO_x emissions are much higher for the diesel pathway (14.7 kg/MWH) than for the LNG pathway (0.6 kg/MWH). In the diesel pathway, NO_x emissions are emitted primarily at combustion (96%) where in the LNG pathway NO_x emissions are emitted throughout the life cycle with the largest activity being LNG transport to Whitehorse (52%). A life cycle stacked bar chart illustrates the contribution by life cycle stage in Figure 3 below.

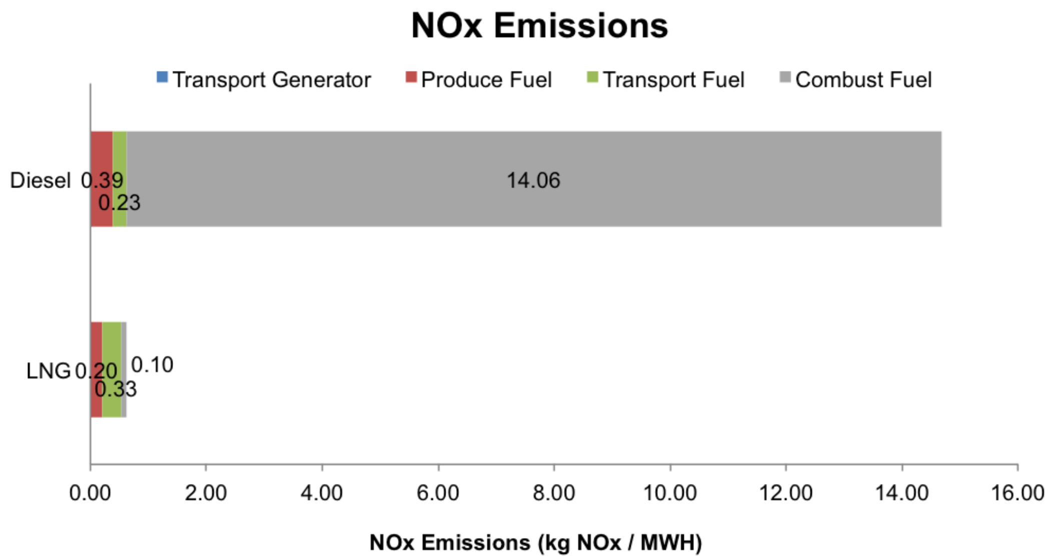


Figure 3. NO_x emissions by stage

Notably, the NO_x emissions factor supplied by the CAT technical specification document for the diesel engine listed a NO_x emission factor (14.06 kg/MWh) almost twice that of the measured values from the existing diesel fleet (8.82 kg/MWh). As discussed in the assumptions and uncertainty sections above, this is due to conservative upper limit factory-based data for the new diesel engines which will be much different than actual operational values. NO_x releases in the LNG pathway are primarily from truck transporting LNG from Calgary to Whitehorse. The next largest source is from producing LNG at Jumping Pound. A portion of these emissions are from direct on-site combustion of produced gas as well as indirect consumption of Alberta grid electricity.

3.1.3 Sulphur dioxide (SO_2) emissions

Life cycle SO_2 emissions are much higher for the LNG pathway (1.5 kg/MWH) than the diesel pathway (0.4 kg/MWH). In both pathways, the overwhelming largest contributing stage is fuel production as seen in Figure 4 below. For LNG, all SO_2 emissions result from the production of LNG at Shell's Jumping Pound facility, while fuel production accounts for 93% of SO_2 emissions in the diesel pathway.

