Appendix 5.1
Greenhouse Gas Emission Life Cycle Assessment of Resource Options (ArcticCan Energy Services 2016)

FINAL REPORT

LIFECYCLE ASSESSMENT FOR ENERGY RESOURCE OPTIONS IN YUKON TERRITORY

Prepared for Yukon Energy Corporation
2 Miles Canyon Rd
Whitehorse YT Y1A6S7
Attention: Shannon Mallory

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September 6, 2016

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September 6, 2016

Yukon Energy Corporation
2 Miles Canyon Rd
Whitehorse YT Y1A6S7
Attention: Shannon Mallory, Environmental Coordinator

Re: Lifecycle Assessment for Energy Resource Options in Yukon Territory

Dear Ms. Mallory:

Please find attached the Final Report. If you have any questions or comments regarding the report, please contact me at (306) 502-5005 or amanuilova@articcanenergy.com.

Yours sincerely,

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ABBREVIATIONS

AD	Anaerobic Digester
API	American Petroleum Institute (API)
C	Carbon
CAPP	Canadian Association of Petroleum Producers
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2e	Carbon dioxide equivalent
GHG	Greenhouse Gas
GWP	Global Warming Potential
HHV	Higher Heating Value
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
Mm^3	Million Cubic Meters
MSW	Municipal Solid Waste
N_2O	Nitrous Oxide
ORC	Organic Rankine Cycle
WRGS	Whitehorse Rapids Generating Station
WTE	Waste-to-Energy

1 EXECUTIVE SUMMARY

There is an increase in concern around the world regarding environmental issues, including the use of natural resources, water, soil and air quality, deforestation, pollution, and emissions. The performance of products, services and processes in terms of its environmental impact has become a key global focal point for policy makers and industry leaders alike. As such, a critical analysis of negative environmental impacts that result from human activity must be performed. One of the most common analytical tools to weigh such impacts is the life cycle assessment (LCA). The purpose of the LCA is to examine and evaluate the overall environmental impact of using a certain product or implementing a certain technology by considering all stages of its life, from raw materials acquisition, to production, transportation, application, energy generation, recycling, and disposal, i.e., from “cradle to grave.”

The results of an LCA can assist decision makers in choosing the most appropriate process or product that has the least environmental impact. LCAs are used in conjunction with other factors, such as performance, cost and feasibility, to assist in the selection of a process or product. With careful selection of the system boundaries, the LCA benefits end-users by exposing the environmental impacts that may be transferred from one medium to another, or from one life cycle stage to another, that may otherwise go unnoticed and unaccounted for.

Yukon Energy Corporation decided to perform a comparative LCA study of various energy resource options as part of their 2016-2035 Resource Plan. The goal of this study is to determine the amount of greenhouse gas (GHG) emissions that would be generated from 13 preselected energy resource options that are available to Yukon Energy for future use, which include both renewable and non-renewable resources. The pathways analysed are as follows:

1. Biomass gasification (combined heat and power, CHP)
2. Waste to energy (municipal solid waste alone and with biomass conventional combustion CHP plant)
3. Biogas (generated from organic waste)
4. Geothermal
5. Wind
6. Solar
7. Pumped storage hydro power plant
8. Small hydro power plant
9. Energy storage (lithium ion batteries)
10. Thermal – diesel
11. Thermal – LNG
12. New transmission line
13. Water diversion project

Included in the study is an analysis of energy storage in the form of batteries as well as the construction of a new transmission line. These options are modelled separately as they may form a part of another energy production pathway.

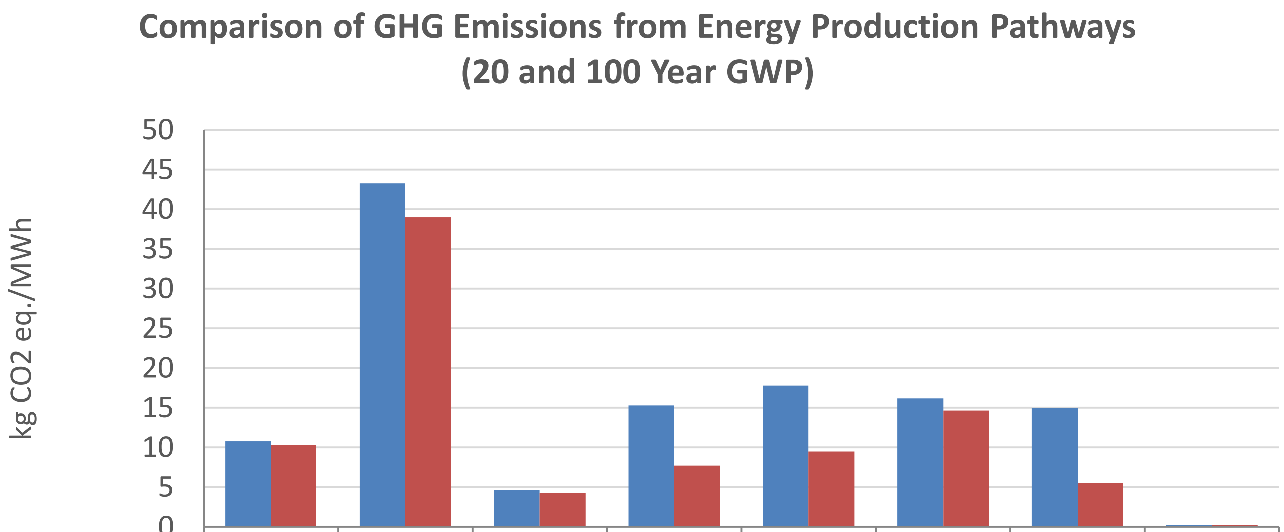
Each resource option is analyzed for GHG emissions using the Global Warming Potential (GWP) for both the 20 year and 100 year time horizon. The GWP factors without feedback are taken from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). The significant difference among the two GWP values is seen in methane emissions (84 and 28 for the 20 year and 100 year time horizons, respectively), which affects GHG emissions results when analyzing resource options that generate significant amounts of methane. Results from estimating the GHG emissions for both time horizons can illustrate immediate and future emissions concentrations released into the atmosphere. This can assist decision makers in deciding which energy resource scenario best addresses their short-term and long-term climate strategy.

This study is based on LCA principles and includes a definition of the system boundary, selection of relevant data (site-specific where possible and North American or European data when Canadian data were unavailable), and calculations of total GHG emissions for each energy resource per functional unit. The functional unit selected is MWh of energy delivered to the grid. In the battery storage and transmission line scenarios, the results are also presented per MWh of energy stored and MWh-km, respectively, to accommodate the appropriate energy source addition in future environmental studies.

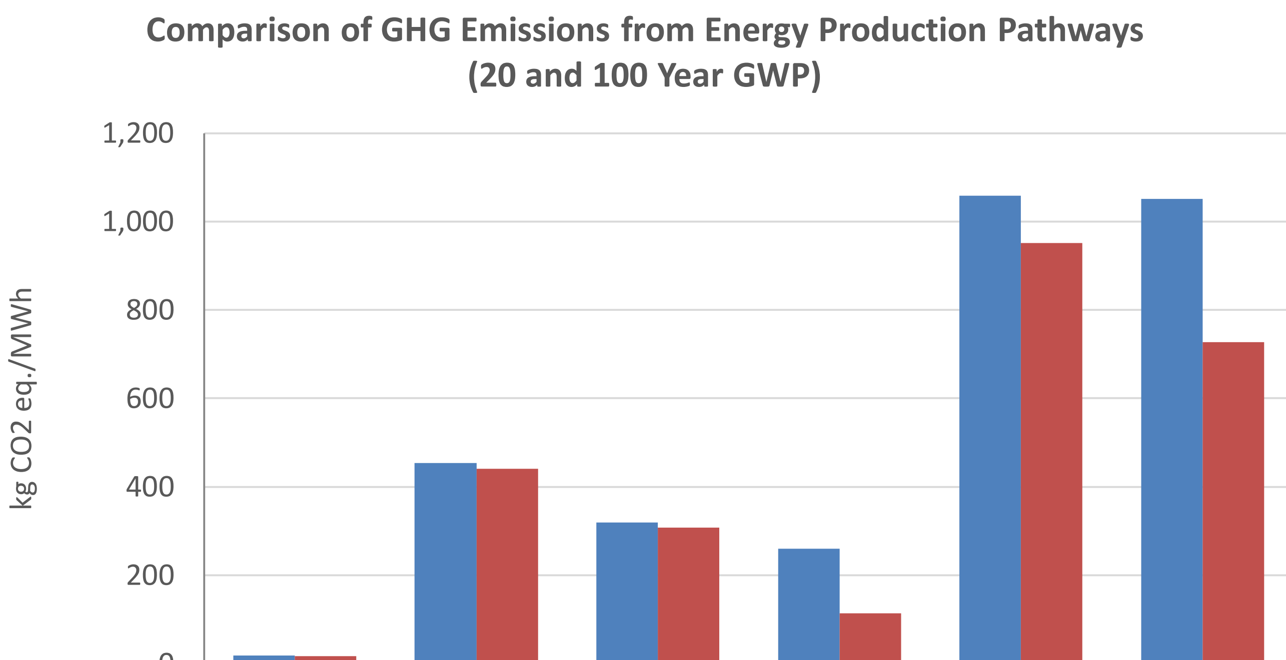
Results in kg of CO_2e/MWh of energy delivered for both the 20 and 100 year GWPs are presented in Figure E.1. Certain pathways (biogas, biomass gasification, waste to energy, small hydro, pumped storage and water diversion) have biogenic CO_2 emissions due to biomass combustion and/or decomposition. Since it is planned to utilize various biomass waste (e.g. dead trees, logging residues, and sawmill residues) as a source of biomass in biomass gasification and waste to energy pathways and municipal organic wastes in biogas pathway, one can argue in support of carbon neutrality of these pathways and exclude the biogenic CO_2 emissions from the total life cycle emissions. The biogenic CO_2 emissions in small hydro, pumped storage and water diversion scenarios originate from biomass decomposition after land inundation. Biomass decomposition is a slow process that lasts several years during which forest may be re-grown in other parts of the territories and recapture CO_2 from the atmosphere. Moreover, the inundated area represents a small fraction of the territories' forest reserves. Therefore, one may consider the emitted CO_2 to be carbon neutral.

The overall results indicate that the diesel and LNG pathways are the greatest GHG emitters with 1,059 and 1,051 kg CO_2e/MWh emitted for the 20 year time horizon, respectively, and 951 and 728 kg CO_2e/MWh emitted for the 100 year time horizon, respectively. The next highest emitters are waste to energy (MSW and MSW + biomass) and biogas pathways. The smallest GHG emitters for both time horizons are solar (approximately 40 kg CO_2e/MWh), followed by biomass gasification, pumped storage, small hydro, water diversion, battery storage, wind, and geothermal (all with less than 18 kg CO_2e/MWh). The 170 km of new transmission line produces just over 0.17 kg CO_2e/MWh for the 20 year and 0.16 CO_2e/MWh for the 100 year time horizon.

Wind, solar, geothermal, battery storage, transmission line, biomass gasification, and waste to energy produce emissions that are almost the same for both the 20 and 100 year time horizons. However, the most notable differences come from the analysis of biogas, diesel, liquefied natural gas (LNG), and hydro projects. These energy resource options emit significant amounts of methane; therefore, their overall GHG emissions vary between the 20 year and 100 year time horizons: (260 kg CO_2e/MWh versus 114 kg CO_2e/MWh for biogas, respectively; 1,059 kg CO_2e/MWh versus 951 kg CO_2e/MWh for diesel, respectively; and 1,051 kg CO_2e/MWh versus 728 kg CO_2e/MWh for LNG, respectively). Methane emissions in biogas pathway originate mainly from anaerobic digestion and waste storage processes, while in the diesel pathway they originate from crude oil extraction. Methane emissions in hydro energy pathways come from biomass decomposition after land inundation.

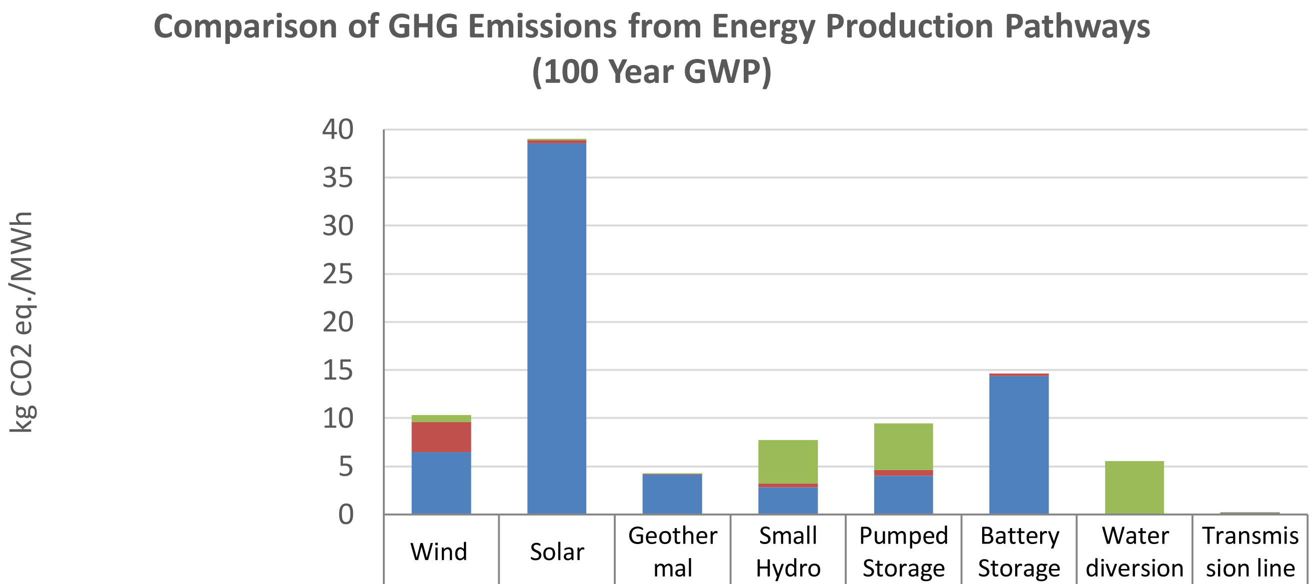


	Wind	Solar	Geothermal	Small Hydro	Pumped Storage	Battery Storage	Water diversion	Transmission line
20 year GWP	10.74	43.24	4.62	15.27	17.73	16.15	14.98	0.17
100 year GWP	10.30	38.99	4.22	7.70	9.47	14.66	5.55	0.16

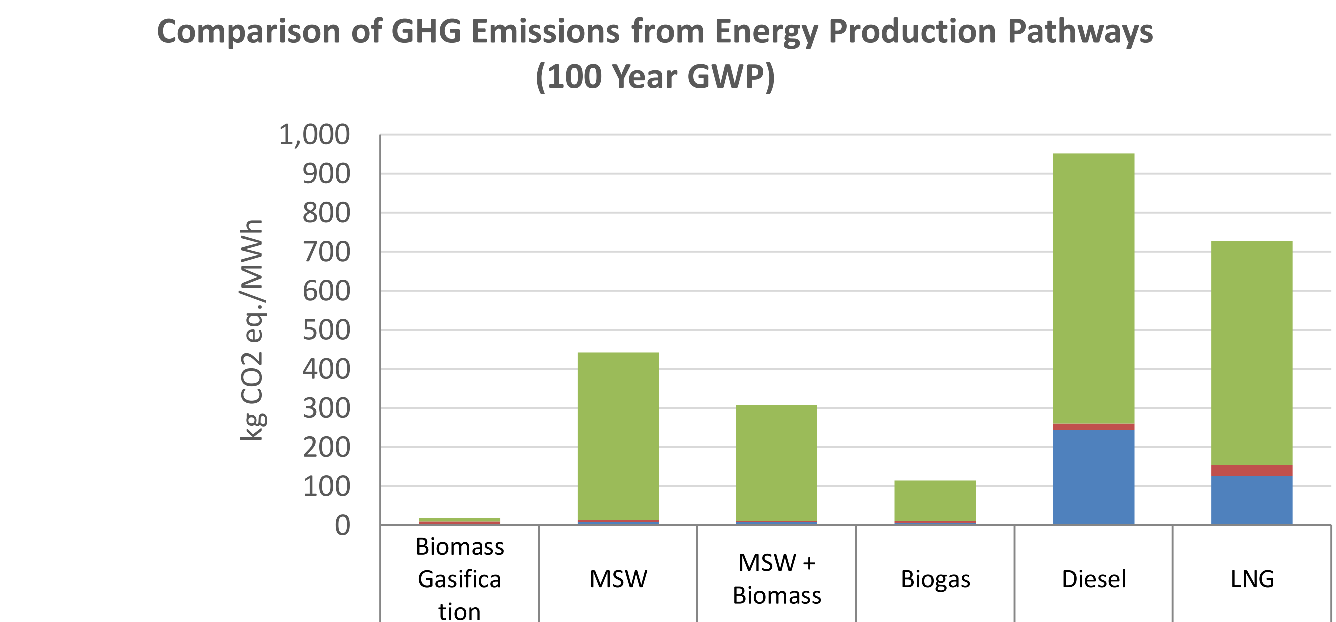


	Biomass Gasification	MSW	MSW + Biomass	Biogas	Diesel	LNG
20 year GWP	17.72	453.67	319.32	259.60	1058.91	1050.76
100 year GWP	17.20	441.40	307.06	113.77	951.11	727.68

Figure E.1. Comparison of GHG emissions from energy production pathways (biogenic CO_2 emissions excluded)



	Wind	Solar	Geothermal	Small Hydro	Pumped Storage	Battery Storage	Water diversion	Transmission line
Operation	0.71	0.10	0.01	4.48	4.88	0.00	5.43	0.0304
Transport of Materials & Fuel	3.09	0.33	0.10	0.41	0.58	0.28	0.00	0.0027
Materials and Fuel Acquisition, Production and Construction	6.49	38.56	4.11	2.81	4.01	14.38	0.12	0.1251



	Biomass Gasification	MSW	MSW + Biomass	Biogas	Diesel	LNG
Operation	8.51	429.37	295.35	103.30	690.43	574.23
Transport of Materials & Fuel	6.90	3.83	3.51	4.65	16.23	28.01
Materials and Fuel Acquisition, Production and Construction	1.79	8.20	8.20	5.83	244.45	125.45

Figure E.2. GHG Emissions from Energy Production Pathways - Contribution Analysis (biogenic CO_2 emissions excluded)

Analysis of the results includes a contribution analysis to determine the contribution each life cycle process has on the total GHG emissions and a sensitivity analysis whereby the effects on the final results by changing parameters are considered. The results of contribution analysis are shown in Figure E.2.

It is seen that operation of the energy generating plant is by far the most significant in terms of GHG emissions in biogas, waste to energy, diesel, and LNG pathways. For wind, solar, geothermal, transmission line and battery storage pathways, the majority of GHG emissions originate from upstream life cycle stages (e.g. materials extraction, components manufacturing). Diesel and LNG thermal plants also had notable GHG emissions contributions from fuel extraction and production life cycle stages.

The fixed and variable GHG emissions are shown in Table E.1. The fixed emissions are emissions associated with power plant and infrastructure construction and include raw materials acquisition, transportation, site preparation, and construction of the plant and transmission line. In the diesel, LNG, biomass gasification and waste to energy pathways, the emissions related to diesel, LNG, biomass and MSW transportation are considered variable emissions. The fixed emissions are expressed in tonnes CO_2e per facility, while variable emissions that originate from power plant operations are expressed in kg CO_2e/MWh.

Table E.1. Fixed and variable GHG emissions from energy production pathways (20 and 100 year GWP)

Energy Production Pathway	Fixed GHG emissions tonnes CO_2e		Variable GHG emissions kg CO_2e/MWh		Variable GHG emissions (biogenic CO_2 excluded) kg CO_2e/MWh	
	20 year GWP	100 year GWP	20 year GWP	100 year GWP	20 year GWP	100 year GWP
Biomass Gasification	679.1	651.7	769.3	768.9	14.53	14.14
Waste to energy: MSW	7,775	7,496	699.8	687.9	444.4	432.5
Waste to energy: MSW + biomass	7,775	7,496	666.0	654.1	310.1	298.2
Biogas	420.9	404.1	1151.2	1005.8	249.1	103.7
Geothermal	6,647	6,077	0.0230	0.0145	0.0230	0.0145
Wind	3,641	3,499	0.7379	0.7108	0.7379	0.7108
Solar	6,726	6,067	0.1284	0.0988	0.1284	0.0988
Pumped storage	16,294	16,098	18.77	10.56	13.09	4.88
Small hydro	6,704	6,630	17.31	9.77	12.02	4.48
Battery storage	904.5	820.9	0.00	0.00	0.00	0.00
Thermal - Diesel	675.2	649.1	1058.48	950.70	1058.48	950.70
Thermal - LNG	1,065	1,023	1050.09	727.04	1050.09	727.04
New transmission line (170km)	29,498	27,284	0.0324	0.0304	0.0324	0.0304
Water diversion project	237.8	223.2	21.30	11.99	14.86	5.43

The sensitivity analysis reveals that the choice of the technology and location of the manufacturing facilities (e.g. in North America versus oversees) can significantly impact the total life cycle emissions in the case of renewable energy sources where upstream life cycle stages are the largest contributors to the total life cycle GHG emissions.

The technology pathways that can potentially support other energy generation options such as small hydro are geothermal, as well as wind and solar coupled with battery storage. Hydro options, in turn, make it feasible to utilize other renewable sources. Pumped storage offers operational flexibility, since it can immediately respond to fluctuations in the demand for electricity. The flexibility and storage capacity of hydro options make them efficient and economical in supporting the use of intermittent sources of renewable energy, such as solar and wind, especially if these energy options are not coupled with battery storage. The waste to energy option has a potential to displace some fossil fuel-based sources, such as diesel and LNG, especially if the produced heat is utilized to make the technology economically viable. However, the waste to energy pathway produces a significant amount of fossil GHG emissions due to MSW combustion.

In summary, this LCA reveals the environmental impacts related to climate change for various energy options for renewable and non-renewable resources which can be used for enhanced decision making and improved strategies regarding long term energy planning for the Yukon Territory.

2 INTRODUCTION

Yukon Energy Corporation is committed to providing long-term, sustainable and reliable energy options for its customers. As part of the long term resource planning process (Resource Plan 2016-2035), Yukon Energy is in the process of evaluating different resource options for energy production. The goal of this study is to estimate greenhouse gas emissions (GHG) from the life cycle of different energy generation options. At the conclusion of this study, a detailed energy sources assessment of the overall GHG emissions associated with each energy source, including fossil fuels and several renewable energy production pathways, are presented. A final analysis of the contributions to the Global Warming Potential (GWP) from each resource option over a 20 year and 100 year timeframe is given. This will allow Yukon Energy to employ best management practices and make informed decisions in planning for future energy developments.

The study follows the current state-of-the-science practices with regard to LCA and is based on ISO 14040 principles and guidelines. Specifically, ISO 14040 and 14044 (2006) standards are applied to determine the key GHG contributors for each life cycle stage of the energy production technologies. Table 1 represents the energy resources pathways that are compared in this study. The studied projects are used as proxy for potential similar projects that may be implemented by Yukon Energy.

Table 1. Energy Resources Pathways

#	Resource option and location	Installed capacity	Annual energy (net)	Impacted area & Transmission line
1	Biomass gasification (Combined Heat and Power, CHP) Haines Junction	Gross power 0.5MW_e Net power 0.369 MW_e, 1,150 kW_{th}	2,585 MWh_e/yr 8,059 MWh_{th}/yr	Brownfield
2	Waste to Energy Municipal Solid Waste (MSW) with biomass conventional combustion (CHP) Whitehorse landfill	1.6MW_e (Scenario 1: 23,750 tonnes MSW/year Scenario 2: 16,100 tonnes MSW per year and 7,650 tonnes biomass per year)	9,975 MWh_e/yr 23,700 MWh_{th}/yr	Brownfield
3	Biogas Whitehorse landfill	185kW (second 100kW unit added in 2020)	885.9 MWh_e/yr	Brownfield
4	Geothermal McArthur Springs	7MW_e gross or 5.5MW_e net (3.86 MW_e taking into account the losses and decrease in production of 3% per year)	48.2 GWh_e/yr	Greenfield 42 km x 30 m of 138kV line
5	Wind Mount Sumanik	6MW_e	14.558 GWh_e/yr	Greenfield (impact area 100 ha) 7.6 km x 30 m of 138kV line
6	Solar Whitehorse Copper	5MW_e	5.2 GWh_e/yr	Brownfield
7	Pumped storage Moon Lake	20.2MW_e	54 GWh_e/yr	Greenfield Inundation area 352.4 ha

#	Resource option and location	Installed capacity	Annual energy (net)	Impacted area & Transmission line
				2.6 km x 30 m of 138kV line
8	Small hydro Drury Creek	8.1MW$_e$	31.7 GWh$_e$/yr	Greenfield Inundation area 190 ha 0.5 km x 30 m of 138kV line
9	Energy storage – lithium ion batteries Takhini Substation	8MW$_e$	2.8 GWh$_e$/yr 5hr discharge time	Greenfield/Brownfield 0.42 ha cleared area footprint
10	Thermal-diesel Takhini Substation	5MW$_e$	39.42 GWh$_e$/yr	Greenfield/Brownfield 4.5-5.5 ha of cleared area footprint
11	Thermal-LNG Takhini Substation	5MW$_e$,	39.42 GWh$_e$/yr	Greenfield/Brownfield 6.5 ha of cleared area footprint
12	New transmission line Whitehorse to Skagway	443 MW reliable transfer capacity	N/A	Greenfield/ Brownfield 170 km of 230kv line and 68 km of an existing 34.5kv line (306 ha plus 102 ha of cleared area footprint)
13	Enhancement – Gladstone Water diversion	Would utilize existing hydro unit capacity	29.7 GWh$_e$/yr	Partial greenfield Inundation area 220 ha

The following issues are examined in this study:

- The amount of the greenhouse gas emissions originating from different energy production technologies that could potentially be implemented in the Yukon,
- Contribution of each life cycle stage to the environmental impact through the determination of an environmental "hot spot" (i.e. any life cycle stage with the highest GHG emissions) in the life cycle of each technology, and
- The technology pathways that either support other energy generation options (e.g. hydro) and/or have the potential to displace another energy source (e.g. fossil fuel-based sources, such as diesel fuel).