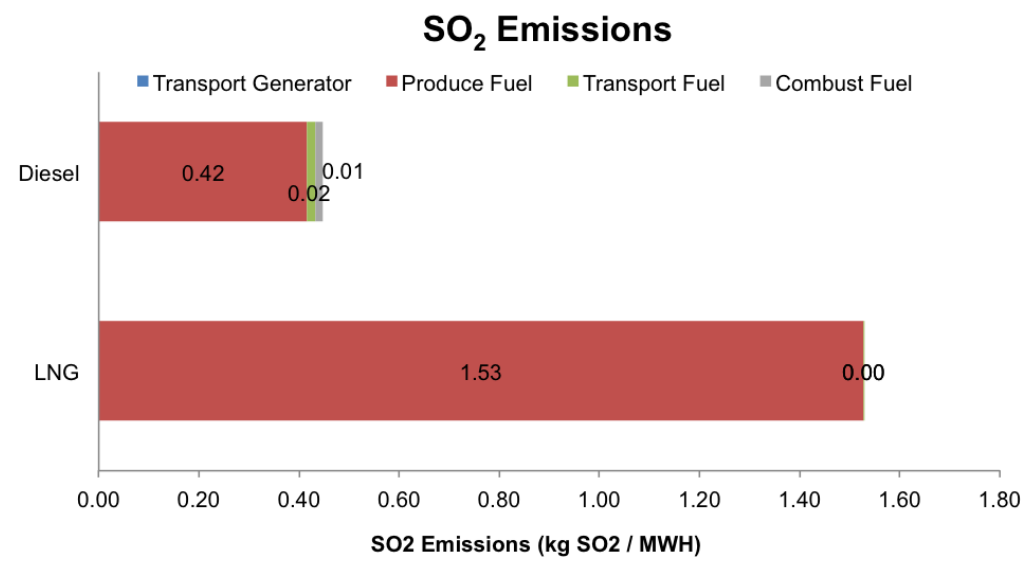


Figure 4. SO_2 emissions by stage

SO_2 emissions from the LNG pathway are high because the gas fields around Jumping Pound are known to have a very high sulphur content. It is possible that LNG that is sourced from sweeter fields (i.e. with lower sulphur content) could have lower life cycle SO_2 emissions than the diesel pathway. It is also worth noting that SO_2 emissions primarily occur in geographical regions outside of the Yukon (i.e. Washington State, USA and Jumping Pound, Alberta) meaning that any environmental impact from freshwater or terrestrial acidification would likely also occur outside the Yukon.

While sulphur emissions are higher for LNG than for the diesel pathway, it is important to recall (as per Table 2. Environmental parameters quantified) that both NO_x and SO_2 have acidifying impacts and can be combined into an Acidifying Deposition Potential or ADP (with NO_x having 79% the acidifying impact of SO_2) measured in units of SO_2 equivalents or SO_2e (see Figure 5).

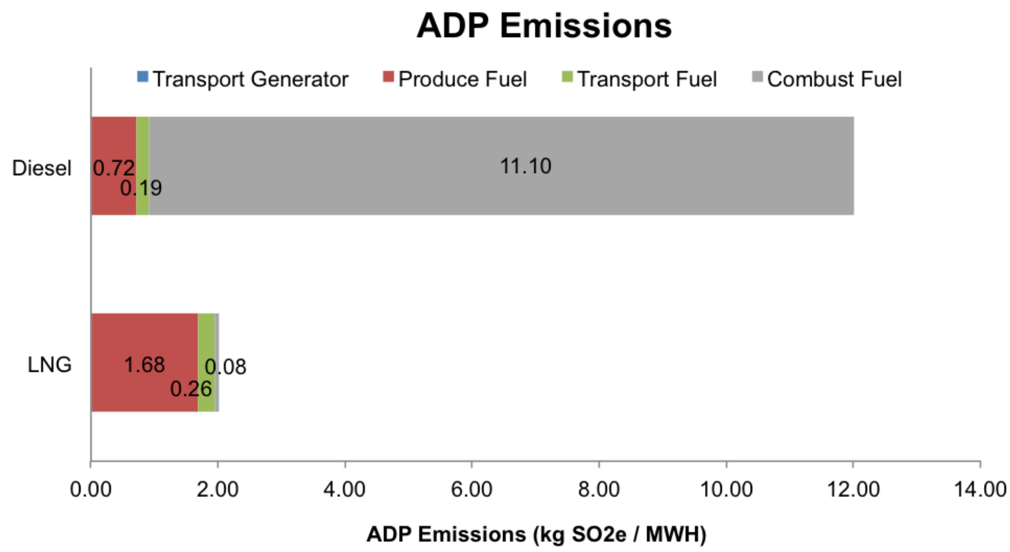


Figure 5. ADP emissions by pathway

In this study, the ADP emissions for the diesel and LNG pathways were 12.0 kgSO_2e/MWH and 2.0 kg SO_2e/MWH respectively. As a result, the diesel pathway emits significantly more ADP emissions (when considering NO_x and SO_2) than the LNG pathway due to the high NO_x emissions at combustion.

3.1.4 Particulate matter (PM) emissions

The life cycle particulate matter emissions are seen graphically in Figure 6 below.

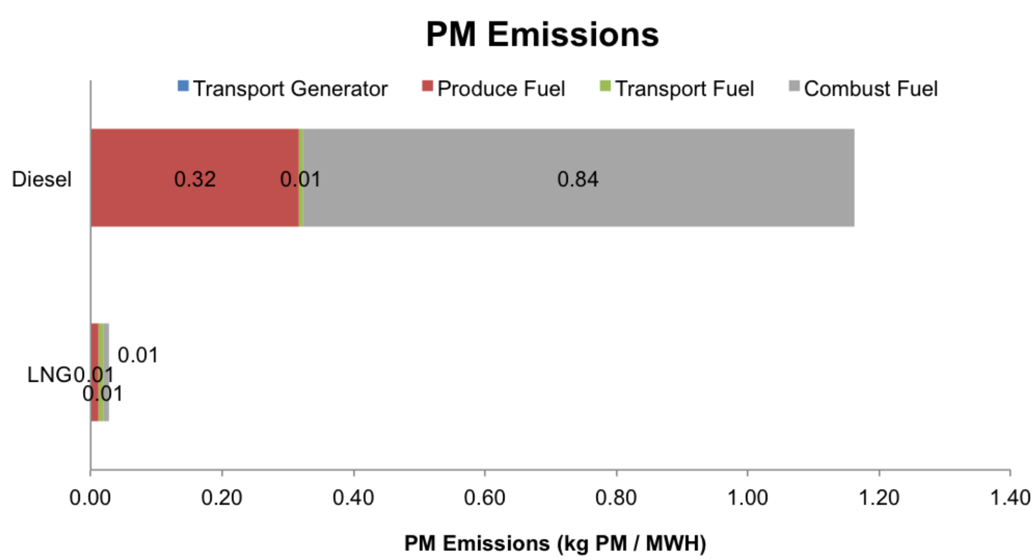


Figure 6. PM emissions by stage

Total PM emissions are much higher for the diesel pathway (1.2 kg/MWH) than for the LNG pathway (0.03 kg/MWH). In the diesel pathway, particulate emissions occur mainly at combustion (72%) where for the LNG pathway it was during fuel production (42%).

3.1.5 Carbon monoxide (CO) emissions

Total CO emissions are much higher for the diesel pathway (1.3 kg/MWH) than for the LNG pathway (0.3 kg/MWH). In both the diesel and LNG pathways, the largest stage contributor to life cycle CO emissions was combustion. 75% of CO emissions in the diesel pathway and 66% of CO emissions in the LNG pathway were produced from combusting fuels for power as shown in Figure 7 below.

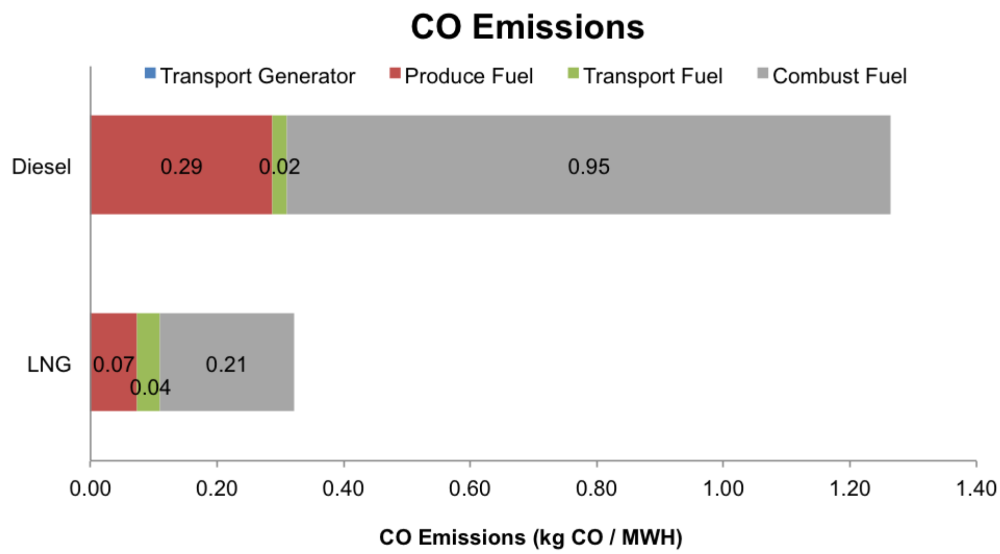


Figure 7. CO emissions by stage

The CAT generator specification noted that the emission factor for CO were "not to exceed" values meaning that the true emissions of CO are likely to be lower. The GE Jenbacher specification did not note if the emission factor were upper limit values.

3.2 Sensitivity analysis

3.2.1 Sensitivity analysis #1 – GWP

Given the increased focus on the 20-year GWP of methane, a sensitivity analysis was performed. The GWP for methane is adjusted from 25 to 72 and N_2O is adjusted from 298 to 289. Note that the GWP for CH_4 changes more dramatically than N_2O because it is a much shorter lived GHG in the atmosphere meaning that it has a much greater impact in the short-term (20-year time horizon) compared to the long-term (100-year time horizon).