The report consists of the following parts:

Chapter 3 – Goal and Scope Definition;

Chapter 4 – Greenhouse Gas Assessment results;

Chapter 5 – Conclusions and Recommendations.

3 STUDY GOAL AND SCOPE

This section of the report provides a general description of the energy systems under study, definition of the system boundaries, and the functional unit. Data quality, assumptions, limitations and GHG assessment methodology are also discussed.

3.1 OBJECTIVES AND INTENDED APPLICATION

The project has the following objectives:

- Using the "cradle-to-grave" approach, develop greenhouse gas emission inventories associated with different energy production pathways in the Yukon Territory,
- Inform decision-makers of the overall contribution of the different technology pathways to the Global Warming impact,
- Rank the energy generation technologies based on their greenhouse gas emissions,
- Provide comparative study results with recommendations on which technology pathways support other energy generation options (e.g. hydro) and which ones have a potential to displace another energy source (e.g. fossil fuel-based sources, such as diesel fuel), and
- Provide input into the evaluation of energy resource options against technical, financial, social and environmental attributes.

The results of this study are intended for the internal use by Yukon Energy to assist with the long term resource planning process (Resource Plan 2016-2035). Results of the LCA study may be made public by Yukon Energy.

3.2 SYSTEMS FUNCTION AND FUNCTIONAL UNIT

The main function of the system under study is to produce energy. In order to compare the environmental footprints of the various energy production scenarios considered in this study, a common functional unit is selected – a unit that provides a reference to which the input and output data are normalized. The functional unit best suited for this study is **MWh of energy delivered to the grid**.

The GHG emissions per MWh of energy delivered to the grid are obtained by dividing the life cycle inventory data (e.g. plant construction data) by total net energy output of the power plant during its lifetime.

The lithium-ion battery storage (scenario #9) LCA is limited to the manufacturing of the battery and site preparation, including materials extraction, production of materials, battery assembly, transportation, and land clearing. The results are presented per MWh of energy stored.

Analysis of the transmission line (scenario #12) is limited to the construction of the line itself, including materials, transportation, and change in land use. The LCA does not consider the potential proximity of the transmission line to the point of energy production or the type of energy source being used. These results are given per MWh-km such that future environmental assessments may include the appropriate energy resource option at that time (transmission line results per MWh-km are presented in section 4.2.12). The results per MWh-km are then used to estimate the environmental impact of 170km of new transmission line.

3.3 DESCRIPTION OF ENERGY RESOURCE PATHWAYS AND SYSTEM BOUNDARIES

This section provides a description of the systems under study and their system boundaries. The system boundary defines the unit processes to be included in the system.

The "cradle-to-grave" approach is applied, which includes the life cycle activities from resource extraction and production of materials through to the generation of electrical energy at the generating station, as well as all transportation stages (Figure 1). Downstream stages (decommissioning, recycling and site remediation) are excluded from the analysis. Exclusion of these activities is a common practice where it is expected that these processes contribute to less than 1% of total impact from the energy resource life cycle[1].

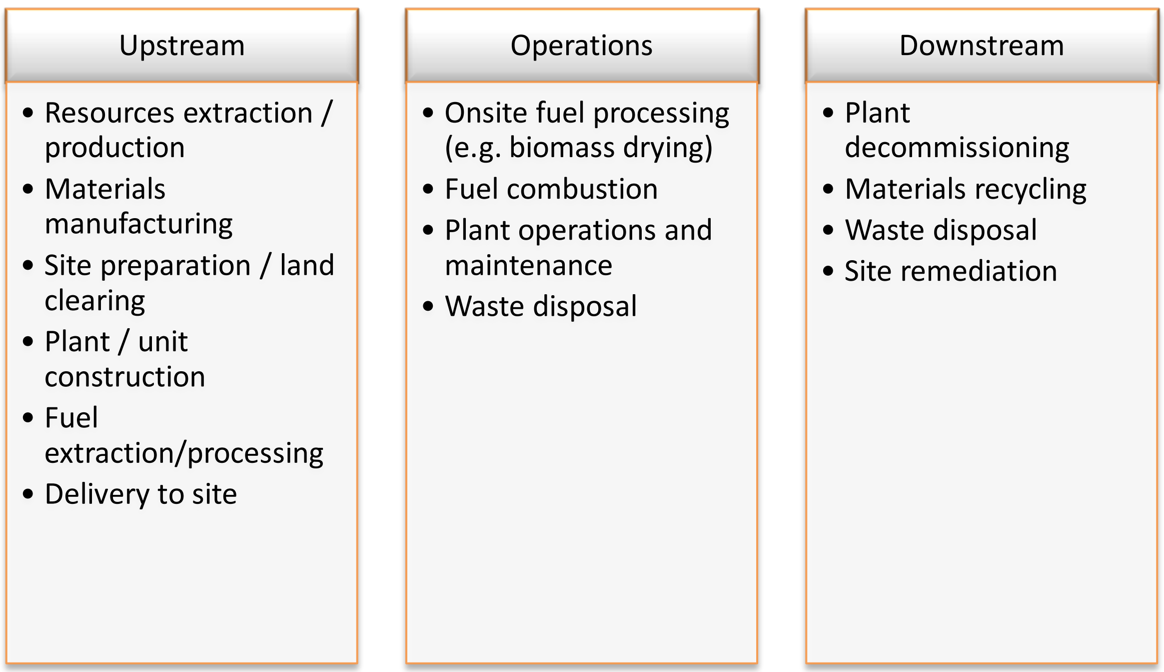


Figure 1. Generalized Life Cycle Stages of an Energy Generation Technology

Most of the processes included in the system boundaries occur in Yukon or Western Canada. However, some unit processes may occur in other Canadian provinces, the US and worldwide. Life Cycle Inventory supporting information that includes a description of all data sources used in the analysis is presented in Appendix A.

[1] Baumann, H. and Tillman, A. (2004) The Hitch Hiker's Guide to LCA. Studentlitteratur AB, Lund, Sweden.

3.3.1 SYSTEM DESCRIPTION: BIOMASS GASIFICATION PLANT

The biomass gasification combined heat and power plant (CHP) with a 0.5 MW_e and 1,150 kW_{th} capacity was chosen to be located in the centre of Haines Junction[2]. The potential project includes two 250 kW_e biomass gasification units that will be supplied by Community Power Corporation (CPC). The plant is expected to produce 2,585 MWh_e net and 8,059 MWh_{th} energy annually. The biomass supply would be primarily sawmill and forest harvesting residues, as well as dead trees from the spruce beetle infestation.

The system boundary is presented in Figure 2 with a description following in Table 2.

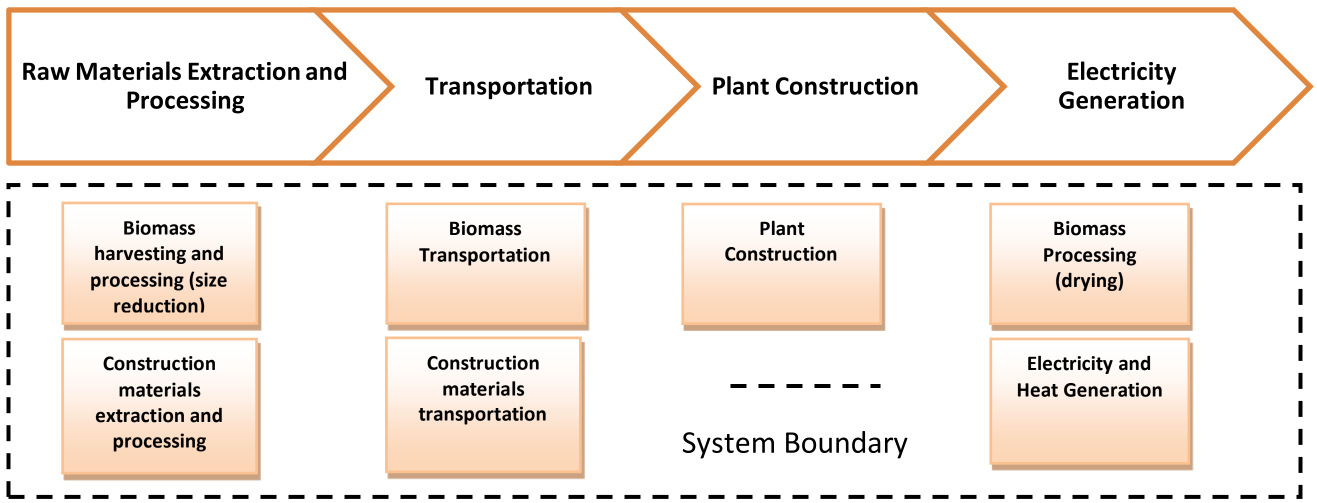


Figure 2. System Boundary of Biomass Gasification Electricity Generation

Table 2. Description of Biomass Gasification Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	<u>Biomass harvesting and processing</u> Sawmill and forest harvesting residues, dead trees from the spruce beetle infestation. Required feedstock: • Oven dry tonnes – 3,000 tonnes/year • With 15% moisture content – 3,789 tonnes/year • Forest harvesting residues: 1,603 tonnes/year • Sawmill residues – 2,190 tonnes/year Biomass processing includes size reduction in the field. <u>Construction materials extraction and processing</u> Raw materials extraction and production of construction materials (steel, aluminum, concrete, etc.)
Transportation	<u>Biomass transportation</u> Sawmill residues are transported 50km by truck, 9t payload Forest harvesting residues - 70km by truck, 9t payload

[2] Stantec. (2013). Front End Engineering Design (FEED) Study. Yukon Bioenergy Demonstration project in Haines Junction, Yukon. Final FEED Report. June 7, 2013.

Life Cycle Activity	Description
	Construction materials transportation Transportation by truck, 22t payload (assumed average distance of 2,400 km)
Plant Construction	Location: Whitehorse landfill Brownfield – no site preparation included
Electricity Generation	Biomass processing Biomass processing includes drying to 15% moisture content Electricity generation 1-Stage Downdraft Gasifier (BioMax), 2xIC Engines, 2 x 250 kW_e Annual energy production (net): • 2,585 MWh_e -682 kWh_e/tonne of biomass • 8,059 MWh_{th} – 2,127 kWh_{th}/tonne of biomass Waste disposal Disposal of waste (e.g. ash) is excluded from analysis
End of life	Lifetime: 20 years

In the CHP plant, heat and electricity are generated simultaneously from the same input of fuel. This increases the plant efficiency and reduces GHG emissions per MWh of energy produced. Although, the produced electricity is more valuable than heat, no allocation of GHG emissions to electricity and heat separately is performed as the goal of the project is to assess total GHG emissions produced by the CHP plant.

3.3.2 System Description: Municipal Solid Waste (MSW) Waste to Energy Plant

For this analysis, a municipal solid waste (MSW) conventional combustion waste to energy (WTE) facility with nominal design capacity of 25,000 tonnes per year has been chosen for evaluation. The actual annual throughput is 95% of the total design capacity or 23,750 tonnes year. In order to maximize the facility efficiency, a CHP plant is selected. The CHP plant will generate up to 4MW of heat and 1.6 MW of electricity. Approximately 16,100 tonnes of MSW and 7,650 tonnes of wood biomass per year until 2035 would be required[3].

The operating life of the WTE facility is assumed to be 25 years (to year 2040). It is likely that the WTE facility will operate longer (if there is waste still available), and the landfill will continue to accept waste/ash past 2040.

Two scenarios are modelled:

1. 2015 feedstock: MSW (16,100 tonnes) + biomass (7,650 tonnes) conventional combustion, and
2. 2035 feedstock: MSW (23,750 tonnes) conventional combustion.

The system boundary is presented in Figure 3 with a description following in Table 3.

Similar to the biomass gasification pathway, no allocation of GHG emissions to electricity and heat is performed.

[3] Morrison Hershfield. (2012). Waste to Energy Updated design Basis and Business Case Analysis. April 24, 2012.

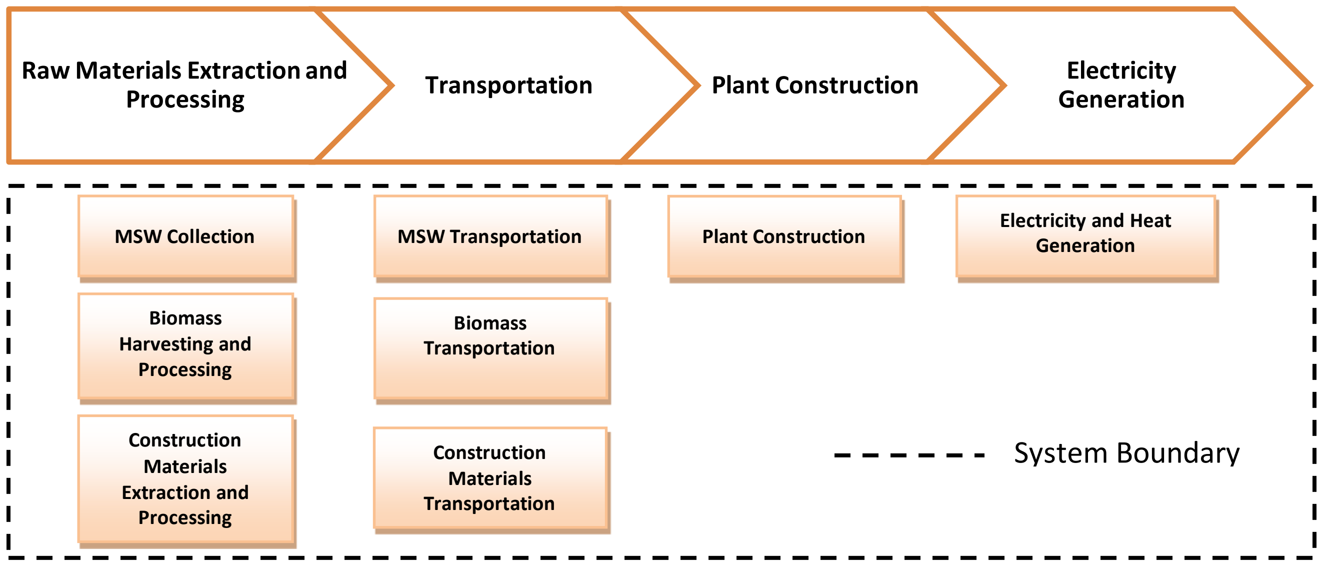


Figure 3. System Boundary of MSW Waste to Energy Electricity Generation

Table 3. Description of MSW Waste to Energy Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	<u>MSW Collection</u> MSW generated within Whitehorse and surrounding communities, used tires, waste oil and abattoir waste <u>Biomass Harvesting and Processing (in Scenario 1 only)</u> Biomass as a supplement fuel during winter (7,650 tonnes/year) Sources: Forest harvesting residues and sawmill residues Biomass processing includes size reduction in the field <u>Construction materials extraction and processing</u> Raw materials extraction and production of construction materials (steel, aluminum, concrete, etc.)
Transportation	<u>MSW transportation</u> 8-9 truckloads of waste per day (truck payload 9t); approximate distance 16 km <u>Biomass transportation</u> Sawmill residues are transported 50km by truck, 9t payload Forest harvesting residues - 70km by truck, 9t payload <u>Construction materials transportation</u> Transportation by truck, 22t payload (assumed average distance of 2,400 km)
Plant Construction	Location: Whitehorse landfill Brownfield (min 2 ha)– no site preparation included
Electricity Generation	Technology (EcoWaste Solutions): Controlled-air two stage conventional combustion WTE facility capacity: 25,000 tonnes/year Annual throughput: 23,750 tonnes/year (95% of total design capacity) Weighted HHV (Higher Heating Value): 14.45 GJ/tonne MSW

Life Cycle Activity	Description
	Electricity production (net): 9,975 MWh_e/year Heat production (net): 23,700 MWh_{th}/year Total electricity produced (net): • 420 kWh_e per tonne of MSW or MSW + biomass (10% electrical efficiency) • 998 kWh_{th} per tonne of MSW or MSW + biomass Waste disposal Disposal of waste (e.g. ash) is excluded from analysis
End of life	Lifetime: 25 years

3.3.3 System Description: Biogas Plant

The site identified for the biogas plant is the Whitehorse Municipal Landfill near the composting site. A dry (high solids) garage style anaerobic digester will be used to treat Whitehorse residential and commercial organic waste and produce electricity and heat. The produced heat will be used on-site to heat the digester to 35°C. Some of the produced electricity will be used internally to operate the digester. Initially, one 100 kW_e unit will be installed and the second 100 kW_e unit will be added in 5 years (2020)[4].

The system boundary is presented in Figure 4 with a description following in Table 4.

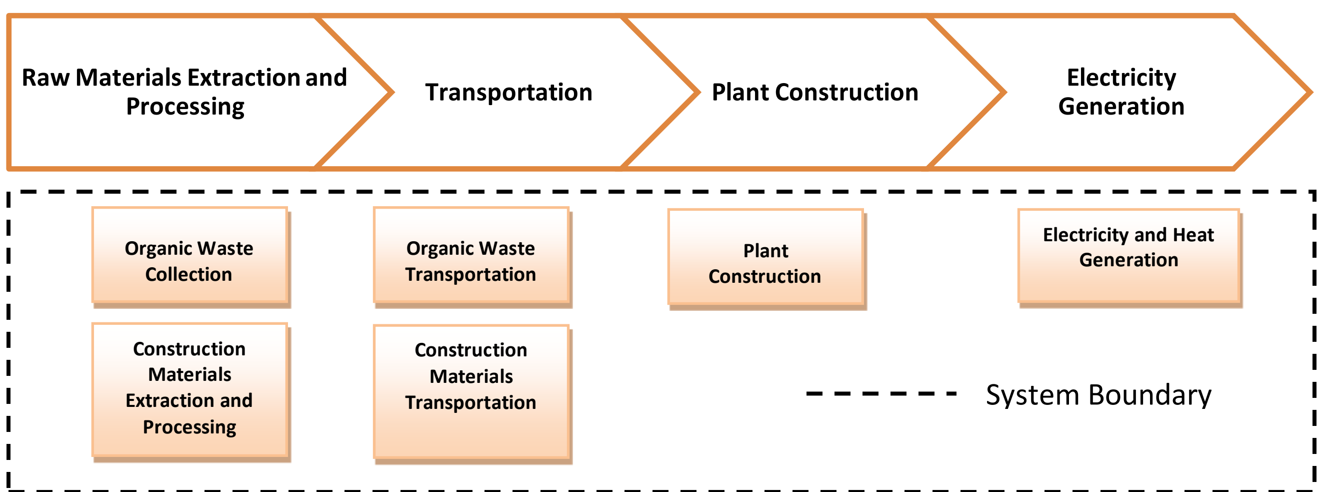


Figure 4. System Boundary of Biogas Electricity Generation

[4] WSP. (2016). Biogas Plant in Whitehorse. Feasibility Study, Whitehorse, Yukon. January 2016.

Table 4. Description of Biogas Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	Organic waste collection Food waste, green yard waste, dry yard waste Construction materials extraction and processing Raw materials extraction and production of construction materials (steel, aluminum, concrete, etc.)
Transportation	Organic waste transportation Approximate distance: 16 km, truck payload 9 tonnes Construction materials transportation Transportation by truck, 22t payload (assumed average distance of 2,400 km)
Plant Construction	Location: Whitehorse landfill Brownfield – no site preparation included
Electricity Generation	Dry garage style anaerobic digester CHP unit Capacity: 185 kW_e (takes into account addition of a second 100 kW unit in 2020) Electric efficiency: 35% Thermal efficiency: 40% (heat production 28.7%, internal heat use 11.3%) Energy loss: 25% Electric output: 56kW_e (33kW_e in April and 100 kW_e in August) Thermal output: 64 kW_{th} (37 kW_{th} in April and 114 kW_{th} in August) Total electricity produced (net): 885.9 MWh_e/yr
End of life	Lifetime: 20 years

3.3.4 System Description: Geothermal Power Plant

McArthur Springs, in Northeast Yukon, was chosen as a geothermal power plant location. The site is located approximately 42 km East of Highway #2 southeast of Stewart Crossing, and approximately 75 km south of Mayo. The net capacity of the plant is 5.5MW[5]. The plant is estimated to produce water at 160°C using a binary cycle Organic Rankine Cycle (ORC) system.

The capacity of a geothermal reservoir decreases over time; thus, a constant decrease of 3% per year has been assumed. The net electricity output of the plant is 48.2 GWh_e/yr taking into account the losses and decrease in production output of 3% per year.

The system boundary is presented in Figure 5 with a description following in Table 5.

[5] KGS. (2016). Geothermal Review and Site Inventory. Draft Report – Rev. A. KGS Group. May 2016.

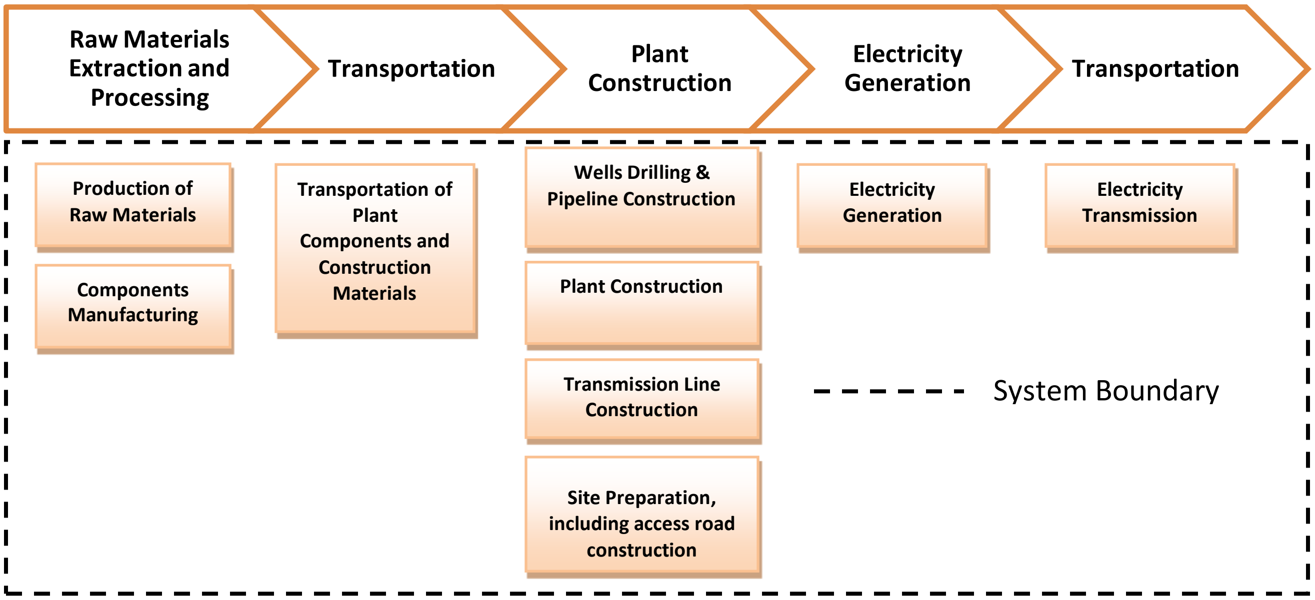


Figure 5. System Boundary of Geothermal Electricity Generation

Table 5. Description of Geothermal Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	Raw materials for plant construction are extracted and processed. Construction materials (aggregates) are assumed to be sourced locally (within 15 km of the site).
Components Manufacturing and Transportation	Power generation and transmission line components are manufactured and transported 2,400km by truck, 22t payload.
Plant Construction	Greenfield site 2 production and 1 injection wells are drilled approximately 1 km apart. Wells are equipped with line-shaft pumps, located in a small building. Pipeline construction to connect the wells to the power plant, access road, wells, and transmission line construction are included in the assessment. One exploration well drilling is included.
Electricity Generation	Binary Organic Rankine Cycle (ORC) geothermal plant with 70% efficiency. Net electricity output: 48.2 GWh_e/yr
Electricity transmission	Produced electricity is transported from MacArthur through 42km of 138kV transmission line.
End of life	Lifetime: 30 years

3.3.5 System Description: Wind Plant

The site chosen for proposed wind power plant is Mount Sumanik in southern Yukon. Mount Sumanik, a large, broad hill complex equipped with Lidar for ongoing wind resource assessment study, is located immediately west of Whitehorse[6]. A three-turbine, 6 MW wind farm with 27% capacity factor is studied.