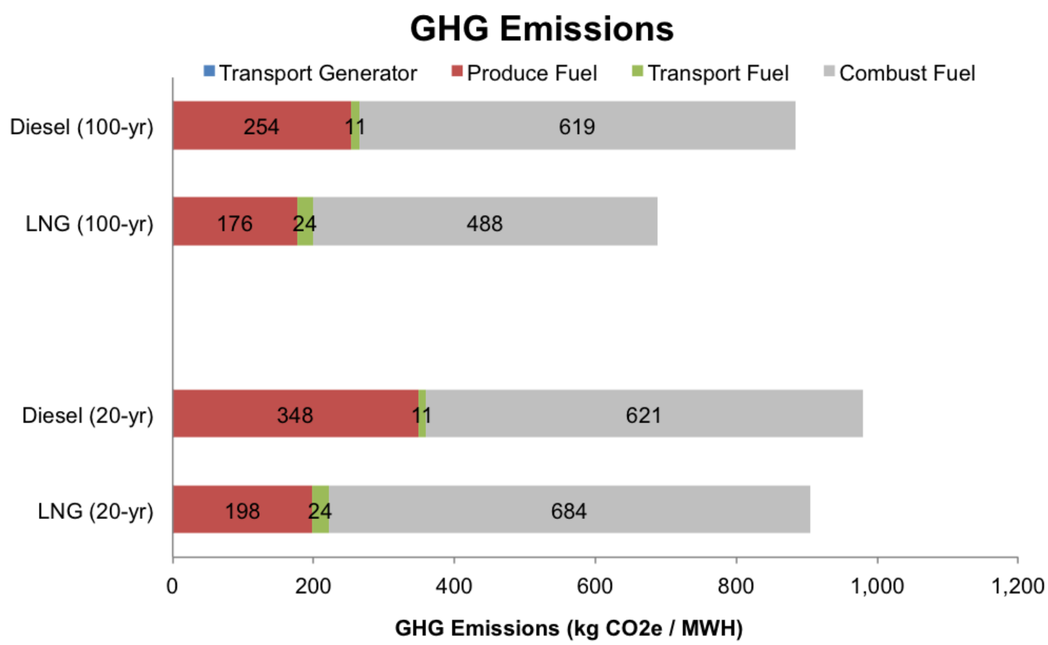


Figure 8. GHG emissions by stage with adjusted GWP

Table 9. Life cycle GHG results with adjusted GWP

	GHGs ($kgCO_2e/MWH$)					
	Diesel (100-yr)	LNG (100-yr)	Diesel (20-yr)	LNG (20-yr)	Diesel	LNG
Transport Generator	0.06	0.05	0.06	0.05	0%	0%
Produce Fuel	254	176	348	198	37%	12%
Transport Fuel	11	24	11	24	0%	0%
Combust Fuel	619	488	621	684	0%	40%
TOTAL	**884**	**688**	**980**	**906**	**11%**	**32%**

As shown in Table 9 above, the total GHG emissions increased more for the LNG pathway than the diesel pathway, and the life cycle stage that is impacted most by the GWP change is the Combust Fuel stage. The next largest stage was the Produce Fuel stage. The other life cycle stages were relatively unchanged.

The increase in the Combust Fuel stage for LNG pathway was very large compared to the diesel pathway. This is due to the large CH_4 component to the GHG emission factor used in the modelling from CEPEI for a lean burning 4-stroke natural gas engine such as the GE

Jenbacher. Other natural gas emissions factors for power generation, such as those in Environment Canada's National Inventory Report, yield much lower methane emissions.

The methane emissions at combustion are, therefore, highly dependent on how the natural gas engine is configured to operate. Unfortunately the methane emission factor was not disclosed in the GE Jenbacher spec itself. If GE is not able to supply this information, then methane stack testing results are particularly important in updating this analysis for GHG comparisons.

The Produce Fuel stage indicates that there are more CH_4 emissions emitted during diesel production (crude extraction and refining) than LNG production (natural gas extraction, gathering, treatment and liquefaction).

It is important to note that the LNG production figures come directly from an internal Shell life cycle study. Shell has a strict "no venting" policy that covers activities from production wells to customer sale while natural gas is under their custody. Because of this, CH_4 emissions may be particularly low compared to LNG production from other producers.

Also, the Shell study is predictive for a future LNG facility at Jumping Pound and is based on engineering design calculations and previous experience deploying similar technologies. This inherently has more uncertainty than measured emissions from a facility that is already operating.

3.2.2 Sensitivity analysis #2 – Diesel engines

YEC has indicated that the most likely generator to replace the existing diesel fleet is the CAT Continuous 3300 manufactured by Caterpillar. The diesel pathway results are generated using the CAT generator emission factors obtained from the CAT technical specification document.

The existing fleet of seven diesel engines is made of up Mirrless (3), EMD (3) and Caterpillar (1) engines. They were put into service between 1968 and 1991 with horsepower ratings between 3600 and 7180 hp. As changing the diesel engines would affect the final results, a sensitivity analysis was run using historical and averaged stack testing results. Table 10 below compares stack test results against GE's design specs.

Table 10. Life cycle results comparing new diesel against existing diesel

	GHGs ($kgCO_2e$/MWH)	NO_x (kg/MWH)	SO_2 (kg/MWH)	PM (kg/MWH)	CO (kg/MWH)
New Diesel	884	14.7	0.4	1.2	1.3
Existing Diesel	1,005	9.4	0.4	0.5	0.8
LNG	688	0.6	1.5	0.03	0.3

The following conclusions are noted:

- GHG emissions decrease with the CAT diesel engines. This is mainly due to the increased efficiency in the new engines (41.6%) versus the existing engines (34.8%).
- The NO_x, PM and CO emissions increase dramatically in the new engines compared with the performance of the existing diesel engines. The spec document may be summarizing performance for operating under specific configurations conducive to producing these emissions; however, the document did not specify this directly.
- SO_2 emissions are unchanged because these mainly depend on sulphur content of the input diesel. Since the new and existing diesel generators use the same fuel, the SO_2 emissions will not change.
- Lastly, whether the diesel pathway is configured with the new diesel engines or the existing diesel engines, both have higher emissions than the LNG pathway across all parameters except for SO_2.

3.2.3 Sensitivity analysis #3 – Natural gas source

LNG sourced from other locations will have different emissions profile based on the natural gas gathering, treatment and liquefaction technology deployed. In this sensitivity, the natural gas treatment facility on-site criteria air contaminant emissions are modified to represent an average Canadian facility whose data is derived from a CAPP study[14]. The natural gas gathering and liquefaction stages remain the same as the Jumping Pound specific base case.

The results are shown in Table 11 below.

Table 11. Life cycle results comparing natural gas origin

	GHGs ($kgCO_2e$/MWH)	NO_x (kg/MWH)	SO_2 (kg/MWH)	PM (kg/MWH)	CO (kg/MWH)
LNG – Jumping Pound	688	0.6	1.5	0.03	0.3
LNG – Canada average	680	0.7	0.4	0.03	0.4
Diesel Base Case	884	14.7	0.4	1.2	1.3

The following conclusions are noted:

- Modifying the natural gas treatment facility, which indirectly reflects differences in the natural gas source itself, shows similar life cycle results for most emissions except for SO_2.
- It is clear that SO_2 emissions from processing the natural gas from Jumping Pound is more intensive than natural gas sourced from elsewhere in Canada.
- SO_2 performance from CAPP average data is significantly more similar to the diesel pathway.

[14] CAPP, *A National Inventory of Greenhouse Gases, Criteria Air Contaminant and Hydrogen Sulphide Emissions by the Upstream Oil and Gas Industry* (2004). The inventory was performed by Clearstone Engineering, a respected expert in the field of air emissions data collection.

- With the exception of SO_2 emissions, the life cycle results for LNG are lower than the diesel base case for both Jumping Pound and Canada average natural gas.

3.3 Areas for further investigation

3.3.1 Water issues

Water impacts were not quantified as part of this study, as neither system is considered particularly water intensive. While water quantity can be an issue of concern for some energy pathways, the potential impacts of discharges to surface water and spills are also of concern.

Of the activities involved in the two pathways considered in this analysis, crude extraction was highlighted as a potential area of concern for spills and crude refining for its water use.

Crude extraction

The main water concern during crude oil extraction in Alaska's North Slope is around spills. On-shore crude extraction activities can result in spills which can reach saltwater, freshwater and Arctic tundra wetlands. The Wilderness Society describes 4,532 spills between 1996 and 2004 totaling more than 1.9 million gallons.[15] That is an average of 1.38 spills per day. Furthermore, TWS notes that coastal and marine waters are difficult to clean up and especially so in the presence of broken ice. Recovery from spills is also slower in the Arctic due to cold temperatures, slower plant growth rates and longer animal life spans.

Furthermore, the state has long-term objectives to develop off-shore drilling resources in Alaska's Outer Continental Shelf. In August 2012, Natural Resources Defense Fund released an issue paper[16] dedicated to off-shore drilling in Alaska. They cite concerns such as a history of spills in Alaska's North Slope region, immense challenges with cleaning up spills, the potential damage to a unique region in the Arctic Coast and Arctic National Wildlife Refuge, and impacts to Alaska Natives like the Inupiat.

Crude refining

Refineries use water to process crude oil into refined products. Approximately 1 to 2.5 litres of water is required for every litre of petroleum product that is produced.[17] Refineries do have the ability to recycle water for continual use; however, actual recycle rates vary by individual refinery.

In October 2010, the International Petroleum Industry Environmental Conservation Association (IPIECA) released a best practices guidebook on water and wastewater

[15] The Wilderness Society, *Drilling and Spilling on Alaska's North Slope.* Available at http://www.nytimes.com/packages/pdf/national/15spill.pdf.

[16] Natural Resources Defense Fund, *Environmental Risks with Proposed Offshore Oil and Gas Development off Alaska's North Slope* (2012). http://www.nrdc.org/land/alaska/files/drilling-off-north-slope-IP.pdf.

[17] U.S. EPA, "Water and Energy Efficiency by Sectors Oil Refineries." http://www.epa.gov/region9/waterinfrastructure/oilrefineries.html#water.

management.[18] The comprehensive document covers water consumption, wastewater, stormwater and sewage, effluent treatment and recycle/reuse issues.

[18] IPIECA, *Petroleum refining water/wastewater use and management* (2010). http://www.ipieca.org/publication/petroleum-refining-water-wastewater-use-and-management.