The system boundary is presented in Figure 6 with a description following in Table 6.

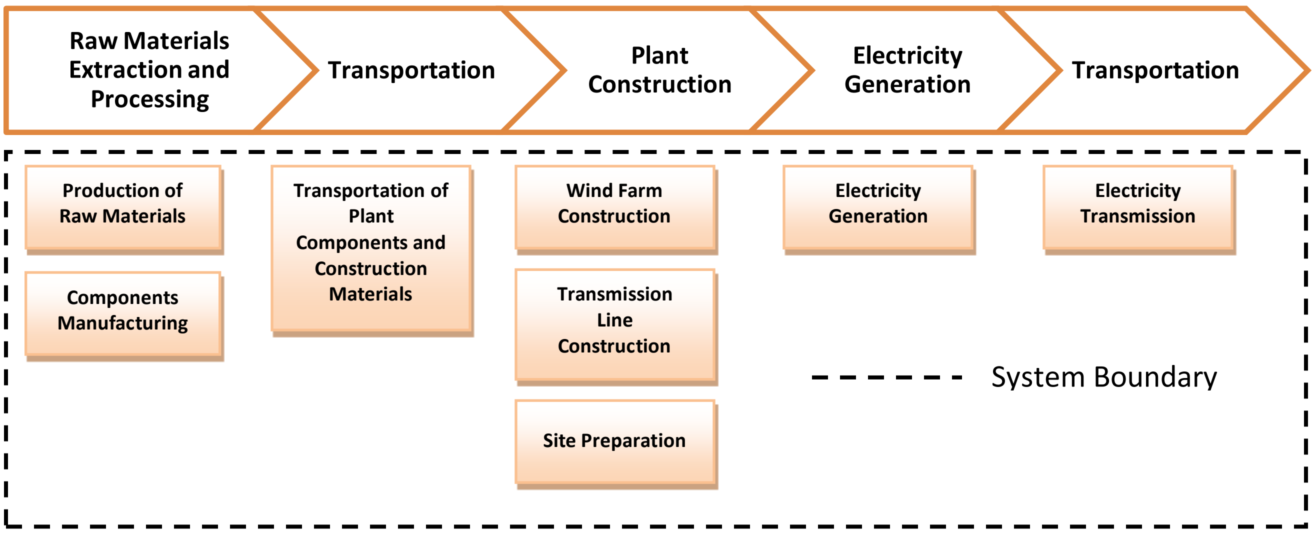


Figure 6. System Boundary of Wind Electricity Generation

Table 6. Description of Wind Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	Raw materials for plant construction (i.e. concrete, steel, etc.) are extracted and processed.
Components Manufacturing and Transportation	It is assumed that wind turbines are manufactured in Denmark. Turbine transport by sea – 5,578 km (Denmark – Montreal) Turbine transport by road – 5,560 km (Montreal – Whitehorse) Transmission line components are transported 2,400km by truck, 22t payload.
Plant Construction	Greenfield site This stage includes construction and installation of the plant at Mount Sumanik and construction of 7.6km transmission line. Total road, transmission line, and wind farm area is 100 ha.
Electricity Generation	Three Vesta V-90 2MW turbines with 27% capacity factor or similar turbines. Gross annual energy production: 16.45 GWh_e/yr; Net (88.5% of theoretical gross output): 14.558 GWh_e/yr
Electricity transmission	Produced electricity is transported to Whitehorse through 7.6km transmission line
End of life	Plant lifetime: 25 years

[6] CBER Ltd., ENVINT Consulting, V3 Energy, LLC. (2016). Yukon Wind Site Inventory. Draft Report. May 16, 2016.

3.3.6 System Description: Solar Plant

A 5 MW photovoltaic solar farm is chosen to be located at the old Whitehorse Copper Mine site near Whitehorse[7]. It is a brownfield site and has an established road access.

The system boundary is presented in Figure 7 with a description following in Table 7.

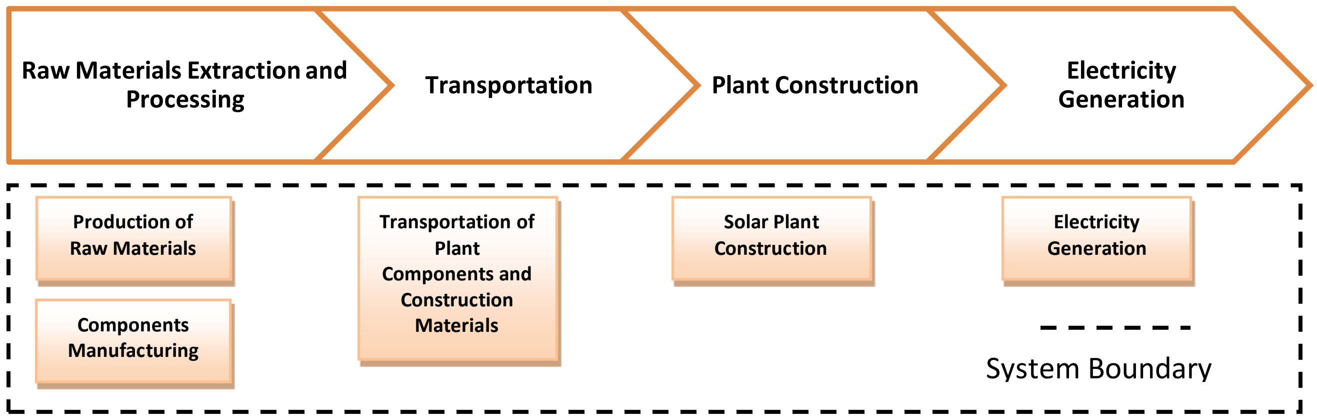


Figure 7. System Boundary of Solar Electricity Generation

Table 7. Description of Solar Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	Raw materials for plant construction (i.e. concrete, steel, etc.) are extracted and processed.
Components Manufacturing and Transportation	Solar PV components (e.g. module, racking, inverter) are manufactured in Japan and transported to Vancouver by sea (7,664 km) and then from Vancouver to Whitehorse 2,400km by truck, 22t payload.
Plant Construction	Brownfield, no site preparation or access road construction is included. Solar PV system is assembled in Whitehorse Copper.
Electricity Generation	Panasonic HIT 330W n-type silicon modules produce electricity at 20% efficiency. Net electricity production: 5.2 GWh_e/yr
End of life	Lifetime: 30 years

3.3.7 System Description: Pumped Storage

The Tutshi-Moon pumped storage project with a capacity of 20.2MW and 54 GWh energy storage is located between Tutshi and Moon Lakes in BC (110 km from Whitehorse and 18 km south of the BC-Yukon border) [8]. This is a greenfield site with the proposed inundation area of 352.4 ha. The site is 2.6 km away from the transmission line.

The system boundary is presented in Figure 8 with a description following in Table 8.

[7] Solvest Inc. Solar Site Inventory. Draft report for RFP #2015-058.

[8] Knight Piésold Ltd. (2016). Based on data from Yukon Energy Corporation Pumped-Storage Assessment, Preliminary Assessment. April 14, 2016.

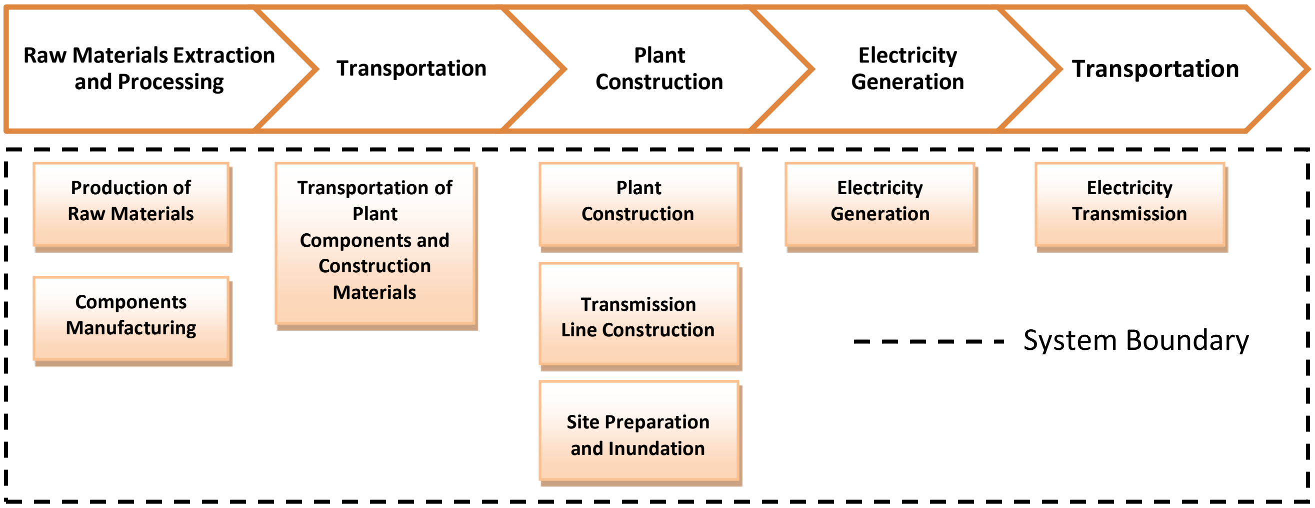


Figure 8. System Boundary of Pumped Storage Electricity Generation

Table 8. Description of Pumped Storage Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	Raw materials for plant construction (i.e. concrete, steel, etc.) are extracted and processed.
Components Manufacturing and Transportation	Plant components are manufactured and transported 2,400km by truck. Equipment manufacturing (motor-generator, transformer, pump-turbine, pressure pipes, etc.) is included in the system boundaries.
Plant Construction	This stage includes construction and installation of the plant and transmission line construction. The main components of the plant are: diversion, dam, spillway, reservoir, intake penstock, substation, and powerhouse with equipment[9]. The concrete dam construction is modelled. The site specifications are as follows: • Upper Reservoir Area (ha): 610 • Lower Reservoir Area (ha): 5600 • Penstock Length (km): 5.8 • 2m wide and 300m long gated concrete spillway • Inundation area is 352.4 ha • Greenfield site
Electricity Generation	Power house (contains a turbine and generator unit, most likely a vertical axis Pelton turbine), located at Tutshi Lake. Net electricity production: 54 GWh/yr
Electricity Transmission	Once electricity is produced, it moves to 2.6 km transmission line (138 kV).
End of life	The lifetime of the plant is 65 years.

[9] Midgard Consulting Inc. (2015). Moon Lake – Pumped Storage, Conceptual Study Report. December 14, 2015.

3.3.8 System Description: Small Hydroelectricity Plant

The Drury Lake project is a small hydro with storage power station with an installed capacity of 8.1 MW[10]. The proposed station location is on Drury Creek between Drury Lake and Little Salmon Lake, in the Yukon River watershed. The site is approximately 170 km north of Whitehorse and is situated within 1 km of the Robert Campbell Highway and the existing Yukon Integrated Grid transmission line.

The system boundary is presented in Figure 9 with a description following in Table 9.

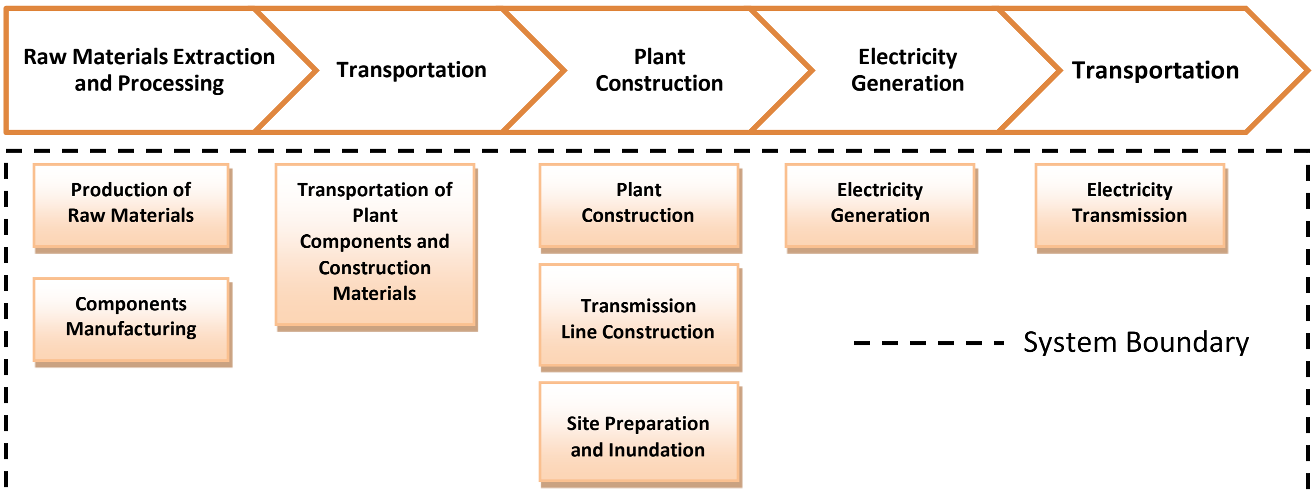


Figure 9. System Boundary of Pumped Storage Electricity Generation

Table 9. Description of Small Hydroelectricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	Raw materials for plant construction (i.e. concrete, steel, etc.) are extracted and processed.
Components Manufacturing and Transportation	Plant components are manufactured and transported 2,400km by truck. Equipment manufacturing is included in the system boundaries.
Plant Construction	This stage includes construction and installation of the plant and transmission line. Plant specification: • 5km of access roads. • Concrete Faced Rockfill Dam (CFRD) or earthfill control dam at the outlet of Drury Lake to provide 5m of storage (operating storage of 135 Mm^3). The concrete dam construction is modelled. The dam would be constructed with an Instream Flow Requirement (IFR) discharge system and a spillway to Drury Creek for flood water management. • Intake weir across Drury Creek, approximately 4 km downstream of the lake outlet. • 4.8 km penstock located on the south side of Drury Creek, comprising 3.6 km of low pressure pipe (LPP) and 1.2 km of high

[10] Knight Piésold Ltd. (2016). Based on data from Yukon Energy Corporation Small Hydroelectric Projects, Screening Assessment. April 22, 2016.

Life Cycle Activity	Description
	pressure pipe (HPP). • Powerhouse and substation at the edge of Drury Creek, upstream of the Robert Campbell Highway and the river mouth at Little Salmon Lake. • 0.5 km of 138 kV transmission line
Electricity Generation	Net electricity production: 31.7 GWh_e/yr
Electricity Transmission	Once electricity is produced, it moves to 0.5 km transmission line, to the existing grid (Yukon Integrated Grid).
End of life	The lifetime of the plant is 65 years.

3.3.9 System Description: Battery Storage

For this portion of the study, a lithium-ion battery was chosen for the analysis. The battery's capacity is 8 MW with 5 hours discharge time[11]. The energy storage system will be treated as a separate substation and the anticipated location is near the S164 Takhini 138 kV / 34.5 kV substation. The energy storage system will connect to the 34.5 kV system (not included in the current analysis). By connecting to the relatively low transmission line voltage of 34.5 kV, the need for a second step-up transformer is avoided.

The system boundary of the battery storage pathway is presented in Figure 10.

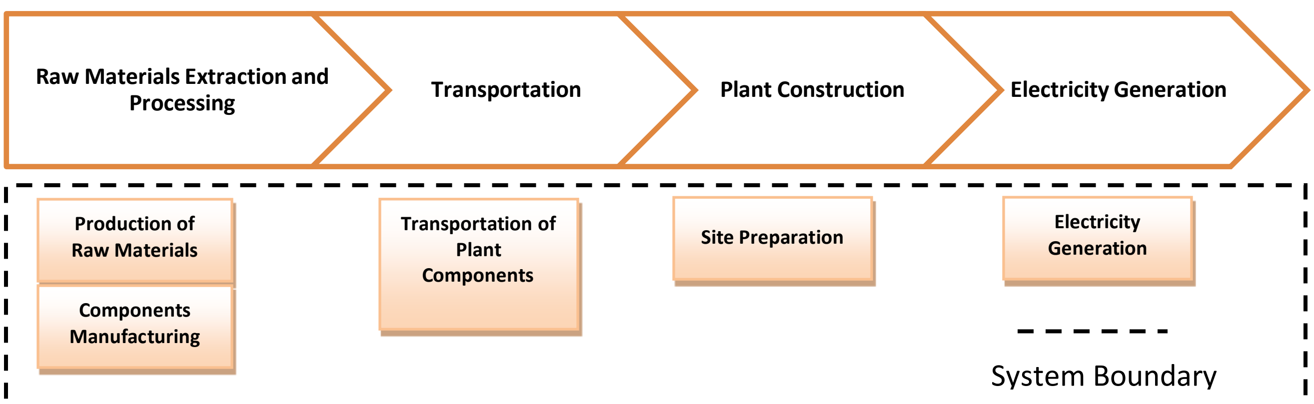


Figure 10. System Boundary of Battery Storage

Table 10. Description of Battery Storage by Life Cycle Stage

Life Cycle Activity	Description
Production of Raw Materials	Raw materials for battery manufacturing are extracted and processed.
Components Manufacturing and Transportation	Battery components are manufactured and transported to the plant location: California to Alaska by sea – 3,226 km Alaska to Whitehorse -1,133 km by truck, 22t payload

[11] TransGrid Solutions Inc. (2016). Evaluation of Energy Storage Technologies. April 18, 2016.

Life Cycle Activity	Description
Plant Construction	<u>Equipment</u> Two (2) PCS Modules packaged in two 40' trailers. Each module includes the following: • Two (2) 2 MW inverters with AC and DC circuit breakers; thermal management; control and protection • Two (2) 2000 kVA padmount transformers : 35 kV : 454 VAC • One (1) MUC (Multiple Unit Control) Greenfield/Brownfield The site preparation includes clearing of 4,200 m^2 (0.42 ha) area
Electricity Generation	Electricity is stored in the battery cell and released when needed. Annual energy storage: 2,780 MWh_e
End of life	Project lifetime: 20 years Battery lifetime: 10-15 years

3.3.10 System Description: Thermal Diesel Plant

The thermal diesel energy production pathway is based on previous LCA studies[12],[13]. The crude oil comes from Alaska North Slope and Alberta and is refined at Puget Sound refinery in Washington State, US. The crude oil is transported to the refinery via ocean freighter. The diesel fuel is transported from Puget Sound refinery to Skagway, Alaska via ocean freighter and from Skagway to Whitehorse via truck transport. A Caterpillar diesel engine (CAT Continuous 3300 generator) with electrical efficiency of 41.6% is used to generate electricity at the plant. The proposed diesel plant will be based at Takhini Substation outside of Whitehorse. The plant capacity is $5MW_e$ and annual net electricity production is 39.42 GWh/yr.

The system boundary is presented in Figure 11 with a description following in Table 11.

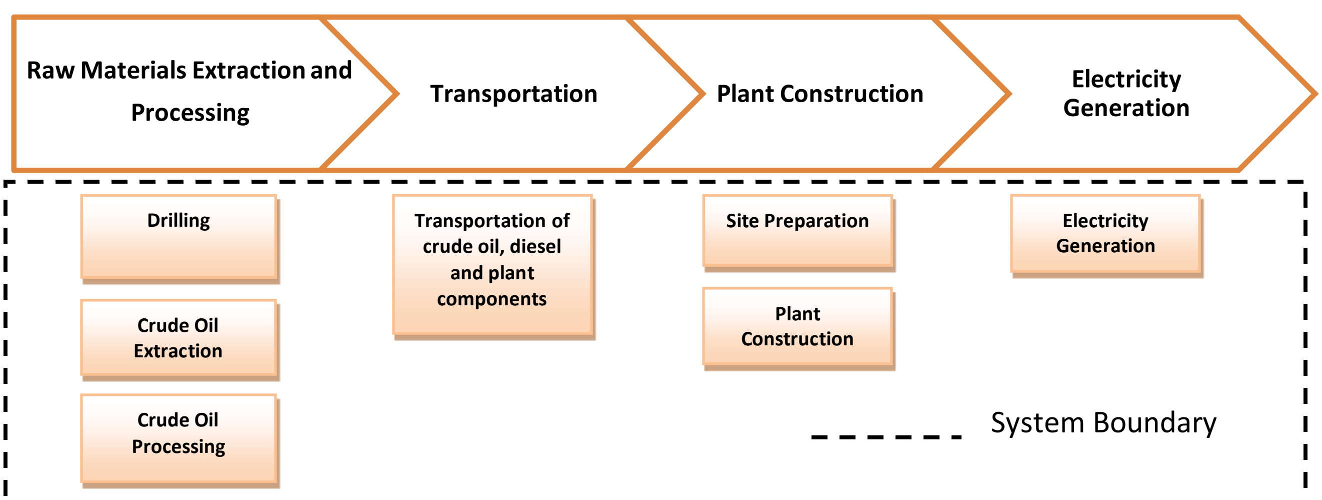


Figure 11. System Boundary of Diesel Electricity Generation

[12] Pembina. (2013). LNG for Yukon Energy Power Generation. A Life Cycle Emissions Inventory. The Pembina Institute. July 2013.

[13] (S&T)^2 Consultants Inc. (2014). Amended Lifecycle Analysis of Diesel and LNG Power Production. March 17, 2014.

Table 11. Description of Diesel Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Extraction of Raw Materials	Crude oil is extracted from Alaska's North Slope and Alberta and transported to Puget Sound refinery via ocean vessel.
Processing and Transportation	Crude oil is refined into diesel fuel and other refined petroleum products. Diesel fuel is transported from Puget Sound refinery to Skagway, AK via ocean barge and from Skagway to Whitehorse via truck transport.
Electricity Generation	Diesel is combusted for power in a CAT Continuous 3300 generator operating at 41.6% efficiency. Net electricity production: 39.42 GWh/yr
Plant Construction	Greenfield/Brownfield Includes 4.5-5.5 ha of land clearing.
End of life	Lifetime: 20 years

3.3.11 System Description: Thermal LNG Plant

Three LCA studies on thermal LNG pathway have been conducted in the period from 2013 to 2014. These are ICF Marbek, 2013[14], Pembina, 2013[12] and (S&T)[2] Consultants Inc., 2014[13]. An analysis of the studies with the focus on upstream emissions from LNG is given in Appendix A.11. The uncertainty of methane emissions estimates is discussed in section 3.4.1.

The LNG comes from the Fortis BC LNG facility at Tillbury Island in Delta, BC. Tillbury has been in operation since 1971 and can liquefy 120,000 cubic meters (4,500 GJ) of natural gas per day. The facility uses electricity to drive the liquefaction process. The energy requirement is 0.5 kWh/kg of LNG (0.039 joules of power per joule of LNG). The LNG is transported from Tillbury to Whitehorse via truck transport. The proposed thermal LNG plant will be based at Takhini Substation outside of Whitehorse. The plant capacity is 5MW$_e$ and annual net electricity production is 39.42 GWh/yr. The system boundary is presented in Figure 12 with a description following in Table 12.

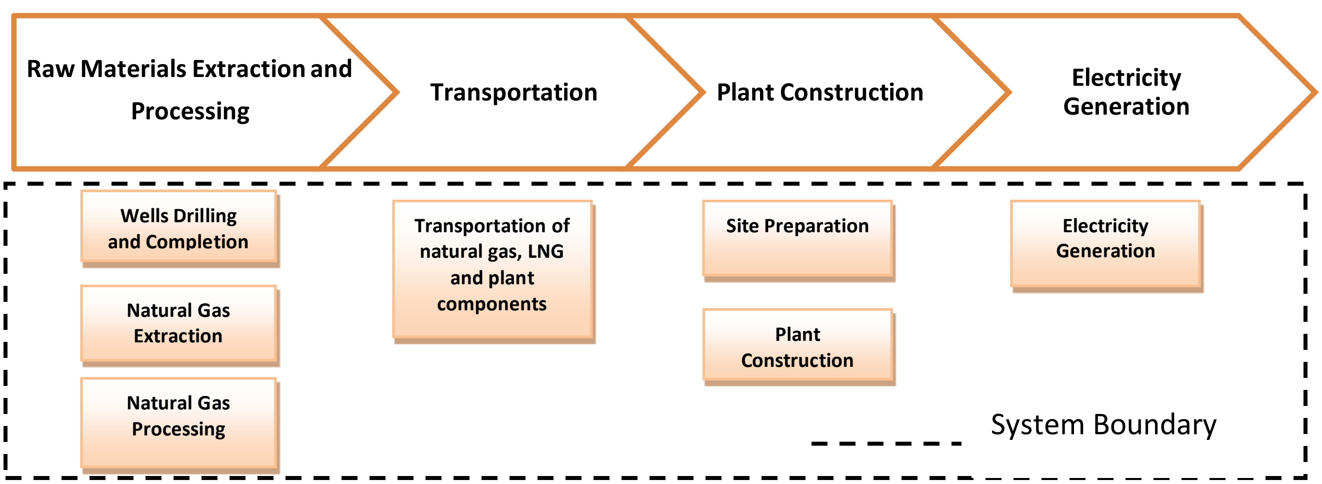


Figure 12. System Boundary of LNG Electricity Generation

[14] ICF Marbek (2013). Yukon Power Plant Fuel Life Cycle Analysis. Final Report. July 2, 2013.

Table 12. Description of Diesel Electricity Generation by Life Cycle Stage

Life Cycle Activity	Description
Extraction of Raw Materials	Natural gas comes from conventional gas fields predominantly in Northeast BC (some NW Alberta natural gas) and delivered to the Fortis BC Tillbury facility from Spectra at Huntington Gate by pipeline.
Processing and Transportation	LNG is treated to remove impurities and liquefied. LNG is transported 5,440 km round trip by truck.
Electricity Generation	LNG is vapourized and combusted to produce power in a Jenbacher generator operating at 46.3% efficiency (47% @ 90% load). Net electricity production: 39.42 GWh/yr
Plant Construction	Greenfield/Brownfield Includes 6.5 ha of land clearing
End of life	Lifetime: 20 years

3.3.12 System Description: New Transmission Line (Whitehorse-Skagway)

A new electric 230kV transmission line, 170 km in length, will be constructed from Whitehorse Generating Station to Skagway. The electricity will be generated at Whitehorse Rapids Generating Station (WRGS) and delivered to the Town of Skagway, Alaska or in the winter generated in Skagway and delivered to Whitehorse. From the WRGS, the corridor follows Highway 1 southeast for 17 km to Carcross Cutoff (the junction of Highways 1 and 2). From Carcross Cutoff, the corridor follows Highway 2 southward, through the town of Carcross for 77 km, to the BC-Yukon border. Once in BC, the corridor continues along Highway 2 for an additional 56 km to the BC-Alaska border. In Alaska, the corridor continues along the same highway (now named Highway 98) for an additional 21 km to Skagway, Alaska. Sixty-eight km of 15m wide 34.5 kV distribution line from Whitehorse to Carcross[15] is included in the analysis.

The full life cycle of Whitehorse-Skagway transmission line is considered. The system boundary is presented in Figure 13.

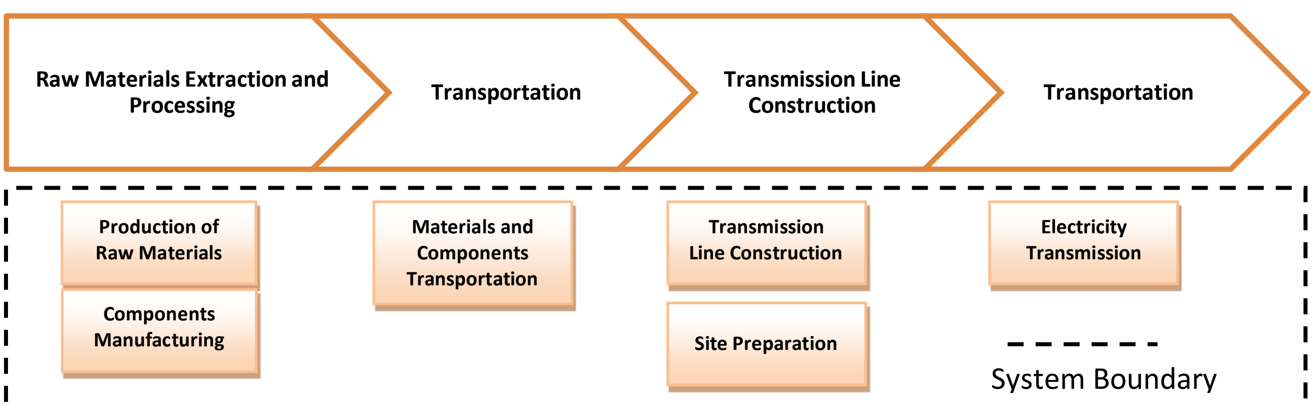


Figure 13. System Boundary of Whitehorse-Skagway Transmission Line

[15] Midgard Consulting Inc. (2016). Yukon Energy Corporation Transmission Options Evaluation. June 2, 2016.

Table 13. Description of Whitehorse-Skagway Transmission Line by Life Cycle Stage

Life Cycle Activity	Description
Production of Raw Material	Raw materials for transmission line construction (i.e. concrete, wood, copper, etc.) are extracted and processed.
Components Manufacturing and Transportation	Transmission line components are manufactured and transported 2,400 km by truck, 22t payload.
Transmission Line Construction	This stage includes site clearing and installation of the transmission line (poles, transmission towers, etc.). Transfer Capacity: 443 MW, 230 kV transmission line Transmission Conductor: Hawk 477 MCM 102 km line, 30m wide right of way clearing and 68 km of an existing 34.5kv line (306 ha plus 102 ha of cleared area footprint)
Electricity Transmission	3880.7 GWh/yr (100% reliable capacity) Transmission Voltage: 230 kV
End of life	Lifetime: 55 years

3.3.13 System Description: Gladstone Diversion Project

The Gladstone Diversion project has been used as a proxy for a potential diversion project. The project will give some additional storage to an existing generating Station. A dam and channels will be constructed on the Gladstone Lake across the divide between the Gladstone Creek and Isaac Creek watershed. This will increase the diverted drainage basin area. The project will utilize capacity of existing hydro units.

The system boundary is presented in Figure 14 with a description following in Table 13.

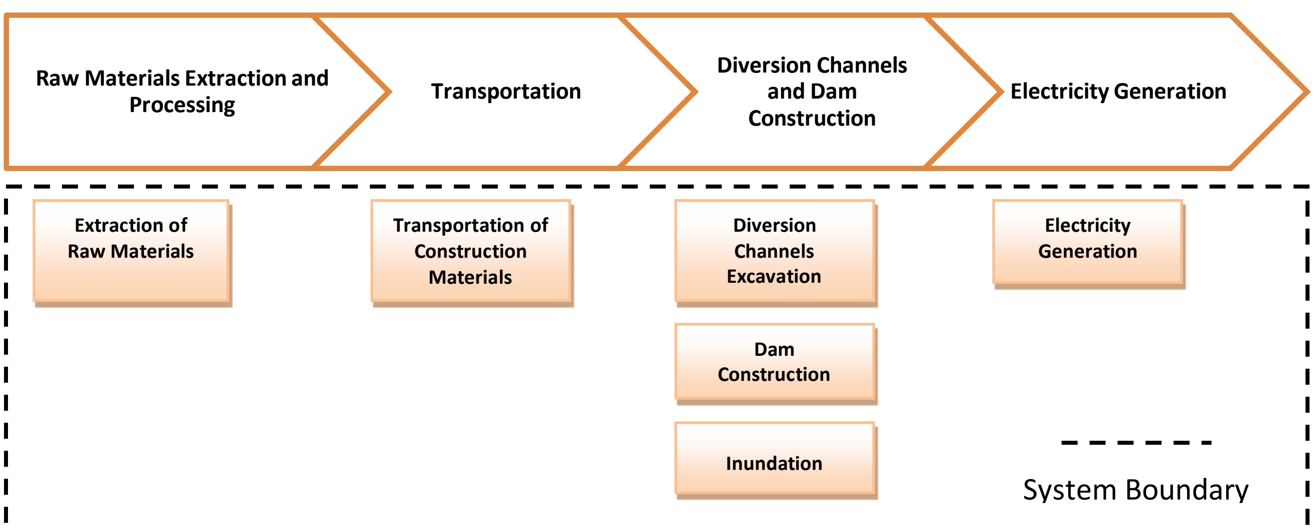


Figure 14. System Boundary of the Gladstone Diversion Project

Table 14. Description of Water Diversion Project by Life Cycle Stage

Life Cycle Activity	Description
Raw Materials Extraction and Processing	Raw materials (gravel, sand) for dam construction are sourced locally
Transportation	Transport distance: 15 km by truck, 22 t payload
Diversion Channels and Dam Construction	Partial greenfield site with inundation area of 220 ha This stage includes diversion channels excavation and dam construction.
Electricity Generation	Net electricity production: 29.7 GWh_e/yr - the project would utilize existing hydro units.
End of life	The lifetime of the project is 24 years. 65 years lifetime is modelled to compare results to other hydro power scenarios.

3.4 Data Quality, Data Sources and Assumptions

Data quality requirements specify the characteristics of the data needed for the study. Description of data quality, sources and assumptions is important to understand the reliability of the study results and properly interpret the outcome of the study[16].

Several different methods of data collection were available, such as personal interaction, previous LCA studies and technical reports prepared for Yukon Energy, and both peer-reviewed and un-reviewed published literature.

The majority of the data used in this project is specific to Yukon and Western Canada. In the absence of the Western Canadian data, information was drawn from other Canadian sources, followed by North American and European sources and, finally, from pre-existing life cycle databases, most notably the Ecoinvent library and GaBi database. The Ecoinvent library is a European database considered to be the most comprehensive and up-to-date inventory currently available[17]. Canadian data was directly substituted into the Ecoinvent library where possible, and the default European data remained when Canadian data was unavailable.

More information on life cycle inventory data, assumptions and data sources can be found in Appendix A: Life Cycle Inventory Supporting Information.

3.4.1 Uncertainty

The quality and reliability of LCA results depend on the quality of data used in the inventory analysis. It is therefore important to identify sources of uncertainty in the inventory data and understand how they affect the results of the study.

Materials and equipment manufacturing locations

The study evaluates potential energy resource options available to Yukon Energy. The studied scenarios are based on the results of feasibility studies conducted for each resource option. A specific

[16] ISO - International Organization for Standardization (2006) 14040. (2006). Environmental Management - Life cycle assessment - Principles and Framework.

[17] Ecoinvent Centre. (2009). Swiss Centre for Life Cycle Inventories Website. http://www.ecoinvent.ch/.

technology or manufacturer is not always identified in the feasibility study. Thus, several assumptions were made and a sensitivity analysis was conducted on selected parameters, such as technology choice (e.g. battery storage pathway) and plant components manufacturing location (e.g. wind pathway).

The manufacturing locations of power plant components are also unknown. It is therefore assumed that most of the materials (e.g. steel, concrete, iron) and plant components are produced in Canada and transported 2,400km by truck to the power plant location.

Power plant construction data

Moreover, site specific data such as plant construction data (e.g. area of land to be cleared, type of dam, excavation area, quantities of construction materials) is available only for some of the pathways.

The power plant construction data in the waste to energy pathways originates from Spath and Mann[18] and is representative of a North American power plant. Small hydro and pumped storage power plant construction data is based on Flury and Frischknecht, 2012[19] and represents a mix of North American and European small hydro and pumped storage power plants. The data is obtained per MWh of energy produced; if the emissions data expressed per MWh is converted back to the total GHG emissions from plant construction using the total energy output of the plant over plant's lifetime, it increases the uncertainty of the results. Site specific data need to be obtained to better understand GHG emissions from power plants construction. It is recommended to update this data when site specific data become available.

Diesel and LNG combustion data

GHG emissions from diesel and LNG combustion are estimated based on emissions factors, not specific operating data, which was not available at the time of the study. The emissions factors are derived from GHGenius 4.03 that are based on the US EPA non-road model for large diesel and natural gas engines. The Jenbacher natural gas engine has up to 2.5% of the methane in the exhaust emissions, while the EPA non-road emission model uses a methane emissions factor of approximately 2.8%[13]. A sensitivity analysis is performed to better understand an effect of different emissions factors on the results.

Upstream emissions in LNG pathway

The accuracy of methane emissions from natural gas extraction, processing, transportation, and storage is an area of concern. Significant differences exist among data reported by industry. The application of correct emissions factors in order to estimate methane emissions is therefore challenging. The 2006 IPCC Guidelines suggests a range of +/-100% uncertainty when applying their values to estimate natural gas methane emissions.

Many emissions in the oil and gas industry are unintentional and do not necessarily correlate with default emissions factors; rather, they are dependent on the operation and condition of the specific equipment itself. The method in which data are collected, various modelling techniques, and the location where the data are collected contribute to the variability. When emissions factors are

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[18] Spath, P.L. and Mann, M. K. (1997). Life Cycle Assessment of a biomass Gasification Combined-Cycle System. NREL. December 1997.

[19] Flury, K. and Frischknecht, R. (2012). Life Cycle Inventories of Hydroelectric Power Generation. ESU- Services. Commissioned by Öko-Institute e.V.

unavailable, studies and assessments are forced to use generic emissions factors, regardless of the range of uncertainty. Therefore, understanding the inherent uncertainty is key to applying emissions factors in life cycle assessments. This report used the Canadian data from CAPP, 2004[20] and GHGenius v4.03. A detailed discussion and an overview of the latest research on the LNG upstream emissions are given in section A.11 of the report.

3.5 LIFE CYCLE ASSESSMENT METHODOLOGY

Life cycle assessment (LCA) is a method for examining the environmental effects of a product or process across its lifespan. It is a "cradle-to-grave" analysis in which complex systems are broken down into elementary flows. The flows are then grouped and categorized based on the effects they have on the environment.

This LCA study follows the general principles set forth by the International Organization for Standardization (ISO) in ISO 14040[15] and ISO 14044[21] for conducting and reporting LCA studies and examines GHG emissions only. The ISO 14040 LCA framework consists of four steps (Figure 15):

1. Definition of goal and scope;
2. Inventory analysis;
3. Impact assessment; and
4. Interpretation of results.

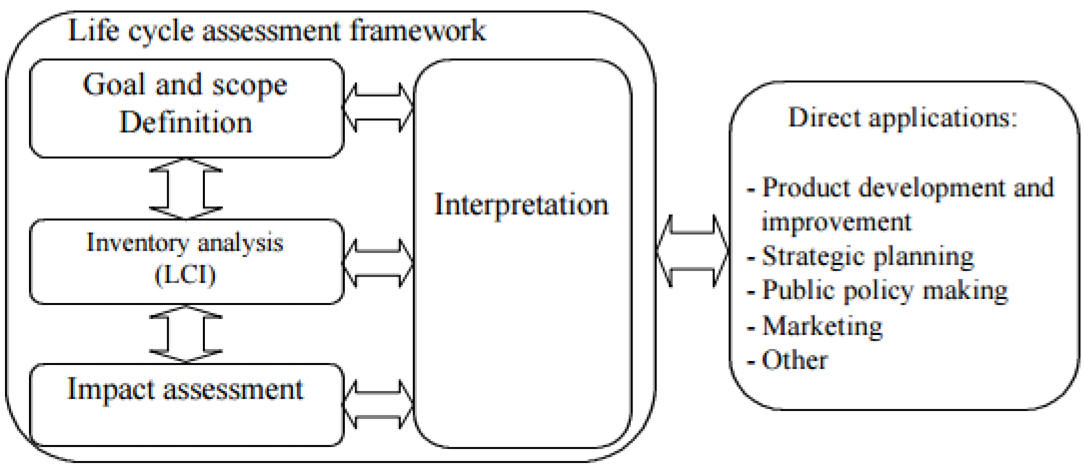

Figure 15. LCA phases

[20] CAPP. (2004). A National Inventory of Greenhouse Gas (GHG), Criteria Air Contaminant (CAC) and Hydrogen Sulphide (H_2S) Emissions by the Upstream Oil and Gas Industry.

[21] ISO - International Organization for Standardization 14044. (2006). Environmental Management – Life Cycle Assessment - Requirement and Guidelines.

3.5.1 Life Cycle Inventory and Life Cycle Impact Assessment Analyses

The second phase of the LCA is life cycle inventory analysis where the energy use and raw material inputs and environmental releases associated with each stage of the life cycle are grouped and quantified.

In the life cycle impact assessment phase the Global Warming Potential (GWP) factors are applied to the life cycle inventory data to calculate the global warming impact of each energy resource pathway. The results are presented as carbon dioxide equivalents (CO_2e). The GWP factors (without feedback) based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) are used to quantify GHG emissions (Table 15).

Table 15. Greenhouse Gases

GHG	Life time[22]	GWP time horizon (IPPC AR5)	
		20 years	100 years
Carbon dioxide (CO_2)		1	1
Methane (CH_4)	12.4	84	28
Nitrous oxide (N_2O)	121	264	265
HFC-23	222	10,800	12,400
HFC-134a	13.4	3,710	1,300
CF_4 (PFC)	50,000	4,880	6,630
Sulphur hexafluoride (SF_6)	3,200	17,500	23,500
Nitrogen trifluoride (NF_3)	500	12,800	16,100

3.5.1.1 Methane Global Warming Potential over 20- and 100-year time horizon

This study recognizes the importance of short-term and long-term mitigation strategies for the release of GHG emissions. To fully understand the environmental impact of each energy source under analysis, both the 20-year and 100-year time horizon are applied. The analysis quantifies and evaluates the released emissions and their respective levels of radiative forcing relative to the CO_2 reference gas.

A GWP for a particular GHG is determined by the gas's ability to absorb certain types of radiation and the length of time the gas remains in the atmosphere.

GWP values are currently reported for time scales of 20 and 100 years by the IPCC. They are regularly updated as newer modelling techniques are developed and as GHG lifetimes and absorption efficiencies are revised[23]. The GWP values are relative to the reference gas CO_2, which has a GWP set to one, regardless of the time period it is reported for. GWPs quantify the amount of radiated energy that will be absorbed by one ton of gas, compared to one ton of CO_2. Hence, larger GWP values indicate a greater warming effect compared to CO_2 for the chosen time horizon under investigation.

[22] The lifetime of a greenhouse gas refers to the approximate amount of time for the atmospheric pollutant to return to its natural level as a result of either being converted to another chemical compound or being taken out of the atmosphere via a sink.

[23] Boucher, O., Friedlingstein, P. Collins, B., and Shine, K.P. (2009). The indirect global warming potential and global temperature change potential due to methane oxidation. *Environ. Res. Lett*. 4, 044007.

LCA standard practice is to use GWPs with a predetermined time horizon regardless of when the emissions occurred[24]. However, the lack of available information on the application of different GWP time scales in LCAs increases the level of uncertainty in the calculated emissions[25]. For example, LCA studies have not focused on the use of different time horizons despite it being a well known factor in the analysis of biofuels, which contribute to methane emissions[26,27]. As well, the choice of timeframe in which to analyze the GHG is somewhat arbitrary. In a 2009 study, data showed that the most optimum GWP time horizon to correlate methane emissions with equivalent CO_2 emissions using to historical temperature data was 44 years[28]. Interestingly, the data could not provide any particular time horizon where N_2O emissions accurately corresponded with historical data. As well, GWP values are weighted equally across the entire time period regardless of any change in their absorption efficiency during that time period[29]. Therefore, analysis with multiple time horizons can provide additional insight into the short and long term environmental effects caused by various GHGs.

The choice of time scale used to report GWP values can significantly affect the actual GWP value due to the varying atmospheric lifespan of each greenhouse gas. The most widely accepted time scale is 100 years, which adequately represents most GHGs due to their significantly long lifetime (Table 14 – GWP for 20 and 100 years). That is, the reported GWP value does not change considerably for the different time scales. It is the most commonly used metric for comparing GHGs and was used under the Kyoto Protocol[30].

Greenhouse gases with shorter lifetimes that are in the order of decades rather than centuries or millennia can have a GWP value that increases by a factor of three for the 20 year time horizon versus the 100 year time horizon. Specifically, methane (CH_4) emissions typically last approximately one decade before being oxidized into CO_2. Additionally, methane's higher energy absorption is significantly greater than CO_2. Over 100 years, it is 28 more times effective at trapping heat compared to CO_2, but over 20 years, it is 84 times more potent at retaining heat. The impact of methane's shorter lifetime and greater ability to trap energy is revealed in its GWP value. Comparatively, CF_4, which has a 50,000 year lifetime, has a lower 20-year GWP value than the 100-year value. Therefore, examining global warming potential effects over shorter timeframes will be included in order to address the immediate effects of methane on global temperatures.

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[24] Peters, G.P., Aamaas, B., Lund, M.T., Solli, C., and Fuglestvedt, J. S. (2011). Alternative "Global Warming" Metrics in Life Cycle Assessment: A Case Study with Existing Transportation Data. *Environ Sci Technol*. 45, 8633-8641.

[25] Levasseur, A., Lesage, P., Margni, M., Deschenes, L., and Samson, R. (2010). Considering time in LCA: Dynamic LCA and its application to global warming assessments. *Environ. Sci. Techno*l. 44: 3169-3174.

[26] Kendall, A., Chang, B., and Sharpe, B. (2009). Accounting for Time-Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations. *Environ. Sci. Technol*. 43: 7142–7147.

[27] Cherubini, F., Peters, G. P., Berntsen, T., Strømman, A. H., and Hertwich, E. (2011). CO_2 emissions from biomass combustion for bioenergy: Atmospheric decay and contribution to global warming. *GCB Bioenergy*. 3: 413–426.

[28] Tanaka, K., O'Neill, B.C., Rokityanski, D., Obersteiner, M., and Tol, R.S.J. (2009). Evaluating global warming potentials with historical temperatures. *Climatic Change*. 96:443-466.

[29] Shoemaker, J., and Schrag, D. (2013). The danger of overvaluing methane's influence on future climate change. *Climatic Change*. 120:903-94.

[30] Reisinger, A., Meinshausen, M., Manning, M., and Bodeker, G. (2010). Uncertainties of global warming metrics: CO_2 and CH_4, *Geophys Res Lett.* 37, L14707.

In this study, the application of the 20 year time horizon for GWP values, in addition to the 100 year time horizon, prioritizes gases with shorter lifetimes rather than focusing on longer-term impacts from GHGs[31]. Carbon dioxide, and many other GHGs, remains in the atmosphere longer than methane by factors greater than 100. The rationale for addressing short term GHG impacts, such as methane emissions, is that it allows additional time to implement more effective means to regulate and reduce CO_2 emissions that ultimately have longer term effects and are necessary for overall climate stabilization. Given that methane is the second most prominent human-induced GHG present in the atmosphere with a short lifespan, a decrease in current CH_4 emissions will reduce anthropogenic-induced warming relatively quickly as the results can be seen in the subsequent few decades, whereas the effects of reduced CO_2 emissions will not be seen for centuries[32,33]. Due to its short lifespan, methane has become an appealing objective for climate mitigation strategies.

The hypothesis that a reduction in methane concentrations will have a significant positive impact on the overall atmospheric burden is supported by the 20 year time horizon in LCA studies. It is suggested that the immediate benefit of reducing short lived GHGs will help avoid the 2^0C increase in the temperature threshold, or the so-called "tipping point" in climate change[34,35]. Moreover, recent studies have shown that the GWP for methane increases substantially for the 20 year time horizon when interactions with aerosols are considered in the calculations[36,37]. A 2015 study on the LCA of biofuels revealed that the choice of GWP timeframe by which to analyze the carbon footprint should be carefully considered, rather than simply choosing the standard 100 year time horizon[38]. The analysis showed that the methane emitted through biogas use had a greater carbon footprint for the 20 year timeframe compared to the 100 year time horizon.

This study recognizes the importance of short-term and long-term mitigation strategies for the release of GHG emissions. To fully understand the environmental impact of each energy source under analysis,

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[31] Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T, Betts, R, Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Dorland, R.V. (2007). Changes in atmospheric constituents and in radiative forcing. paper presented at the climate change 2007: the physical science-basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

[32] Intergovernmental Panel on Climate Change (IPCC) (2007). Climate Change 2007: The Physical Science Basis, edited by S.Solomon et al., Cambridge Univ. Press, Cambridge, U.K.

[33] Intergovernmental Panel on Climate Change (IPCC) (2009), Meeting Report of the Expert Meeting on the Science of Alternative Metrics, 75 pp., IPCC WGI Tech. Support Unit, Bern.

[34] Shindell, D, Kuylenstierna, J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen K., Hoglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N.T.K., Milly, G.,Williams M, Demkine, V., and Fowler, D. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. *Science.* 33:183–189.

[35] Howarth, R., Santoro, R., and Ingraffea, A. (2012). Venting and leaking of methane from shale gas development: response to Cathles et al. *Climatic Change*. 113:537–549.

[36] Shindell, D.T., Faluvegi, G., Koch, D.M., Schmidt, G.A., Unger, N., and Bauer, S.E. (2009). Improved attribution of climate forcing to emissions. *Science* 326(5953):716–718.

[37] Howarth RW, Santoro R, Ingraffea A (2011). Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change*. 106:679–690.

[38] Pfister, S. and Scherer, L. (2015). Uncertainty analysis of the environmental sustainability of biofuels. Energy*, Sustainability and Society*. 5:30.

both the 20-year and 100-year time horizon are applied. This information is critical to stakeholders in order to make an informed decision as they prepare for future energy scenarios.

3.5.2 Results Interpretation

In the final stage of the LCA, results of the impact assessment phase are interpreted and presented. Two major analyses in determining the validity of the results are conducted:

- Contribution analysis - a measure of the effect each process has on the complete environmental profile of the life cycle. The processes that make up the largest portions of the total impact assessment are then subjected to rigorous data quality checks and sensitivity analyses, and
- Sensitivity analysis - determines the effect of changing parameters and assumptions on the final results. It is essential to determine whether the final results are resistant to small changes through the life cycle.

4 GREENHOUSE GAS EMISSIONS ASSESSMENT RESULTS

4.1 LIFE CYCLE INVENTORY

Life cycle inventory models have been developed to quantify and compare GHG emissions for the 13 scenarios under study. Detailed descriptions of the life cycle inventory data used in this study are presented in Appendix A: Life Cycle Inventory Supporting Information.