4 Conclusions

The following are the key conclusions drawn from this analysis, which consider two specific fuel supply pathways having specified sources:

- The environmental performance of the LNG system modelled was better than the diesel pathway across all categories of environmental impact. SO_2 emissions, outside of being combined with NO_x for an equivalent impact category, were much higher for the LNG system due to high sulphur concentration in the gas fields supplying Shell's Jumping Pound facility.
- The LNG pathway continues to have lower GHG emissions than the diesel pathway after adjusting the GWPs to 20-yr values for both methane and nitrous oxides; however the difference between the two systems is slightly smaller (by approximately 2.5%). Methane emissions at combustion are highly dependent on operating conditions (i.e. lean vs rich burning).
- Air emissions from the diesel generators and gas turbines were modelled using theoretical factory-based emissions and not actual operating data, given they would be brand new units. While not expected to change the conclusions, actual emissions performance may differ as:
    - Upper ranges (more conservative values) are applied in the model.
    - Operator behaviour would impact emissions.
- Water use associated with refining and potential spills associated with crude oil transport were not quantified but can be taken into consideration.
- LNG performance is specific to Shell's Jumping Pound facility, and upstream impacts may differ from other gas sources.

Appendix A. Overview of Life Cycle Assessment

Life Cycle Assessment (LCA) is a systematic and quantitative tool developed in the 1960s to help analysts and decision makers evaluate the environmental performance of a product, process or service.

It sums together the environmental releases at the major stages in a pathway to form a more complete picture of a product's total potential impact to society as shown in Figure 9 below.

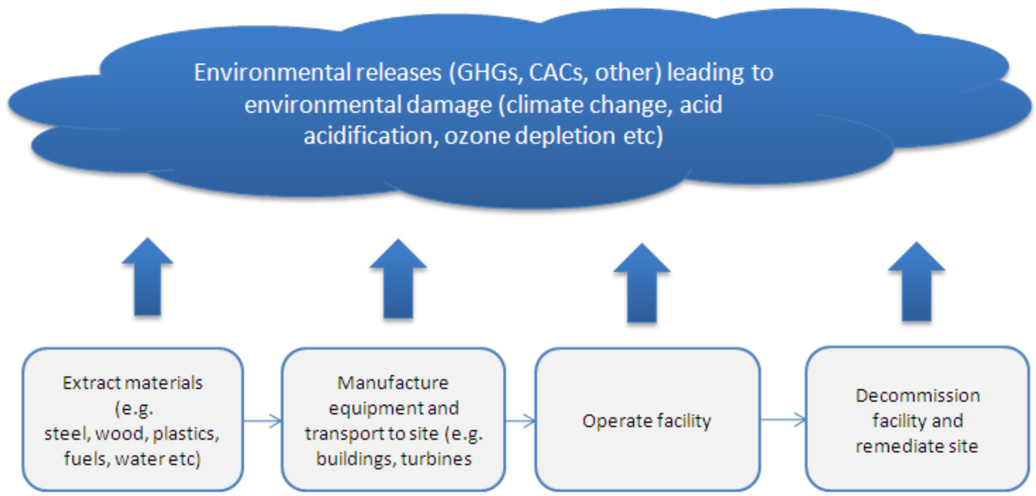
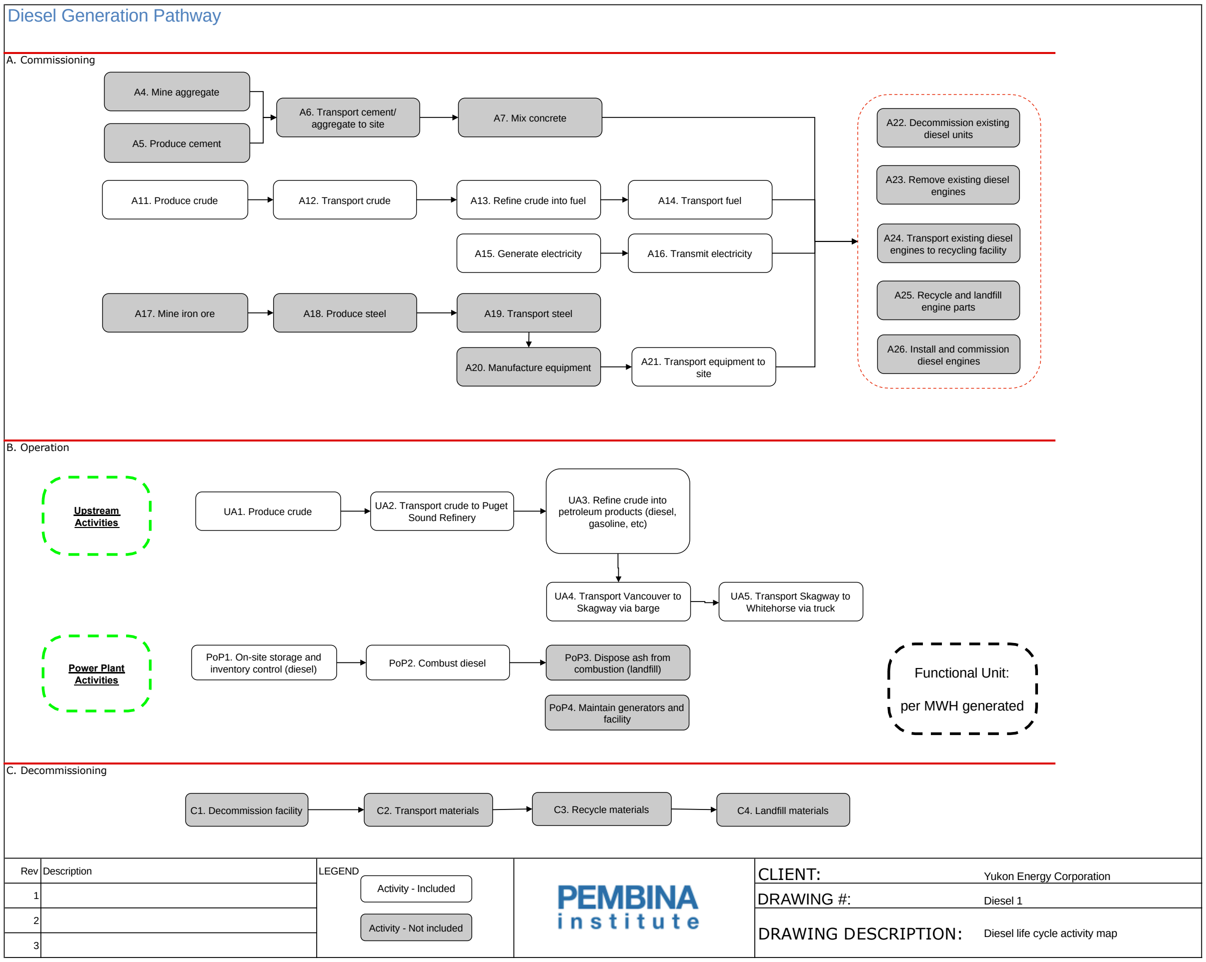