4.2 RESULTS

The results are presented per MWh of energy delivered, including the transmission line results that are converted to MWh by multiplying the results in kg CO_2e/MWh-km by the transmission line length of 170km. The contribution analysis results are grouped into three categories:

1. Materials and Fuel Acquisition, Production and Construction
2. Transport of Materials and Fuel, and
3. Operation.

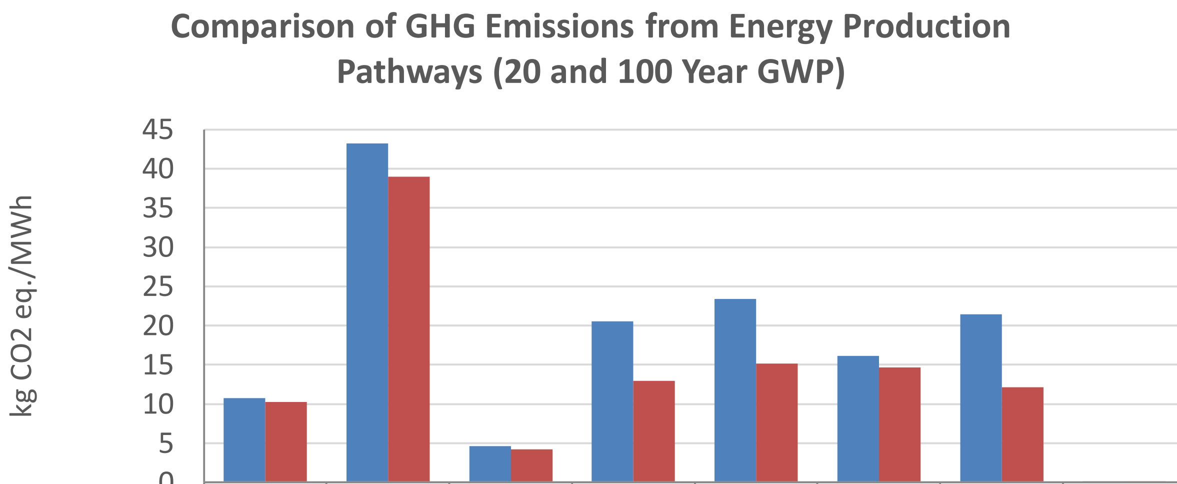
Materials and fuel acquisition, production and construction include raw materials for plant construction acquisition, processing, components manufacturing, site preparation, and plant and transmission line construction. In the diesel pathway, crude oil extraction (includes leakage, vented and flared emissions), diesel production, crude oil and diesel storage, and power plant construction (extraction and processing of raw materials, site preparation) are included in this stage.

Transport of materials and fuels include transportation of raw materials and components, as well as transportation of fuel such as biomass, MSW, diesel, and LNG.

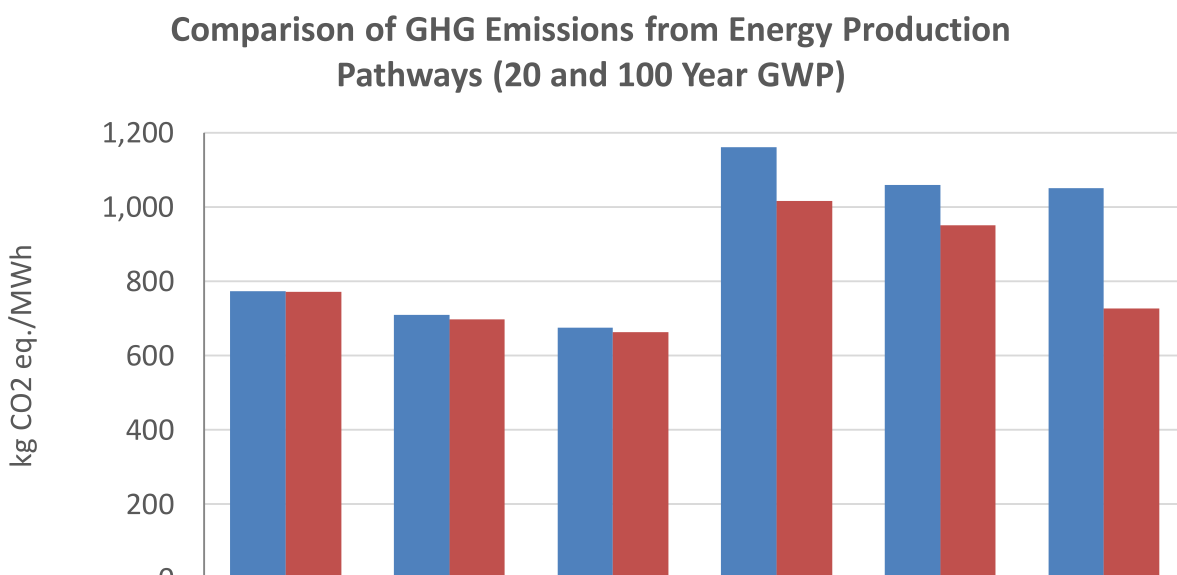
Operation category includes onsite fuel processing (e.g. biomass drying), fuel combustion, plant operations and maintenance, as well as yearly right of way clearing in the transmission line pathway. In the hydro pathways, emissions from land inundation are also included in the operation category.

A comparison of total GHG emissions (including biogenic CO_2) produced by all resource options under consideration for the 20 and 100 year GWP time horizons is presented in Figure 16. The resource options can be grouped into three categories of emitters: those producing GHGs just over 1,000 kg CO_2e/MWh, resources producing well over 600 kg CO_2e/MWh, and those that produce GHGs below 45 kg CO_2e/MWh. In the first category, the top three overall GHG emitters are biogas, diesel and LNG, where each pathway produces more than 1,000 kg CO_2e/MWh. However, it should be noted that biogas pathway has biogenic CO_2 emissions included in the operation stage. More information on accounting for biogenic CO_2 emissions can be found in the next section (4.2.3). Biomass gasification produces 772 kg CO_2e/MWh, and MSW and MSW with biomass combustion produce around 700 kg CO_2e/MWh. Both plants are combined heat and power plants that have higher efficiencies due to produced heat utilization. Last, the remaining resources (geothermal, wind, solar, battery storage, transmission line, small hydro, pumped storage and water diversion) produce approximately 43 kg CO_2e/MWh or less.

In most of the scenarios, except for the biogas, LNG and hydro options, the GHG emissions among the two time horizons are similar. The difference in GHG emissions for the biogas, LNG and hydro options for the 20 year and 100 year time horizons is due to the larger amounts of methane produced and the significantly larger difference between the two GWPs, as previously discussed.



	Wind	Solar	Geothermal	Small Hydro	Pumped Storage	Battery Storage	Water diversion	Transmission line
20 year GWP	10.74	43.24	4.62	20.56	23.41	16.15	21.43	0.17
100 year GWP	10.30	38.99	4.22	12.99	15.15	14.66	12.10	0.16



	Biomass Gasification	MSW	MSW + Biomass	Biogas	Diesel	LNG
20 year GWP	772.49	709.08	675.24	1161.71	1058.91	1050.76
100 year GWP	771.97	696.81	662.98	1015.88	951.11	727.68

Figure 16. Comparison of total GHG emissions (including biogenic CO_2) from energy production pathways (20 and 100 year GWP)

4.2.1 COMPARISON OF GHG EMISSIONS FROM ENERGY PRODUCTION PATHWAYS FOR 20 YEAR GWP

The contribution analysis results for the 20 year time horizon presented in Figure 17 reveal that wind, geothermal, transmission line, battery storage and solar energy options GHG emissions come primarily from materials acquisition, production and construction rather than operation of the plant. It is also seen that operation of the energy generating plant is by far the most significant in terms of GHG emissions in biogas, biomass gasification, waste to energy, diesel, and LNG pathways. The hydro power pathways' GHG emissions originate mainly from the operation life cycle stage due to land inundation. The CO_2 emissions from land inundation are considered biogenic and further discussed in section 4.2.3 of the report.

4.2.2 COMPARISON OF GHG EMISSIONS FROM ENERGY PRODUCTION PATHWAYS FOR 100 YEAR GWP

Figure 18 compares GHG emissions under the 100 year time horizon for all resource pathways. The trends are nearly identical to the results shown in Figure 17 for the emitted GHGs under the 20 year time horizon. Overall, total GHG emissions are lower when applying the 100 year GWP. This is expected due to the lower GWP for methane for the 100 year time horizon.

In the 100 year GWP scenario, there is only one energy resource option (biogas) that is greater than 1,000 kg CO_2e/MWh. After biogas, diesel and LNG were the next highest emitters, similar to the results using the 20 year GWP. However, while biogas, diesel and LNG were calculated to have less GHG emissions for the 100 year GWP, LNG emitted significantly less compared to the calculated value using the 20 year GWP. The remaining energy resource options produced approximately 40 kg CO_2e/MWh or lower, in a similar manner to the calculated GHG emissions under the 20 year time horizon.

4.2.3 ANALYSIS OF BIOGENIC CO_2 EMISSIONS

Biogenic CO_2 emissions are those that relate to either the natural carbon cycle or the use of biological material to produce energy, through processes such as combustion, fermentation, digestion and decomposition. Bioenergy is often assumed to be "carbon-neutral". This is due to photosynthesis sequestering CO_2 from the atmosphere in the biogenic material in a short timeframe[39]. However, according to the EPA Science Advisory Board's Biogenic Carbon Emissions Panel, biomass energy does not necessarily guarantee carbon neutrality[40]. In some cases, the production, processing and combustion of biomass can be done in a carbon neutral manner; however, it should not always be assumed that carbon neutrality will be the case unless a complete life cycle assessment of production and consumption cycle of the feedstock is performed.

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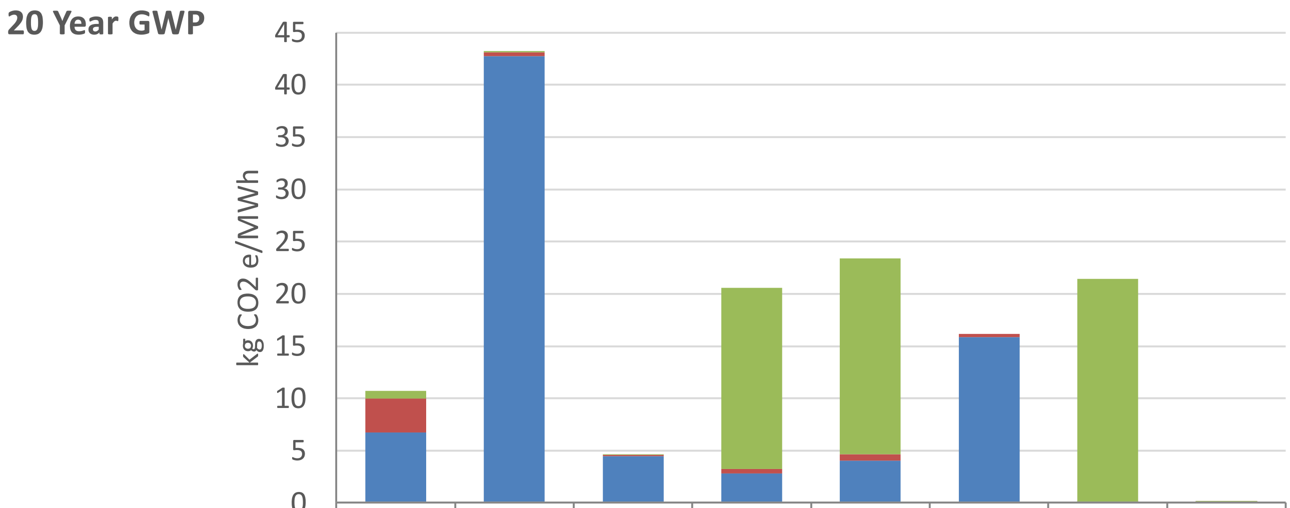
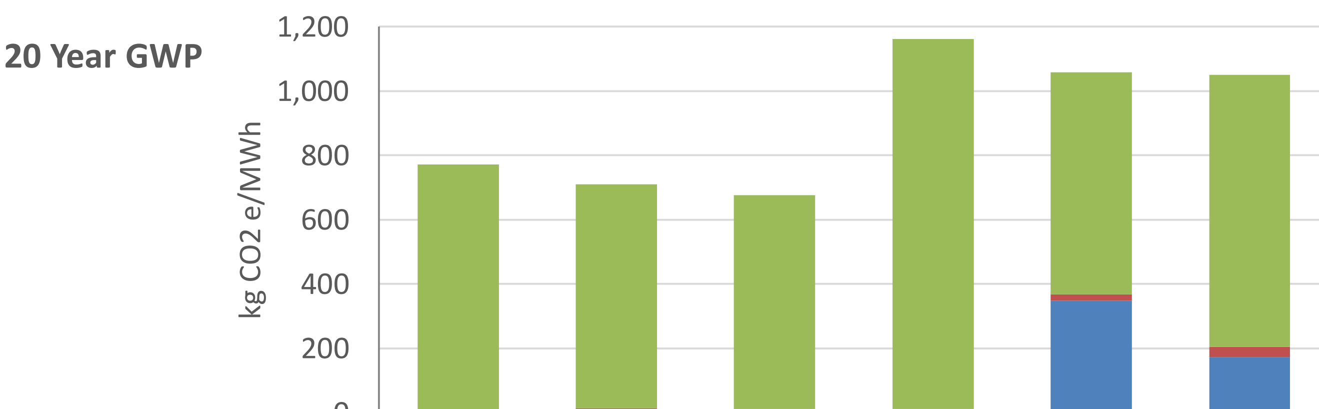
[39] EPA. Office of Atmospheric Programs, Climate Change Division. (2011). Accouting Framework for Biogenic CO2 Emissions from Stationary Sources. https://www3.epa.gov/climatechange/Downloads/ghgemissions/Biogenic-CO2-Accounting-Framework-Report-Sept-2011.pdf

[40] Voegele, E. (2014). EPA releases updated biogenic emissions framework. http://biomassmagazine.com/articles/11234/epa-releases-updated-biogenic-emissions-framework

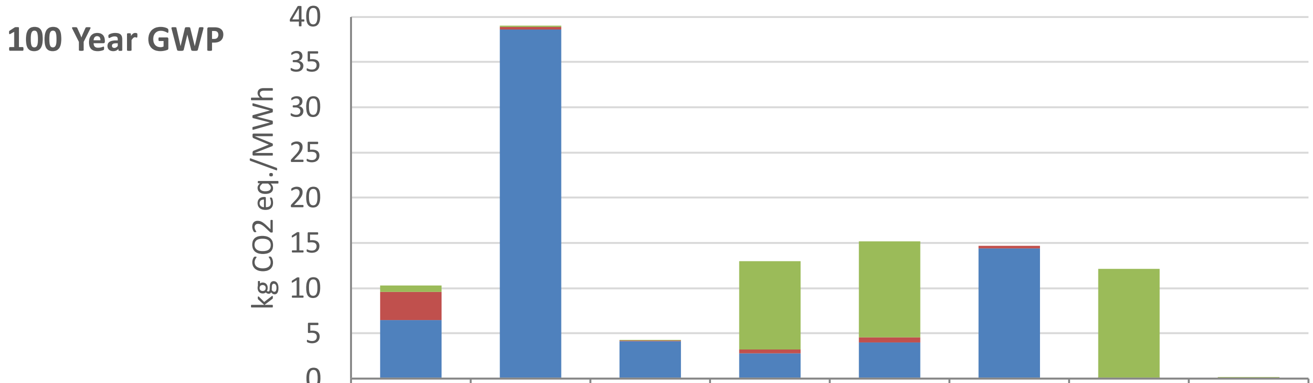


	Wind	Solar	Geothermal	Small Hydro	Pumped Storage	Battery Storage	Water diversion	Transmission line
Operation	0.74	0.13	0.02	17.31	18.77	0.00	21.30	0.0324
Transport of Materials & Fuel	3.29	0.35	0.10	0.44	0.61	0.30	0.0003	0.0027
Materials and Fuel Acquisition, Production and Construction	6.72	42.76	4.49	2.82	4.03	15.85	0.12	0.1355

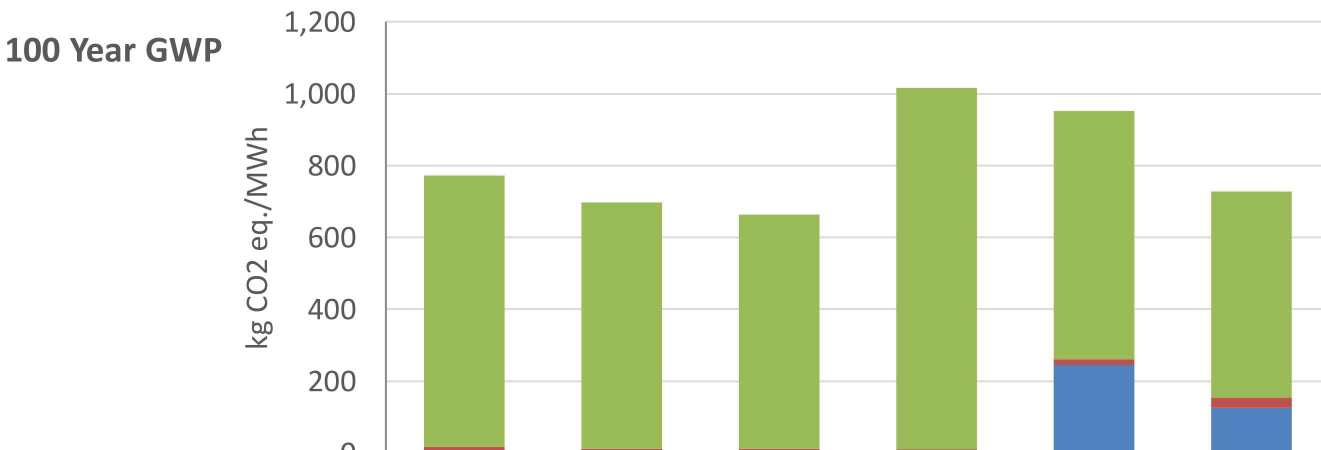


	Biomass Gasification	MSW	MSW + Biomass	Biogas	Diesel	LNG
Operation	763.30	696.52	663.01	1150.81	692.29	846.86
Transport of Materials & Fuel	7.34	4.08	3.74	4.93	18.22	31.44
Materials and Fuel Acquisition, Production and Construction	1.84	8.49	8.49	5.97	348.40	172.47

Figure 17. Contribution analysis of GHG emissions (including biogenic CO_2) from energy production pathways (20 year GWP)



	Wind	Solar	Geothermal	Small Hydro	Pumped Storage	Battery Storage	Water diversion	Transmission line
Operation	0.71	0.10	0.01	9.77	10.56	0.00	11.99	0.0304
Transport of Materials & Fuel	3.09	0.33	0.10	0.41	0.58	0.28	0.00	0.0027
Materials and Fuel Acquisition, Production and Construction	6.49	38.56	4.11	2.81	4.01	14.38	0.12	0.1251



	Biomass Gasification	MSW	MSW + Biomass	Biogas	Diesel	LNG
Operation	754.77	684.78	651.27	1005.41	690.43	574.23
Transport of Materials & Fuel	15.41	3.83	3.51	4.65	16.23	28.01
Materials and Fuel Acquisition, Production and Construction	1.79	8.20	8.20	5.83	244.45	125.45

Figure 18. Contribution analysis of GHG emissions (including biogenic CO_2) from energy production pathways (100 year GWP)

The recent study of using forest wood for energy in Massachusetts, US examined the carbon-neutrality and showed that using wood to produce energy results in an initial "carbon debt", because burning wood releases more CO_2 into the atmosphere per unit of energy than fossil fuels[41]. However, when forests grow back and recapture CO_2 from the atmosphere, the "carbon dividend" is realized. The length of time it takes to get carbon dividends depends on the type of biomass used to produce energy, the fossil fuel that biomass replaces, the bioenergy combustion technology and the forest management practices. For example, using forest biomass in district heating in Massachusetts can provide carbon dividends within 10 to 20 years.

The biomass feedstock used in this study consists of forest logging residues, dead trees, and sawmill residues. Since the waste material is used as biomass feedstock, one can argue in support of carbon neutrality of the studied pathways.

Biogenic CO_2 Originating from Studied Pathways

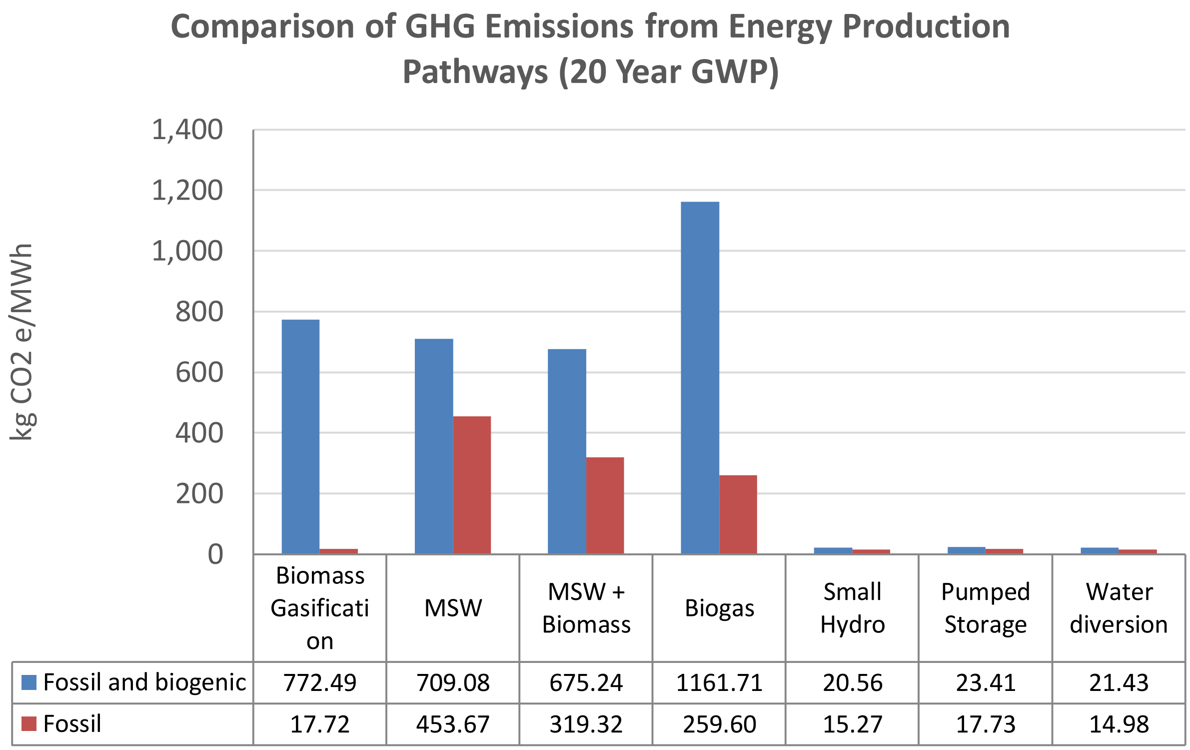
The biomass gasification, biogas, waste to energy (MSW and MSW & biomass combustion) and hydro (small hydro, pumped storage and water diversion) scenarios have biogenic emissions that originate from operations stage. A comparison of total GHG emissions with the results where biogenic CO_2 emissions are excluded is presented in Figure 19. The results that exclude biogenic CO_2 emissions are further presented in Figures 20 - 22.

Biogenic CO_2 emissions in the biogas and biomass gasification pathways originate from biogas combustion and biomass gasification life cycle stages, while fossil emissions come from raw materials acquisition, transportation and plant construction stages. If biogenic CO_2 emissions are excluded, it results in significantly lower life cycle emissions (260 and 114 kg CO_2e/MWh for biogas and 17.72 and 17.20 kg CO_2e/MWh for biomass gasification over the 20 and 100 year time horizons, respectively).

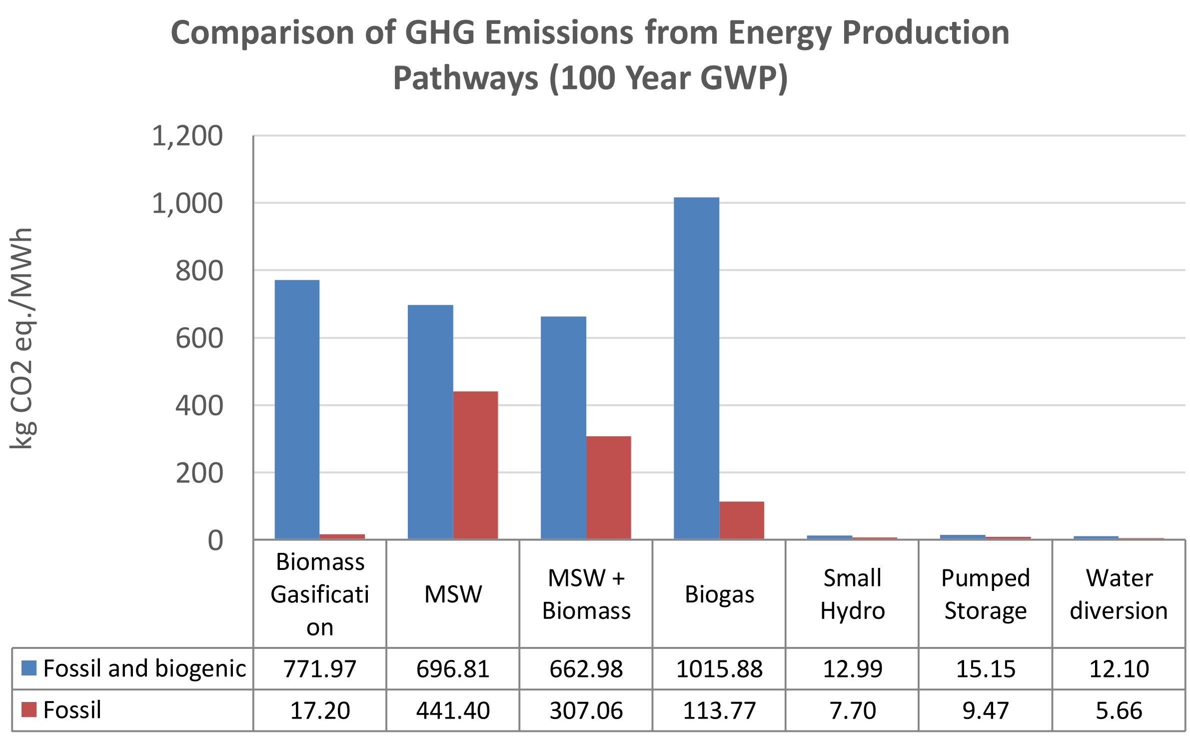
While GHG emissions from fossil sources are quite small in the biogas and biomass gasification scenarios, waste to energy pathways (MSW and MSW with biomass combustion) have notable fossil GHG emissions. This is due to higher quantities of waste in the MSW that contribute to fossil GHG emissions as well as fossil GHG emissions originating from plant construction and MSW collection. Paper, wood waste, and organics in the MSW are assumed to contribute to the biogenic CO_2 emissions. All other groups of waste contribute to fossil CO_2 emissions.

In the hydro pathways (pumped storage, small hydro, water diversion), after exclusion of biogenic CO_2 emissions that originate from biomass decomposition after land inundation, the GHG emissions are significantly lower, especially for the 100 year time horizon.

[41] MCCS. (2010). Biomass Sustainability and Carbon Policy Study. Natural Capital Initiative, Manomet Center for Conservation Sciences, Brunswick ME, USA.

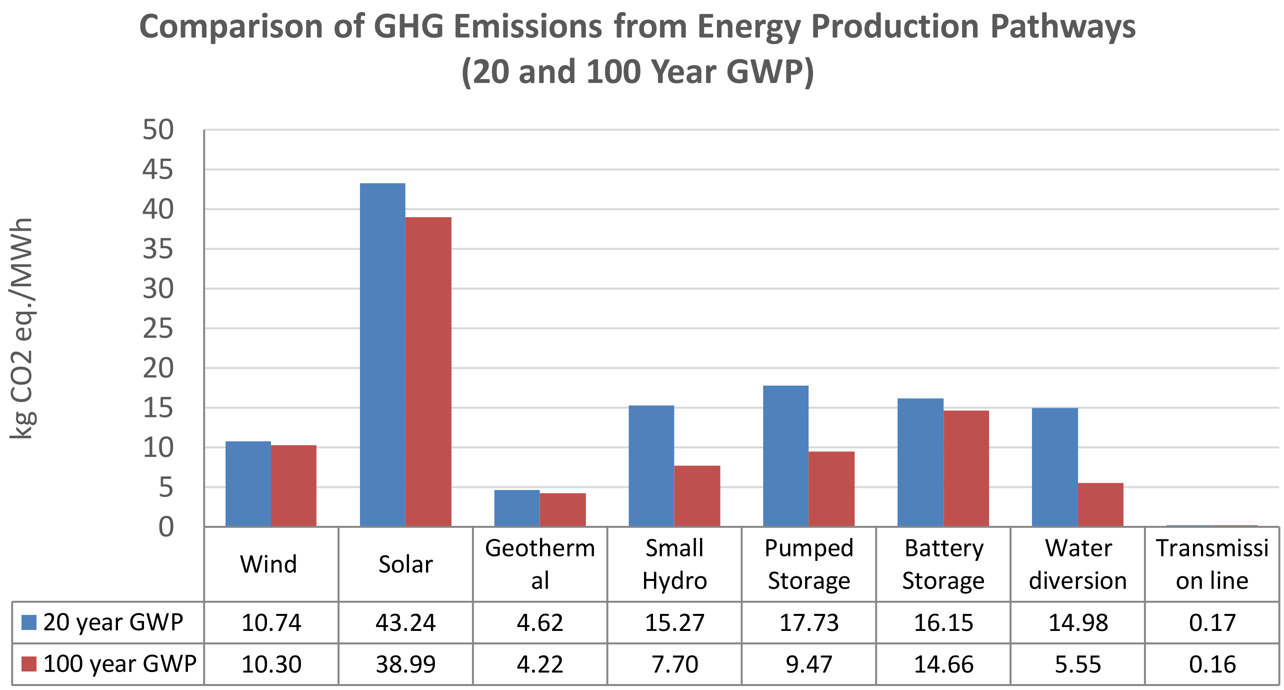


	Biomass Gasification	MSW	MSW + Biomass	Biogas	Small Hydro	Pumped Storage	Water diversion
Fossil and biogenic	772.49	709.08	675.24	1161.71	20.56	23.41	21.43
Fossil	17.72	453.67	319.32	259.60	15.27	17.73	14.98

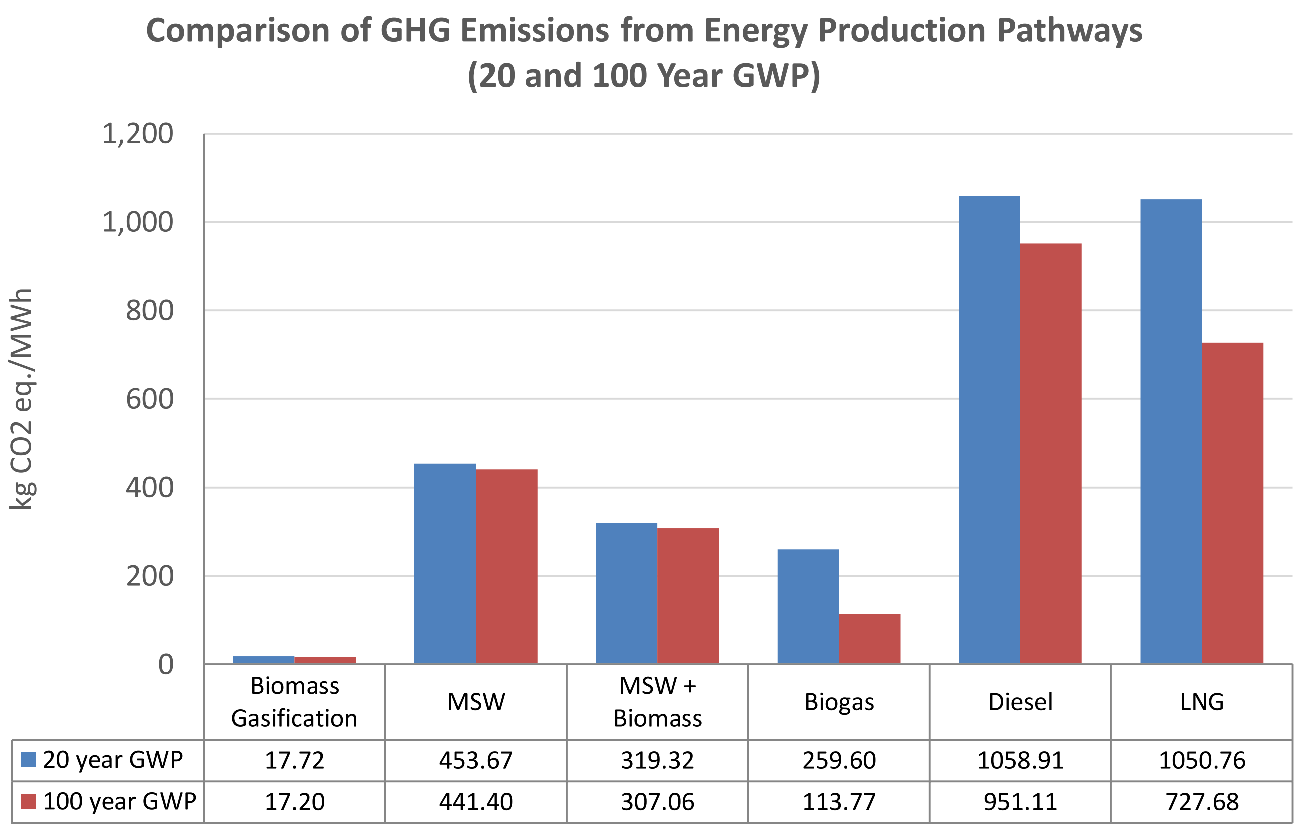


	Biomass Gasification	MSW	MSW + Biomass	Biogas	Small Hydro	Pumped Storage	Water diversion
Fossil and biogenic	771.97	696.81	662.98	1015.88	12.99	15.15	12.10
Fossil	17.20	441.40	307.06	113.77	7.70	9.47	5.66

Figure 19. Comparison of total GHG emissions with results where biogenic CO_2 is excluded

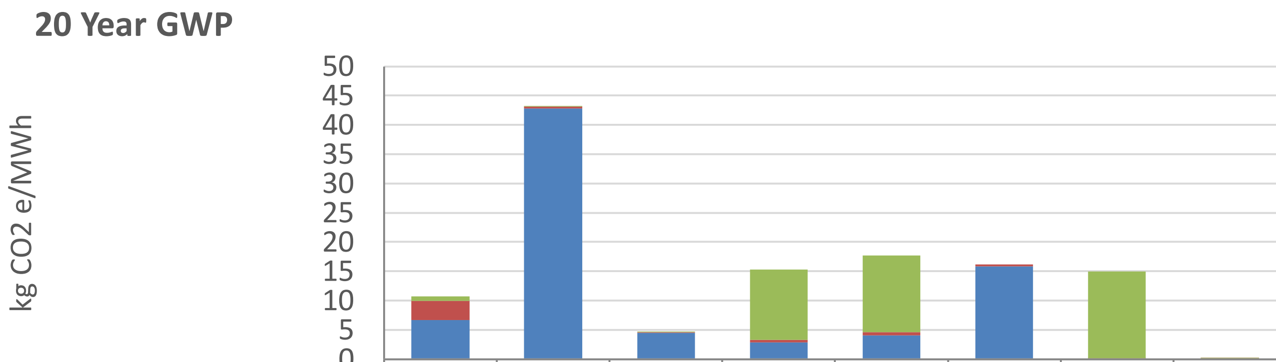


	Wind	Solar	Geotherm al	Small Hydro	Pumped Storage	Battery Storage	Water diversion	Transmissi on line
20 year GWP	10.74	43.24	4.62	15.27	17.73	16.15	14.98	0.17
100 year GWP	10.30	38.99	4.22	7.70	9.47	14.66	5.55	0.16

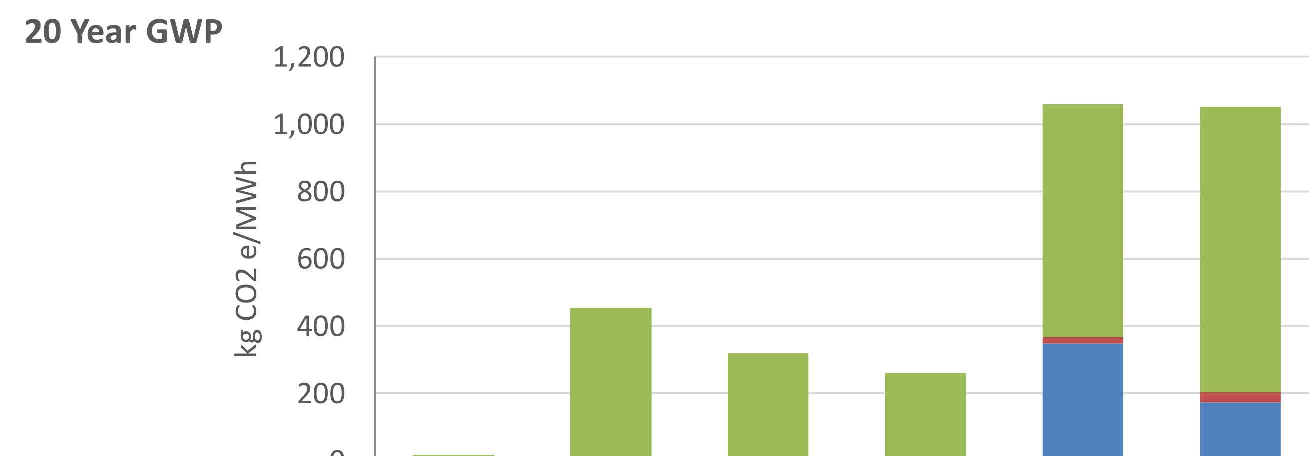


	Biomass Gasification	MSW	MSW + Biomass	Biogas	Diesel	LNG
20 year GWP	17.72	453.67	319.32	259.60	1058.91	1050.76
100 year GWP	17.20	441.40	307.06	113.77	951.11	727.68

Figure 20. Comparison of GHG emissions from energy production pathways (biogenic CO_2 emissions excluded)

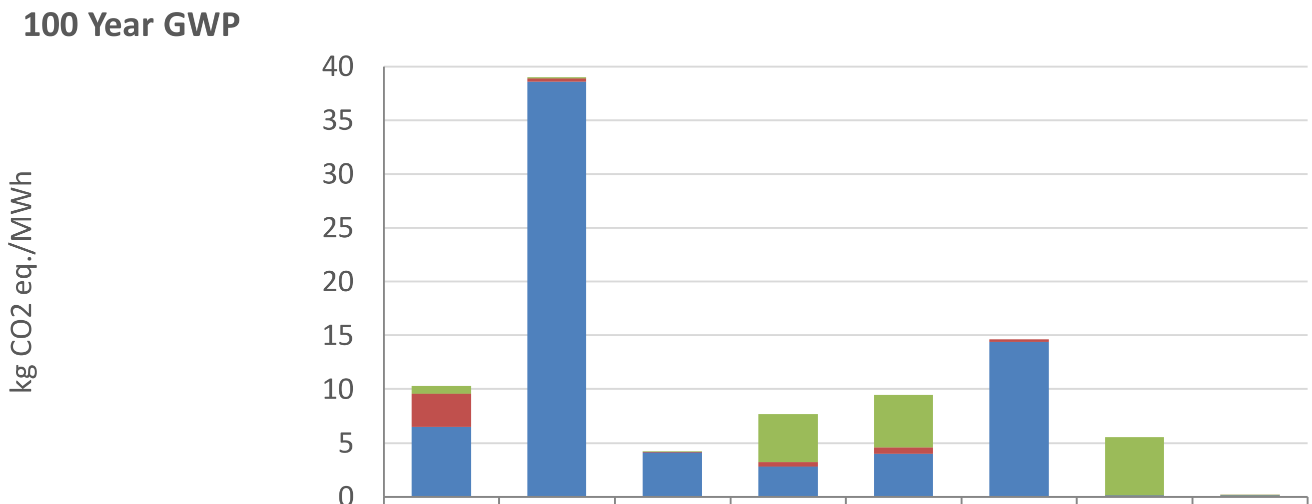


	Wind	Solar	Geothermal	Small Hydro	Pumped Storage	Battery Storage	Water diversion	Transmission line
Operation	0.74	0.13	0.02	12.02	13.09	0.00	14.86	0.0324
Transport of Materials & Fuel	3.29	0.35	0.10	0.44	0.61	0.30	0.0003	0.0027
Materials and Fuel Acquisition, Production and Construction	6.72	42.76	4.49	2.82	4.03	15.85	0.12	0.1355

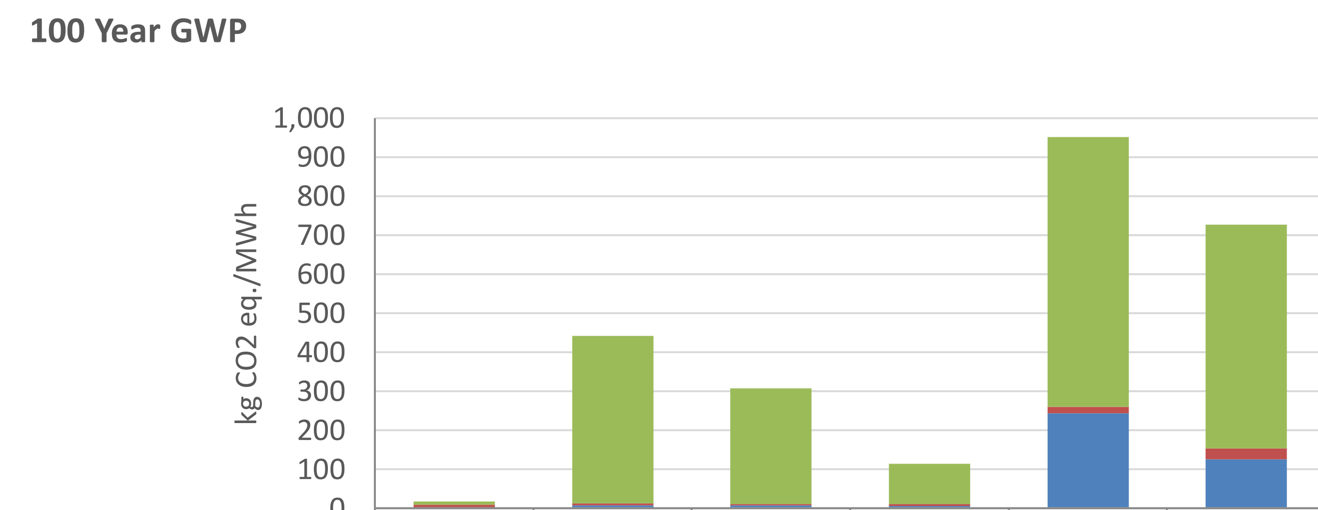


	Biomass Gasification	MSW	MSW + Biomass	Biogas	Diesel	LNG
Operation	8.53	441.11	307.09	248.70	692.29	846.86
Transport of Materials & Fuel	7.34	4.08	3.74	4.93	18.22	31.44
Materials and Fuel Acquisition, Production and Construction	1.84	8.49	8.49	5.97	348.40	172.47

Figure 21. GHG emissions from energy production pathways - contribution analysis, 20 year GWP (biogenic CO_2 emissions excluded)



	Wind	Solar	Geothermal	Small Hydro	Pumped Storage	Battery Storage	Water diversion	Transmission line
Operation	0.71	0.10	0.01	4.48	4.88	0.00	5.43	0.0304
Transport of Materials & Fuel	3.09	0.33	0.10	0.41	0.58	0.28	0.00	0.0027
Materials and Fuel Acquisition, Production and Construction	6.49	38.56	4.11	2.81	4.01	14.38	0.12	0.1251



	Biomass Gasification	MSW	MSW + Biomass	Biogas	Diesel	LNG
Operation	8.51	429.37	295.35	103.30	690.43	574.23
Transport of Materials & Fuel	6.90	3.83	3.51	4.65	16.23	28.01
Materials and Fuel Acquisition, Production and Construction	1.79	8.20	8.20	5.83	244.45	125.45

Figure 22. GHG emissions from energy production pathways - contribution analysis, 100 year GWP (biogenic CO_2 emissions excluded)

4.3 CONTRIBUTION ANALYSIS

Contribution analysis is a measure of the effect each process has on the complete environmental profile of the life cycle. The impact each process or life cycle stage has on the total life cycle GHG emissions is identified and discussed below.

4.3.1 BIOMASS GASIFICATION

The biomass gasification is a CHP plant. The total amount of electricity and heat produced from the plant is considered in the calculations. No allocation of emissions to electricity or heat was performed.

Figure 23 presents GHG emissions from biomass gasification in Haines Junction. The total GHG emissions are 771.97 kg CO_2e/MWh based on the 100 year GWP. The primary source of emissions is the operation of the plant, which contributes to almost 99% of the total emissions with 97.7% coming from biogenic CO_2 emissions. The remaining 1.1% of emissions are produced from materials acquisition, transportation of materials and biomass, and plant construction.

According to current GHG accounting protocols and standards, biogenic CO_2 emissions should be accounted and reported separately from all other GHG emissions[42]. The biomass combustion is considered carbon-neutral and biogenic CO_2 emissions are reported separately from other emissions (Table 16).

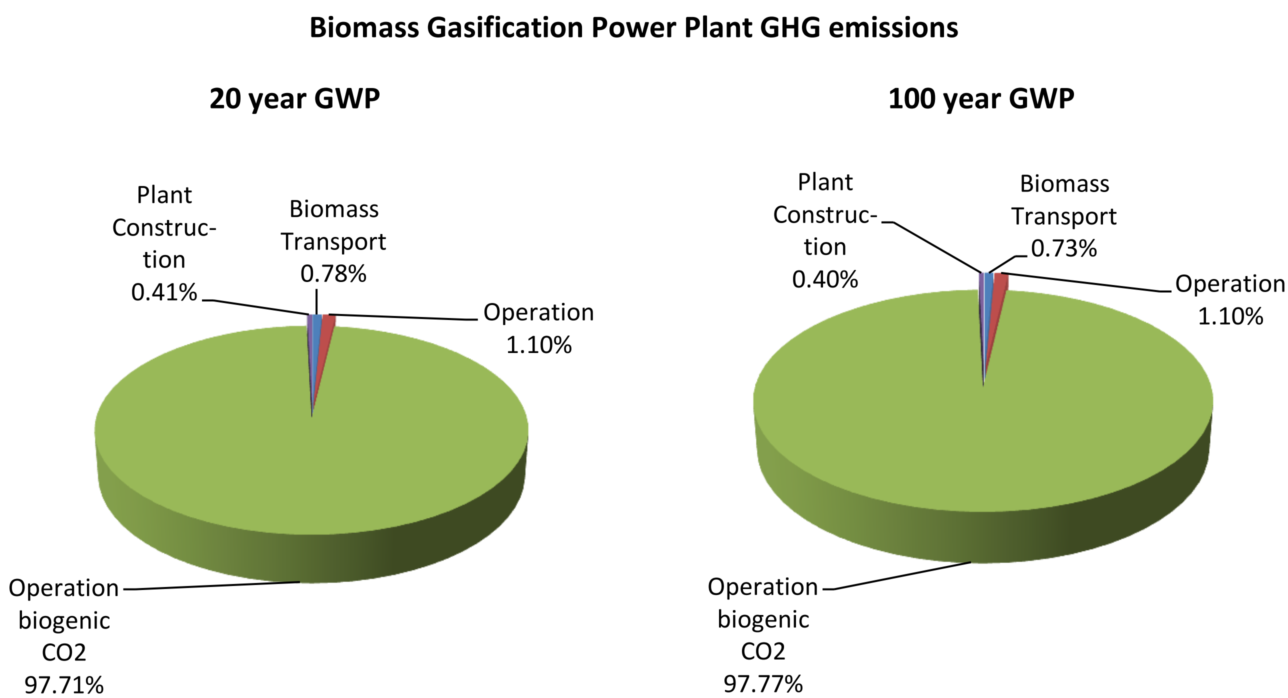


Figure 23. Biomass Gasification Power Plant GHG emissions (20 and 100 year GWP)

[42] Greenhouse Gas Accounting Protocol (2016). http://www.ghgprotocol.org/

Table 16. Biomass Gasification Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Bio	N_2O	SF_6	CH_4				
Materials Acquisition	1.7673	0.0000	9.29E-06	2.71E-13	0.0008	1.8388	0.24	1.7928	0.23
Materials Transportation	1.2247	0.0000	9.77E-06	5.36E-13	1.47E-03	1.3511	0.17	1.2685	0.16
Biomass Transportation	5.4245	0.0000	0.0001	2.37E-12	0.0065	5.9921	0.78	5.6268	0.73
Operation	8.1754	754.77	0.0012	0.0000	0.0004	763.30	98.81	763.28	98.87
Total	**16.5919**	**754.77**	**0.0013**	**3.18E-12**	**0.0092**	**772.49**	**100**	**771.97**	**100**

4.3.2 WASTE TO ENERGY MSW

There are two scenarios considered for the MSW combustion power plant.

Scenario 1: MSW & Biomass Conventional Combustion

Scenario 1, which is based on a combined combustion of 16,100 tonnes of waste and 7,650 tonnes of biomass, is presented in Figure 24. The amount of emitted GHGs is 675.24 kg CO_2e/MWh based on the 20 year GWP, with plant operation accounting for nearly all of the GHGs (98%) for both time horizons. Nearly 53% of the GHGs from operations originate from biogenic CO_2. The remaining 1.8% of GHGs is produced by transportation of materials and plant construction.