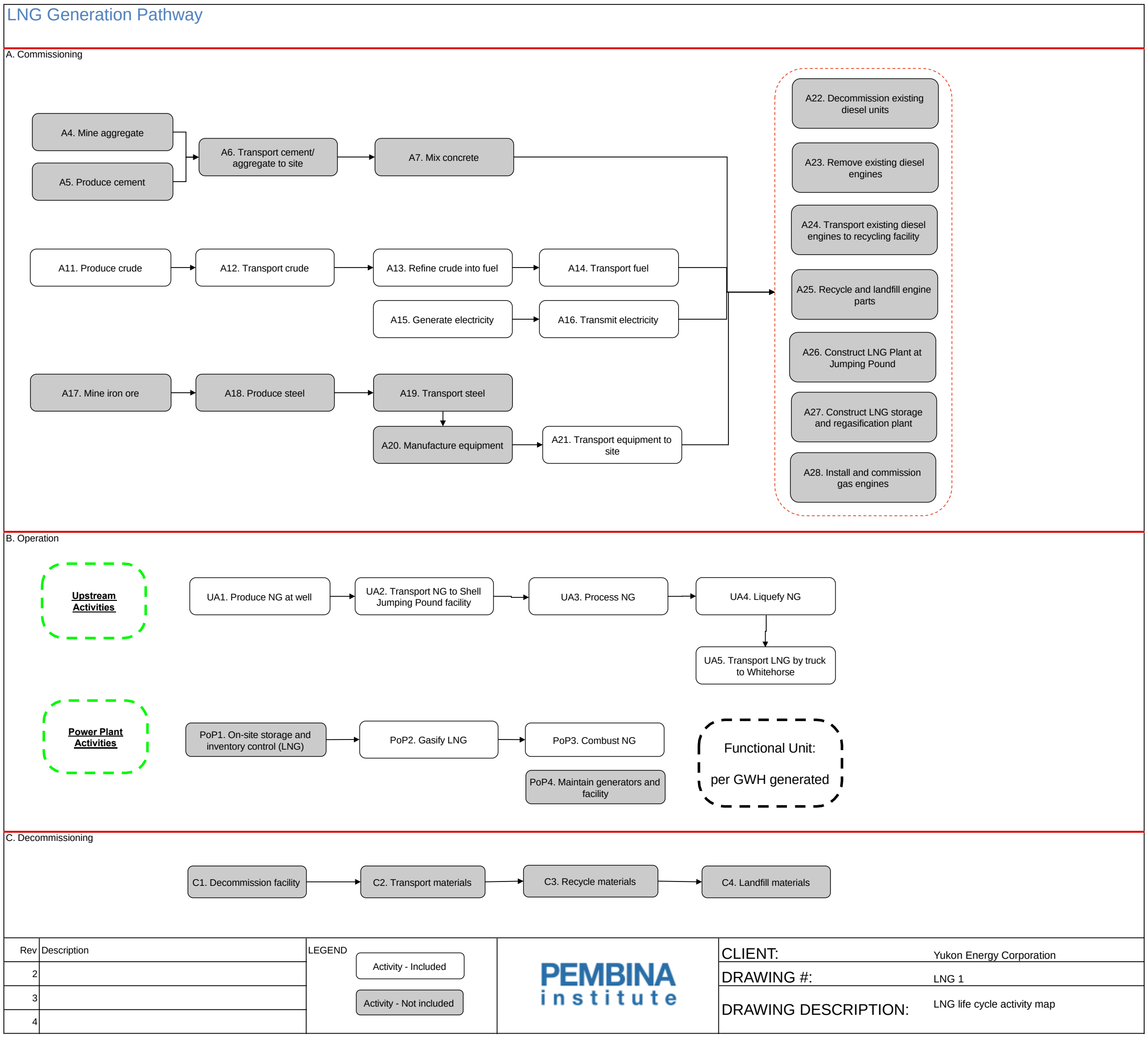
Figure 9. Conceptualized LCA Diagram

LCA is most often used to evaluate the environmental performance among competing options. Analysts and decision-makers can use LCA results to make informed decisions in the following ways:

- **Assess potential environmental impacts** on human health and environmental degradation.
- **Identify "hotspots"**: Identify those processes that are contributing the most environmental releases. These processes are generally the areas where the most environmental benefit can be realized in future efficiency improvements.
- **Identify environmental trade-offs**: One option may be a better performer in many categories but not all categories. It is useful to know when there are environmental trade-offs.
- **Avoid shifting environmental problems**: Policy and technology decisions can simply shift environmental impacts to another geographical region or upstream/downstream in the process. LCA eliminates this issue.
- **Tabulate resource consumption** and track mass and energy flows through the system.

Appendix B. Detailed life cycle activity maps




LNG Generation Pathway
A. Commissioning
A4. Mine aggregate
A5. Produce cement
A6. Transport cement/ aggregate to site
A7. Mix concrete
A11. Produce crude
A12. Transport crude
A13. Refine crude into fuel
A14. Transport fuel
A15. Generate electricity
A16. Transmit electricity
A17. Mine iron ore
A18. Produce steel
A19. Transport steel
A20. Manufacture equipment
A21. Transport equipment to site
A22. Decommission existing diesel units
A23. Remove existing diesel engines
A24. Transport existing diesel engines to recycling facility
A25. Recycle and landfill engine parts
A26. Construct LNG Plant at Jumping Pound
A27. Construct LNG storage and regasification plant
A28. Install and commission gas engines
B. Operation