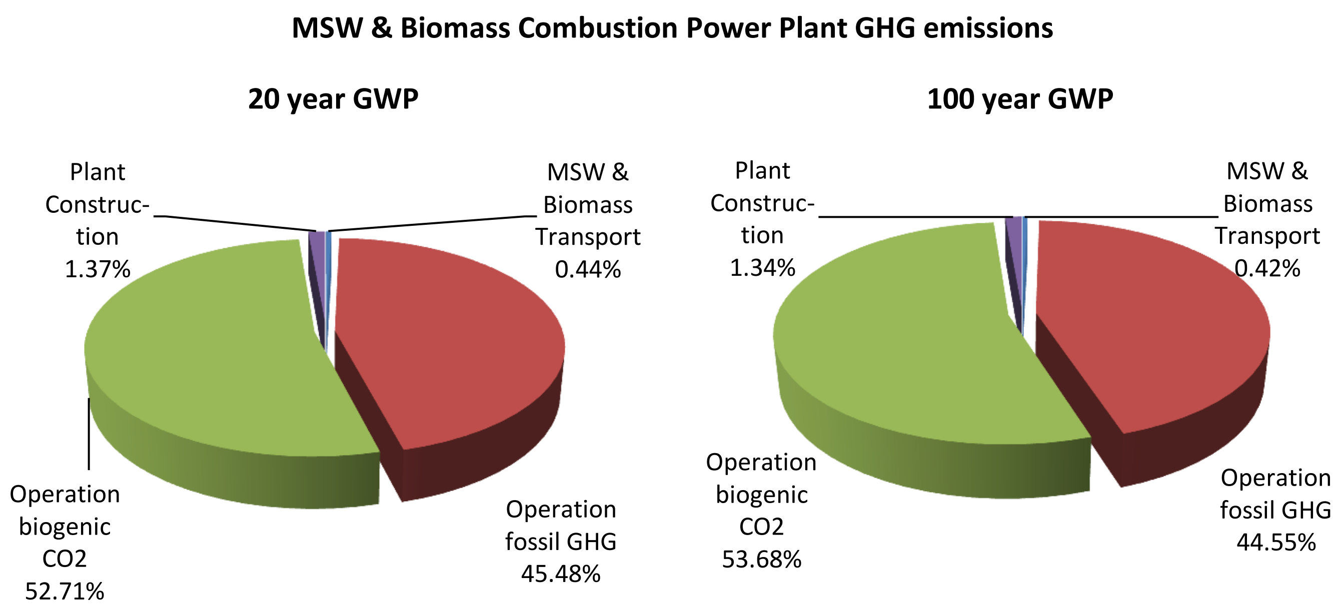


Figure 24. MSW & Biomass Combustion Power Plant GHG emissions (20 and 100 year GWP)

Table 17. MSW & Biomass Combustion Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Biogenic	N_2O	SF_6	CH_4				
Materials Acquisition	8.0435	0.0000	4.99E-05	7.62E-11	0.0051	8.4856	1.26	8.1997	1.24
Materials Transportation	0.6799	0.0000	5.43E-06	2.97E-13	8.18E-04	0.7501	0.11	0.7043	0.11
Biomass Transportation	2.7055	0.0000	3.70E-05	1.18E-12	0.0033	2.9891	0.44	2.8066	0.42
Operation	282.05	355.92	0.0280	0.0000	0.2101	663.01	98.19	651.27	98.23
Total	**293.48**	**355.92**	**0.0281**	**7.77E-11**	**0.2193**	**675.24**	**100**	**662.98**	**100**

<u>Scenario 2: MSW Conventional Combustion</u>

In Scenario 2 (Figure 25), where 23,750 tonnes of MSW are combusted, the amount of GHG emissions is slightly higher at 709 kg CO_2e/MWh based on the 20 year GWP. The source of the GHGs is divided among the pathways in the same manner as Scenario 1, with operations accounting for 98% of GHG emissions for both GWPs under consideration. The biogenic CO_2 contributes to over 36% of total GHG emissions from operations.

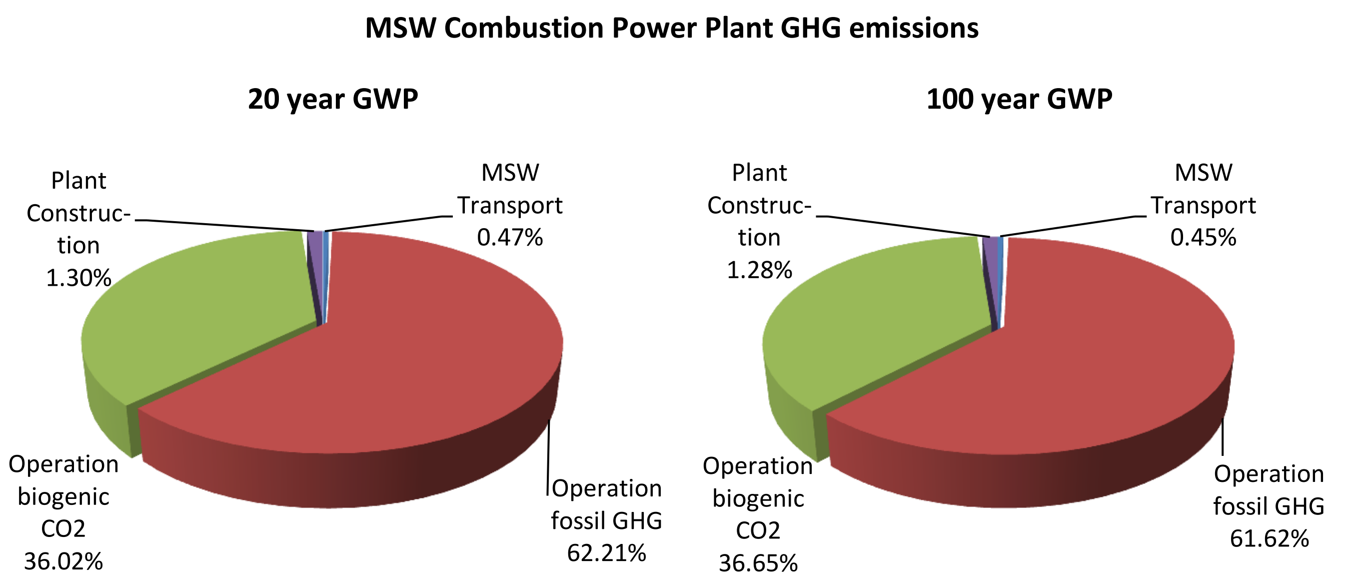


Figure 25. MSW Combustion Power Plant GHG emissions (20 and 100 year GWP)

Table 18. MSW Combustion Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Biogenic	N_2O	SF_6	CH_4				
Materials Acquisition	8.0435	0.0000	4.99E-05	7.62E-11	0.0051	8.4856	1.20	8.1997	1.18
Materials Transportation	0.6799	0.0000	5.43E-06	2.97E-13	8.18E-04	0.7501	0.11	0.7043	0.10
Biomass Transportation	3.0135	0.0000	4.14E-05	1.32E-12	0.0036	3.3288	0.47	3.1260	0.45
Operation	416.07	255.41	0.0280	0.0000	0.2101	696.52	98.23	684.78	98.27
Total	**427.81**	**255.41**	**0.0281**	**7.78E-11**	**0.2196**	**709.08**	**100**	**696.81**	**100**

4.3.3 Biogas

Results of the biogas resource option located at the Whitehorse landfill are shown in Figure 26. The biogas power plant (AD operation) produces a large amount of methane emissions. As such, the amount of GHGs produced over a 20 year timeline versus 100 years is significantly different due to the difference in the GWPs. Calculations using the 20 year GWP show the plant releasing 1,162 kg CO_2e/MWh whereas only 1,016 kg CO_2e/MWh are released based on the 100 year GWP. The combustion of biogas (CHP operation) releases 902.11 kg CO_2e/MWh of biogenic CO_2.

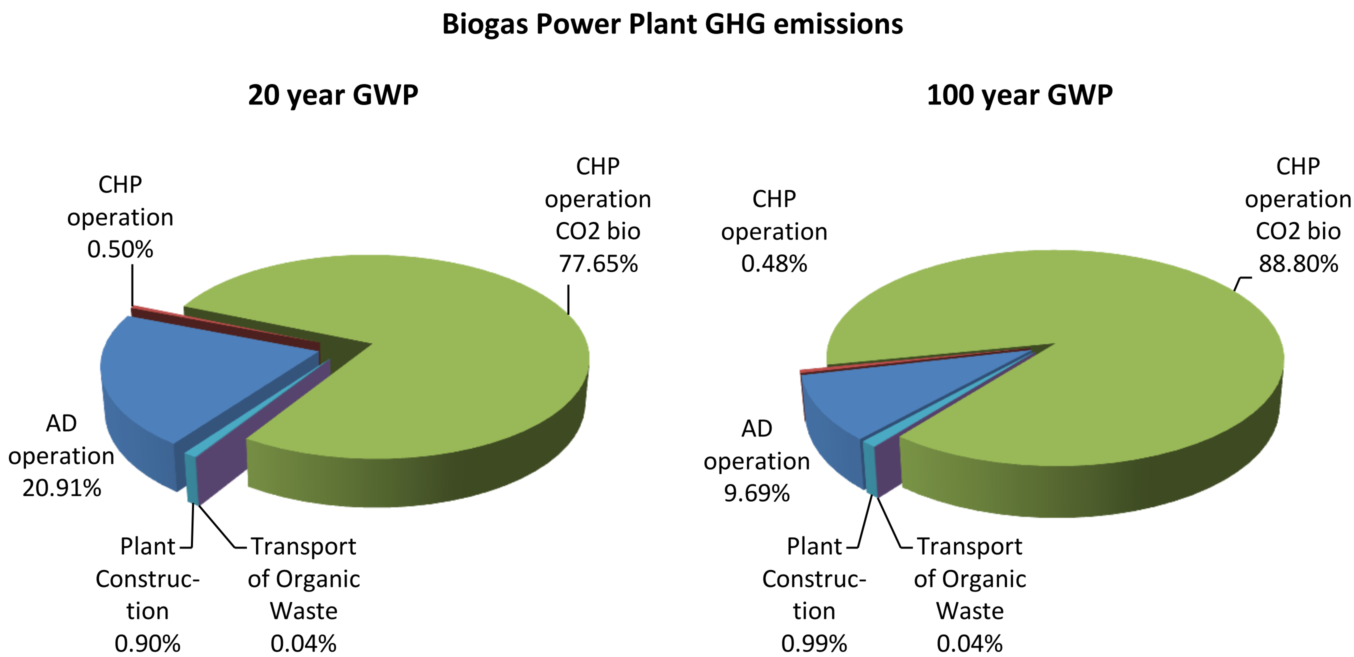


Figure 26. Biogas Power Plant GHG emissions (20 and 100 year GWP)

Table 19. Biogas Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Biogenic	N_2O	SF_6	CH_4				
Materials Acquisition	5.7469	0.0000	3.06E-05	9.31E-13	2.52E-03	5.9663	0.51	5.8254	0.57
Materials Transportation	4.0962	0.0000	3.27E-05	1.79E-12	4.93E-03	4.5189	0.39	4.2429	0.42
AD Operation	18.7826	0.0000	0.0281	0.0000	2.5800	242.92	20.91	98.47	9.69
CHP Operation	0.0000	902.11	0.0164	0.0000	0.0173	907.89	78.15	906.94	89.28
Waste Transportation	0.4050	0.0000	5.38E-06	0.0000	4.04E-06	0.4067	0.04	0.4065	0.04
Total	**29.0306**	**902.11**	**0.0446**	**2.72E-12**	**2.6047**	**1161.71**	**100**	**1015.88**	**100**

4.3.4 GEOTHERMAL

Figure 27 shows the results for a geothermal plant that will be located at McArthur Springs with 4.6 kg CO_2e/MWh GHG emissions produced based on the 20 year GWP and 4.2 kg CO_2e/MWh based on the 100 year GWP. For both GWPs, plant and transmission line construction account for more than 99% of the emitted GHGs. The length of the transmission line in this pathway is 42 km and the line construction and operation accounts for 0.74% and 0.17% of the total impact in the 20 year scenario, respectively and 0.75% and 0.18% in the 100 year scenario, respectively (Table 20).

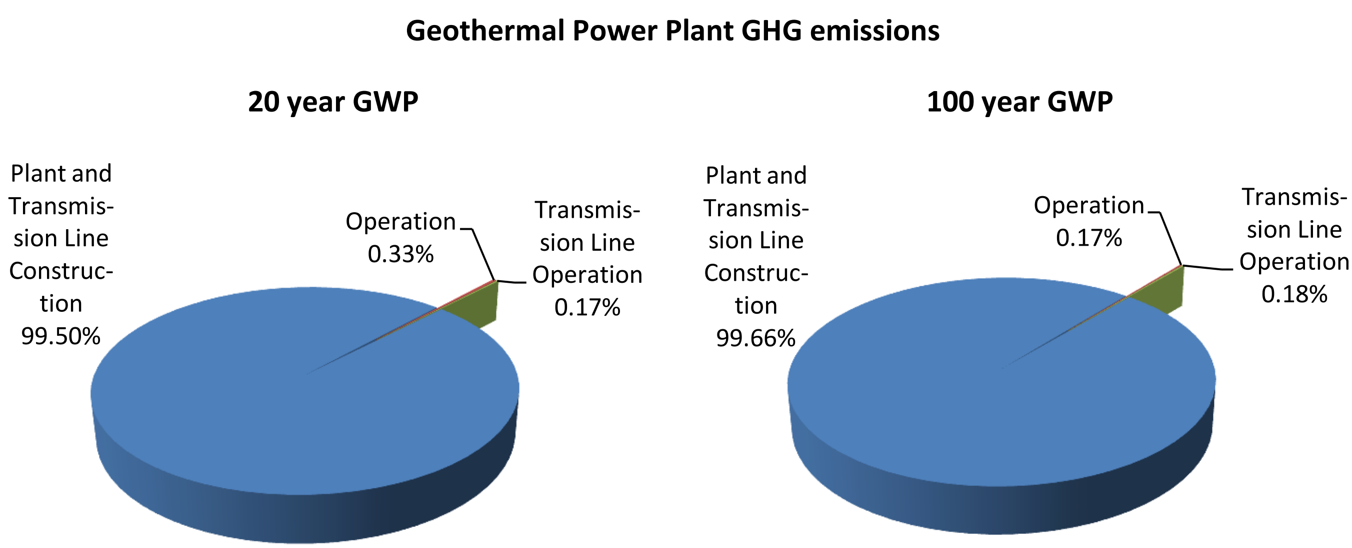


Figure 27. Geothermal Power Plant GHG emissions (20 and 100 year GWP)

Table 20. Geothermal Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh				Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4				
Plant construction	3.9612	5.33E-05	2.59E-10	0.0070	4.5626	98.76	4.1711	98.91
Transmission line construction	0.0302	5.39E-07	2.61E-12	4.58E-05	0.0341	0.74	0.0316	0.75
Operation	0.0024	2.13E-06	0.0000	1.44E-04	0.0150	0.33	0.0070	0.17
Transmission line operation	0.0070	9.44E-07	2.60E-11	0.0000	0.0080	0.17	0.0075	0.18
Total	**4.0007**	**5.69E-05**	**2.88E-10**	**0.0072**	**4.6198**	**100**	**4.2171**	**100**

4.3.5 WIND

Figure 28 presents GHG emissions from wind power generation. The total GHG emissions are 10.7 kg CO_2e/MWh using the 20 year GWP. The majority of the emissions (62%) originate from plant and transmission line construction life cycle stages. The wind turbines are transported by sea freighter from Denmark to Montreal and then by truck to Whitehorse. This accounts for 30% of the total life cycle impact. Almost 7% of GHG emissions come from wind power plant operations and transmission line operations. Since the length of the transmission line is only 7.6km, most of GHGs from operations originate from wind plant operations. The difference in emissions between the two time horizons is very small.

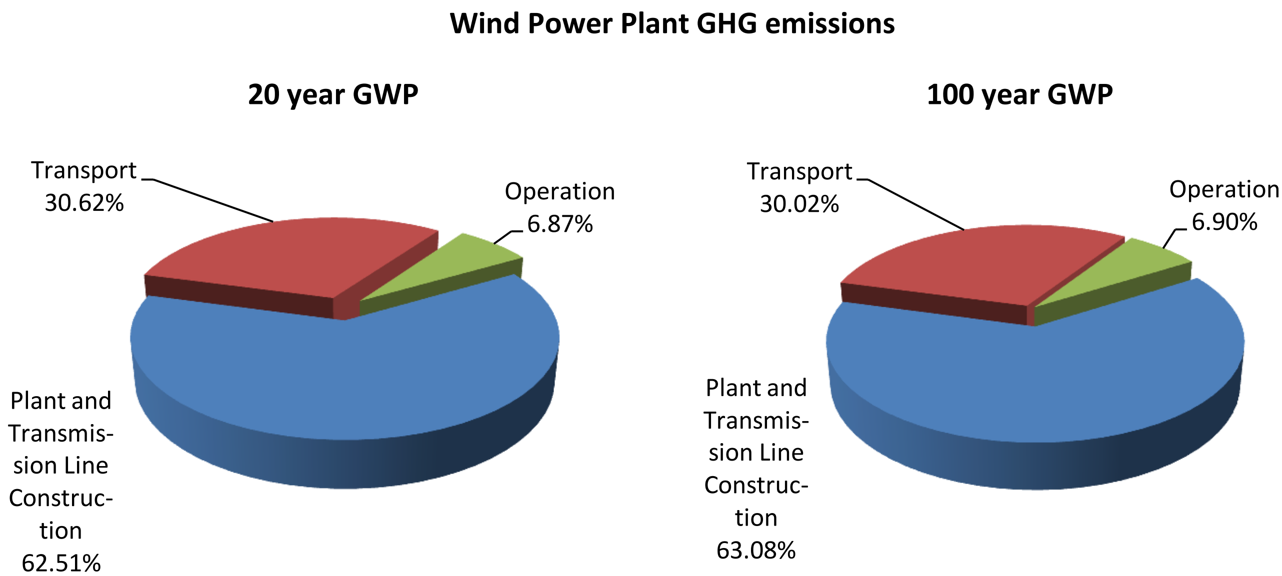


Figure 28. Wind Power Plant GHG emissions (20 and 100 year GWP)

Table 21. Wind Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh				Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4				
Plant and Transmission Line Construction	6.3215	2.34E-04	7.37E-10	0.0040	6.7154	62.51	6.4942	63.08
Materials Transportation	2.9853	2.30E-05	1.29E-12	0.0035	3.2892	30.62	3.0907	30.02
Operation	0.6913	2.24E-05	4.71E-12	4.85E-04	0.7379	6.87	0.7108	6.90
Total	**9.9980**	**2.79E-04**	**7.43E-10**	**0.0080**	**10.7425**	**100**	**10.2956**	**100**

4.3.6 SOLAR

Results for the solar resource option are shown in Figure 29, where GHGs are mostly generated by PV panels manufacturing (93%) for both the 20 and 100 year GWPs. The Panasonic 330W panels are manufactured in Japan and transported to Vancouver by sea freighter and then to Whitehorse by truck. The amount of GHGs emitted is 43.24 kg CO_2e/MWh for the 20 year time horizon and 38.99 kg CO_2e/MWh for the 100 year time horizon.

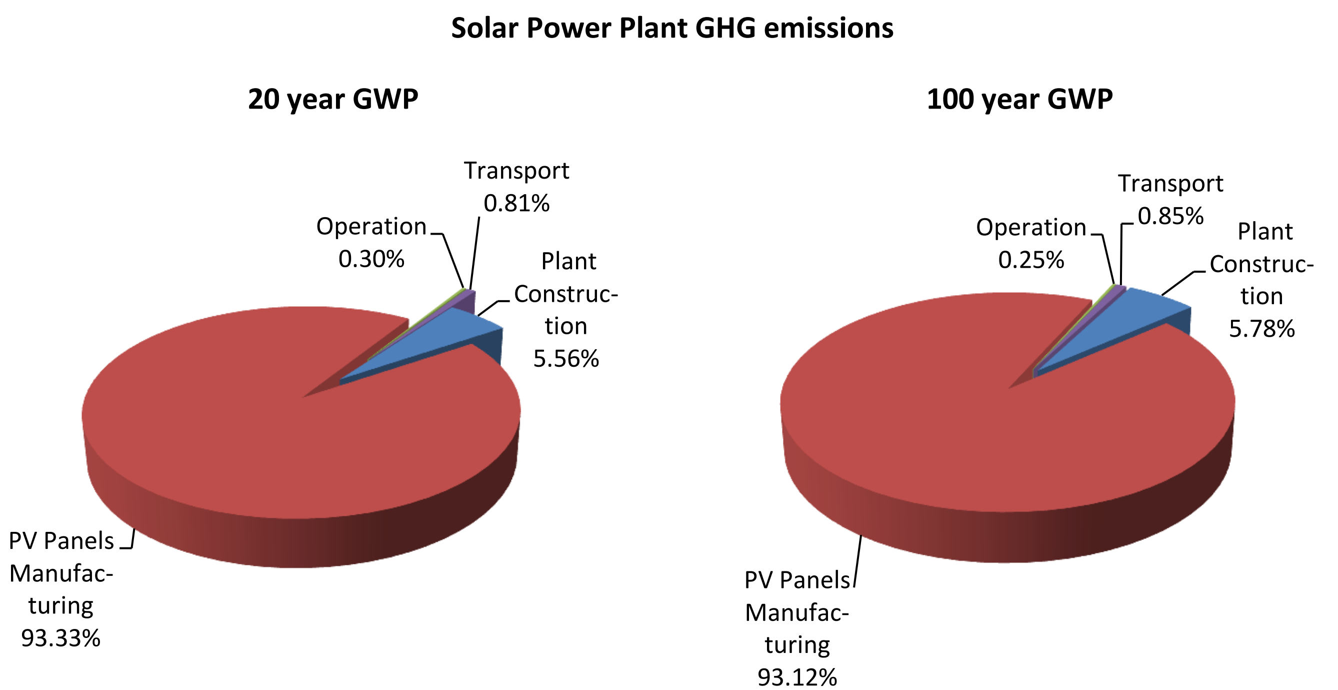


Figure 29. Solar Power Plant GHG emissions (20 and 100 year GWP)

Table 22. Solar Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh				Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4				
Plant Construction	2.1678	4.14E-05	3.52E-08	2.66E-03	2.4028	5.56	2.2541	5.78
PV Panels Manufacturing	34.1087	6.42E-04	0.0000	0.0724	40.3605	93.33	36.3064	93.12
Operation	0.0836	1.65E-06	1.65E-13	5.27E-04	0.1284	0.30	0.0988	0.25
Transportation	0.3182	2.33E-06	1.39E-13	3.83E-04	0.3510	0.81	0.3296	0.85
Total	**36.6784**	**6.88E-04**	**3.52E-08**	**0.0760**	**43.2426**	**100**	**38.9888**	**100**

4.3.7 PUMPED STORAGE HYDRO POWER PLANT

Located at Moon Lake, pumped storage results are shown in Figure 30. The total GHG emissions are 23.41 kg CO_2e/MWh under the 20 year time horizon GWP factor, with 15.15 kg CO_2e/MWh for the 100 time horizon GWP. Nearly 70% of emissions came from the operation of the plant calculated using the 100 year GWP while 80% came from the 20 year GWP calculation. These emissions originated from biomass decomposition after land inundation. Biogenic CO_2 emissions from land inundation are shown separately and are 24% for the 20 year GWP and over 37% for the 100 year GWP. Plant and transmission line construction accounted for over 30% of GHG emissions using the 100 year GWP but only 19.83% for the 20 year GWP. The differences in distribution of GHG emissions over the 20 and 100 year time horizons are due to different methane GWP values.

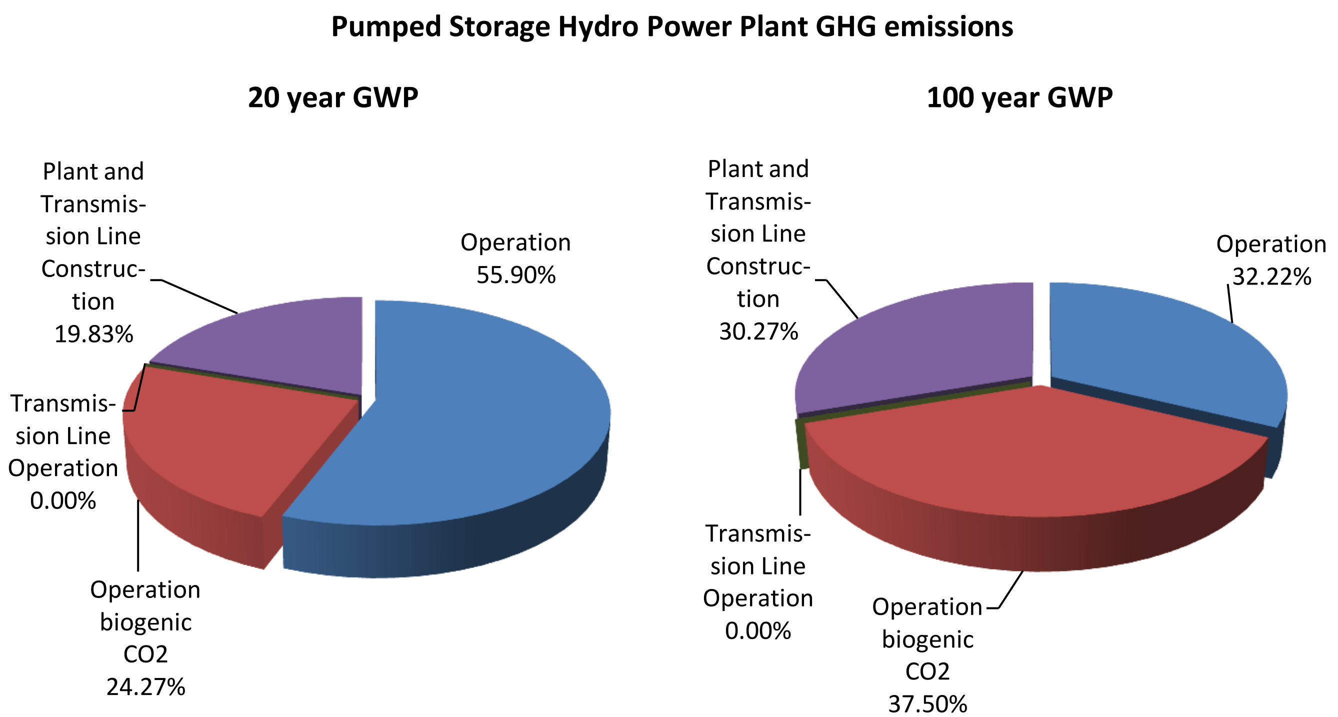


Figure 30. Pumped Storage Power Plant GHG emissions (20 and 100 year GWP)

Table 23. Pumped Storage Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Biogenic	N_2O	SF_6	CH_4				
Plant construction	4.5487	0.0000	2.96E-05	1.33E-12	9.93E-04	4.6400	19.82	4.5844	30.26
Transmission line construction	0.0019	0.0000	3.33E-08	1.62E-13	2.83E-06	0.0021	0.01	0.0020	0.01
Operation	0.0000	5.6814	0.0029	3.40E-10	0.1466	18.7682	80.17	10.5626	69.72
Transmission line operation	0.0004	0.0000	5.84E-08	1.61E-12	5.43E-07	0.0005	0.00	0.0005	0.00
Total	**4.5510**	**5.6814**	**0.0030**	**3.43E-10**	**0.1477**	**23.4108**	**100**	**15.1494**	**100**

4.3.8 Small Hydro

The scenario of constructing a small hydro plant at Drury Creek generated 20.56 kg CO_2e/MWh for the 20 year GWP and nearly 12.99 kg CO_2e/MWh for the 100 year GWP. The results, shown in Figure 31, show that the largest difference is in plant operation, where 84% of emissions are calculated using the 20 year GWP and 75% calculated in the 100 year GWP. As with the pumped storage option, these emissions come from land inundation. The other two differences are similar to the pumped storage results in the above section: 16% versus 25% are attributed to plant and transmission line construction and transmission line operation for the 20 year versus 100 year GWP, respectively.