Upstream Activities
UA1. Produce NG at well
UA2. Transport NG to Shell Jumping Pound facility
UA3. Process NG
UA4. Liquefy NG
UA5. Transport LNG by truck to Whitehorse
Power Plant Activities
PoP1. On-site storage and inventory control (LNG)
PoP2. Gasify LNG
PoP3. Combust NG
PoP4. Maintain generators and facility
Functional Unit:
per GWH generated
C. Decommissioning
C1. Decommission facility
C2. Transport materials
C3. Recycle materials
C4. Landfill materials
Rev
Description
2
3
4
LEGEND
Activity - Included
Activity - Not included
PEMBINA institute
CLIENT:
Yukon Energy Corporation
DRAWING #:
LNG 1
DRAWING DESCRIPTION:
LNG life cycle activity map

Appendix C. Comparisons with other published life cycle studies

Table 12. Comparing diesel pathway GHG results with other published studies

	% Upstream	% Combustion
Jacobs ULSD[19] (from Arab-medium)	23	77
CARB ULSD[20]	21	79
NETL[21] (Alaskan North Slope Crude)	27	73
Pembina Institute (Alaskan North Slope Crude)	30	70

Table 13. Comparing LNG results with other published studies

	Life Cycle GHG Emissions (gCO_2e/kWh)
Jaramillo et al[22] – low end estimate	408
Jaramillo et al – high end estimate	1090
Pembina Institute	688

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[19] Jacobs Consultancy, *Life Cycle Assessment Comparison of North American and Imported Crudes* (2009), Figure 8.1.

[20] CARB, *Detailed California-Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California* (2009).

[21] NETL, *Life-Cycle Greenhouse-Gas Emissions Inventory for Fischer-Tropsch Fuels* (2001), Table 31.

[22] Paulina Jaramillo, W. Michael Griffin, and H. Scott Matthews, "Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation," *Environmental Science and Technology* 41, no. 17 (2007). Low end and high end values converted from Figure 1.

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