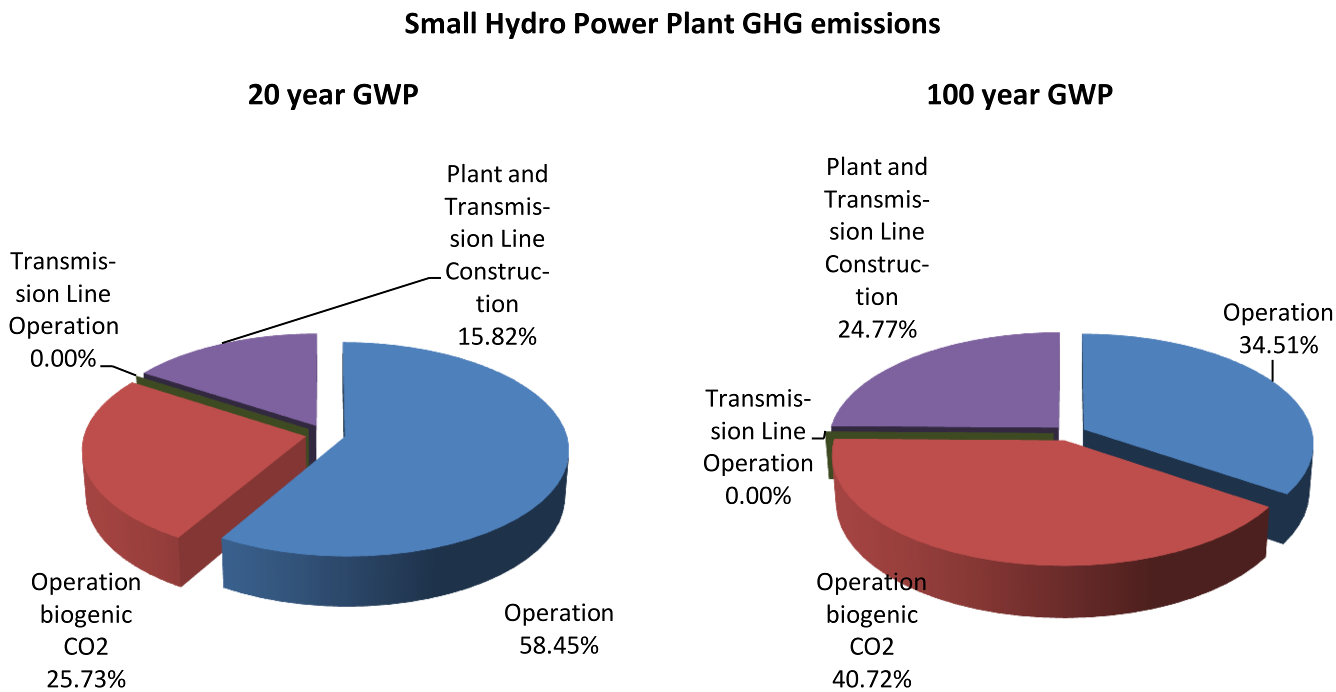


Figure 31. Small Hydro Power Plant GHG emissions (20 and 100 year GWP)

Table 24. Small Hydro Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Biogenic	N_2O	SF_6	CH_4				
Plant construction	3.1938	0.0000	2.10E-05	1.35E-12	6.44E-04	3.2534	15.82	3.2174	24.76
Transmission line construction	0.0004	0.0000	6.41E-09	3.11E-14	5.45E-07	0.0004	0.00	0.0004	0.00
Operation	0.0000	5.2904	0.0027	0.00E+00	0.1346	17.3101	84.18	9.7736	75.22
Transmission line operation	0.0001	0.0000	1.12E-08	3.10E-13	1.04E-07	0.0001	0.00	0.0001	0.02
Total	**3.1942**	**5.2904**	**0.0027**	**1.69E-12**	**0.1353**	**20.5640**	**100**	**12.9915**	**100**

4.3.9 Energy Storage: Lithium Ion Batteries

Lithium ion batteries were chosen as the preferred means to store energy and results are shown in Figure 32. The functional unit for this application is MWh of energy stored. Almost the entire amount of GHG emissions is from battery manufacturing (98%) for both time horizons (Table 25). The total GHG emissions are 16.15 kg CO_2e/MWh for the 20 year time horizon and 14.66 kg CO_2e/MWh for the 100 year time horizon.

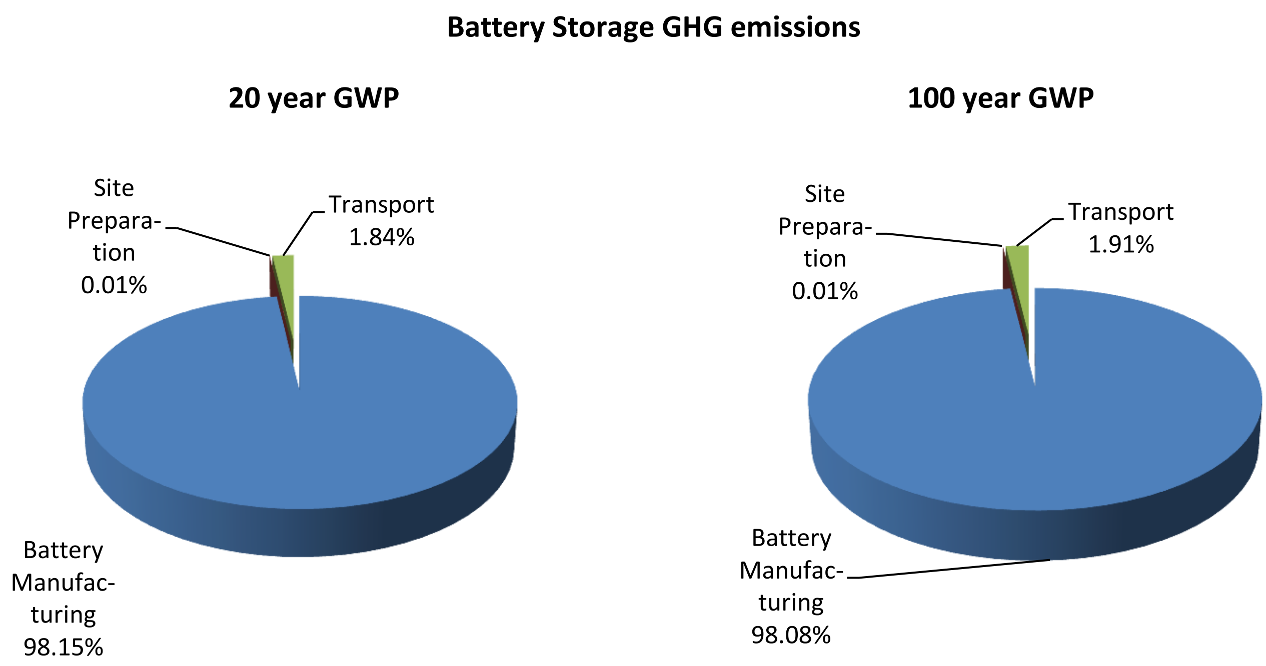


Figure 32. Lithium Ion Battery GHG emissions (20 and 100 year GWP)

Table 25. Lithium Ion Battery GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh						Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4	CF_4	C_2F_6				
Battery Manufac-turing	13.1879	2.48E-04	0.0000	0.0280	4.31E-05	5.9E-06	15.8520	98.15	14.3777	98.08
Site Prepara-tion	0.0017	2.61E-07	1.29E-17	1.22E-07	0.0000	0.0000	0.0018	0.01	0.0018	0.01
Opera-tion	0.2697	2.08E-06	1.18E-13	0.0003	0.0000	0.0000	0.2975	1.84	0.2793	1.91
Total	**13.4593**	**2.51E-04**	**1.18E-13**	**0.0283**	**4.31E-05**	**5.9E-06**	**16.1513**	**100**	**14.6588**	**100**

4.3.10 Thermal-Diesel

Figure 33 shows the results for a Diesel plant at Takhini Substation. Total GHG emissions are 1,058.91 kg CO_2e/MWh under the 20 year time horizon, where operations account for over 65%, extraction of resources accounts for nearly 19%, and fuel production and transportation accounts for over 15% of the produced GHGs. The remaining 0.04% comes from plant construction. A slightly smaller amount of GHGs were calculated using the 100 year GWP values, giving an estimate of 951.11 kg CO_2e/MWh. In this case, plant operation contributed to over 72% of the GHG emissions, fuel production and transportation accounted for 15%, and extraction of resources was only 12% - a 7% decrease compared to the 20 year time horizon. This is due to a lower GWP of methane emissions from crude oil extraction under the 100 year time horizon. Similar to the results from the 20 year time horizon, plant construction accounts for the remaining 0.04% of GHGs.

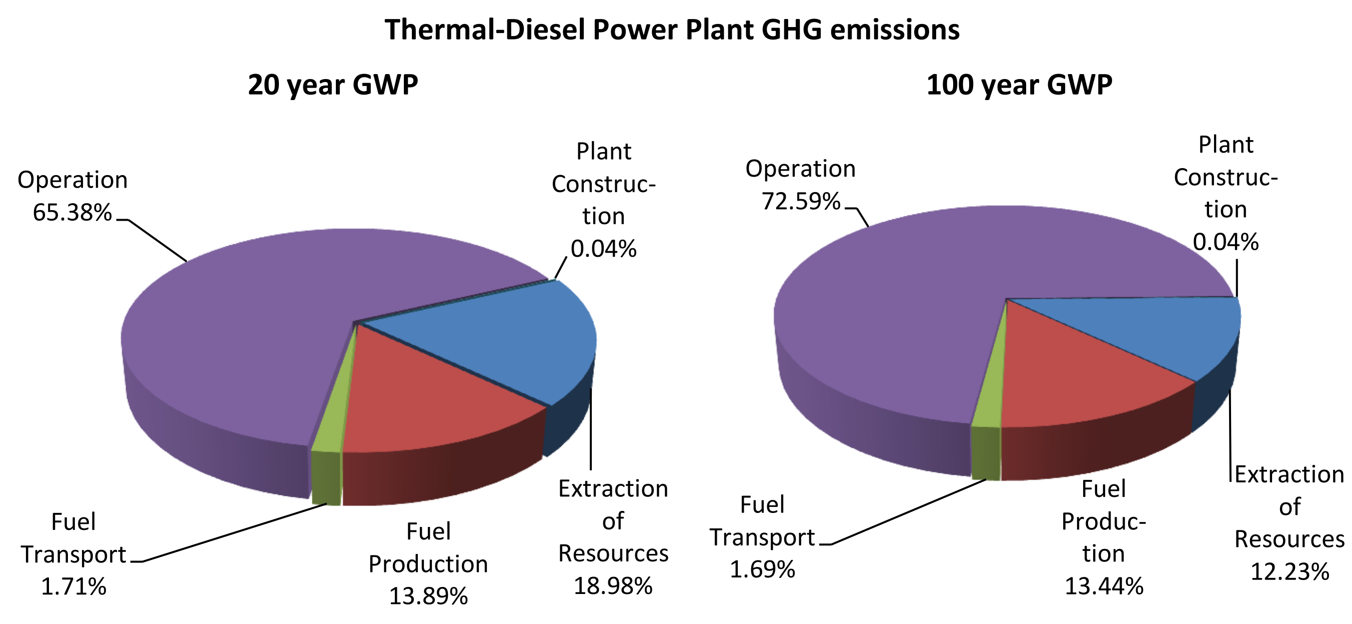


Figure 33. Thermal-Diesel Power Plant GHG emissions (20 and 100 year GWP)

Table 26. Thermal-Diesel Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh				Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4				
Resource Extraction	73.3456	0.0024	0.0000	1.5124	201.02	18.98	116.33	12.23
Materials Acquisition	0.2608	1.34E-06	3.66E-14	0.0001	0.2723	0.03	0.2649	0.03
Materials Transportation	0.1416	1.98E-06	5.94E-14	1.64E-04	0.1559	0.01	0.1468	0.02
Fuel Production	116.69	0.0058	0.0000	0.3439	147.10	13.89	127.85	13.44
Fuel Transportation	14.9790	0.0004	0.0000	0.0353	18.06	1.71	16.09	1.69
Operation	620.30	0.2607	0.0000	0.0378	692.29	65.38	690.43	72.59
Total	**825.72**	**0.2693**	**9.60E-14**	**1.9297**	**1058.91**	**100**	**951.11**	**100**

Figure 33 show GHG emissions that originate from five life cycle stages. The processes included in each life cycle stage are described below.

- Resource Extraction - crude oil extraction, leakage, vented and flared gas emissions;
- Fuel Production – crude oil transport via ocean vessel, diesel production at the refinery, crude oil and diesel storage;
- Fuel Transportation – diesel fuel transport by ocean barge and truck to Yukon Energy;
- Plant Construction (includes materials acquisition and transportation) – extraction and processing of raw materials, transport of materials, site preparation;
- Operation – diesel fuel combustion.

4.3.11 THERMAL-LNG

Results for a thermal LNG plant located at the Takhini Substation are shown in Figure 34. In this scenario, an LNG power plant produces approximately one-third more GHGs when analyzed using the 20 year GWP values (1,050.76 kg CO_2e/MWh) in comparison to the 100 year GWP values (727.68 kg CO_2e/MWh). This is primarily due to the different methane GWP values. Extraction of resources (6.6% versus 4.9%), fuel production and transportation (12% versus 15%) and plant operation (81% versus 79%) are the primary differences in GHG emission for the 20 year versus 100 year time horizon, respectively. Using the 20 year GWP, GHG emissions were double for extraction of resources (70 kg CO_2e/MWh) and approximately one-third higher for plant operation (847 kg CO_2e/MWh).

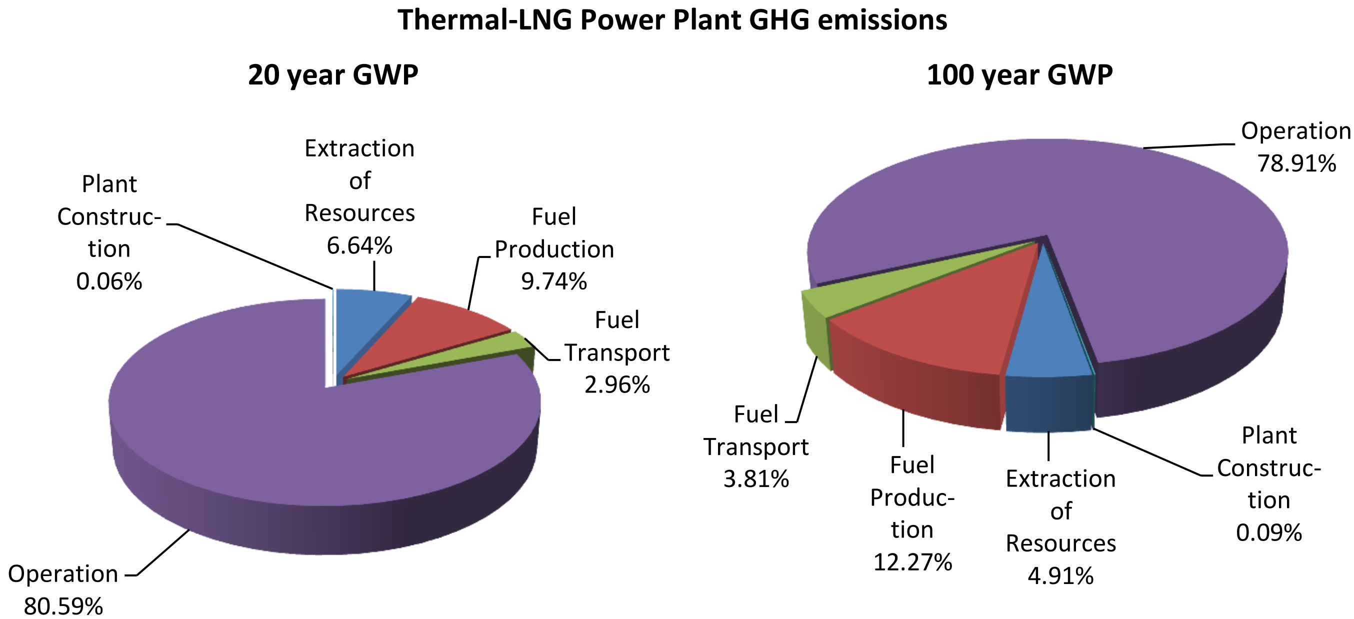


Figure 34. Thermal-LNG Power Plant GHG emissions (20 and 100 year GWP)

Figure 34 show GHG emissions that originate from five life cycle stages. The processes included in each life cycle stage are described below.

- Resource Extraction - natural gas extraction, leakage and flare emissions;
- Fuel Production – fuel processing (treatment & liquefaction), distribution by pipeline, fuel storage;
- Fuel Transport – LNG transport by truck to Yukon Energy;
- Plant Construction – extraction and processing of raw materials for plant construction, transport of materials , site preparation;
- Operation – LNG combustion.

Table 27. Thermal-LNG Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh				Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4				
Resource Extraction	18.5317	9.02E-04	0.0000	0.6069	69.7494	6.64	35.7639	4.91
Material Acquisition	0.3641	1.96E-06	6.06E-14	0.0002	0.3775	0.04	0.3689	0.05
Material Transportation	0.2701	3.13E-06	1.15E-13	3.17E-04	0.2976	0.03	0.2798	0.04
Fuel Production	81.86	0.0035	0.0000	0.2327	102.34	9.74	89.31	12.27
Fuel Transportation	25.82	0.0008	0.0000	0.0609	31.14	2.96	27.73	3.81
Operation	433.18	0.0178	0.0000	4.8687	846.86	80.59	574.23	78.91
Total	**560.02**	**0.0231**	**1.76E-13**	**5.7697**	**1050.76**	**100.00**	**727.68**	**100.00**

4.3.12 NEW TRANSMISSION LINE

Figure 35 and Table 28 present the results for the completion of a new 230 kV transmission line from Whitehorse to Skagway. It is assumed that the line operates at 100% reliable capacity (3880.7 GWh/yr). The functional unit for this scenario is MWh-km. Total GHG emissions per MWh-km are 0.001 kg CO_2e/MWh-km under the 20 year time horizon and 0.0009 CO_2e/MWh-km under the 100 year time horizon. Materials acquisition accounts for 78% of the GHGs in both scenarios. The line operation accounts for 19% of the total impact with the majority of impact originating from yearly vegetation clearing. The difference in results between the 20 year and 100 year time horizons is quite small.

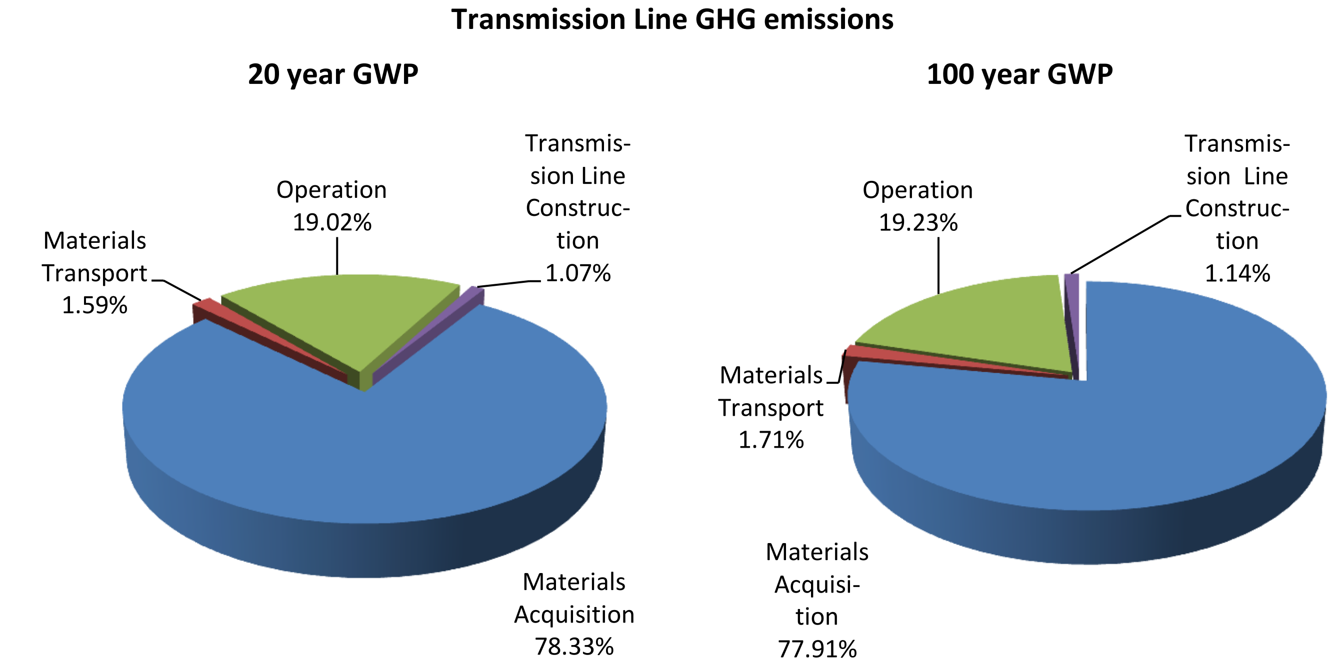


Figure 35. Transmission Line GHG emissions (20 and 100 year GWP)

Table 28. Transmission Line GHG emissions summary of results per MWh-km

Life Cycle Stage	Emissions, kg/MWh-km				Total, kg CO_2e/MWh-km (20 year GWP)	%	Total, kg CO_2e/MWh-km (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4				
Materials Acquisition	6.91E-04	1.12E-08	6.22E-14	1.08E-06	7.8388E-04	78.33	7.2368E-04	77.91
Materials Transportation	1.59E-05	1.08E-10	1.21E-21	1.77E-10	1.5899E-05	1.59	1.5889E-05	1.71
Transmission Line Construction	1.02E-05	1.53E-09	0.00E+00	5.10E-10	1.0660E-05	1.07	1.0633E-05	1.14
Operation	0.000167	2.25E-08	6.20E-13	2.09E-07	0.000190	19.02	0.000179	19.23
Total	**0.000883**	**3.53E-08**	**6.82E-13**	**1.28E-06**	**0.001001**	**100**	**0.000929**	**100**

The total GHG emissions in MWh for a 170km transmission line are estimated by multiplying the MWh-km results in Table 28 by the length of the transmission line (170km). The results are shown in Table 29.

Table 29. Transmission Line GHG emissions summary of results per MWh

Life Cycle Stage	Emissions, kg/MWh				Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4				
Materials Acquisition	0.1174	1.90E-06	1.06E-11	1.83E-04	0.1333	78.33	0.1230	77.91
Materials Transportation	0.0027	1.83E-08	2.05E-19	3.01E-08	0.0027	1.59	0.0027	1.71
Transmission Line Construction	0.0017	2.61E-07	0.0000	8.67E-08	0.0018	1.07	0.0018	1.14
Operation	0.0284	3.82E-06	1.05E-10	0.0000	0.0324	19.02	0.0304	19.23
Total	**0.1502**	**6.00E-06**	**1.16E-10**	**0.0002**	**0.1701**	**100**	**0.1579**	**100**

4.3.13 Water Diversion Project

Figure 36 and Table 30 present the results for the Water Diversion Project. Total GHG emissions for the 24 year project lifetime are 58.03 kg CO_2e/MWh-km under the 20 year time horizon and 32.78 CO_2e/MWh-km under the 100 year time horizon. The GHG emissions from operation originate from land inundation. These emissions are higher per MWh than in the small hydro and pumped storage pathways due to a shorter project life of 24 years, instead of 65 years in other pathways.

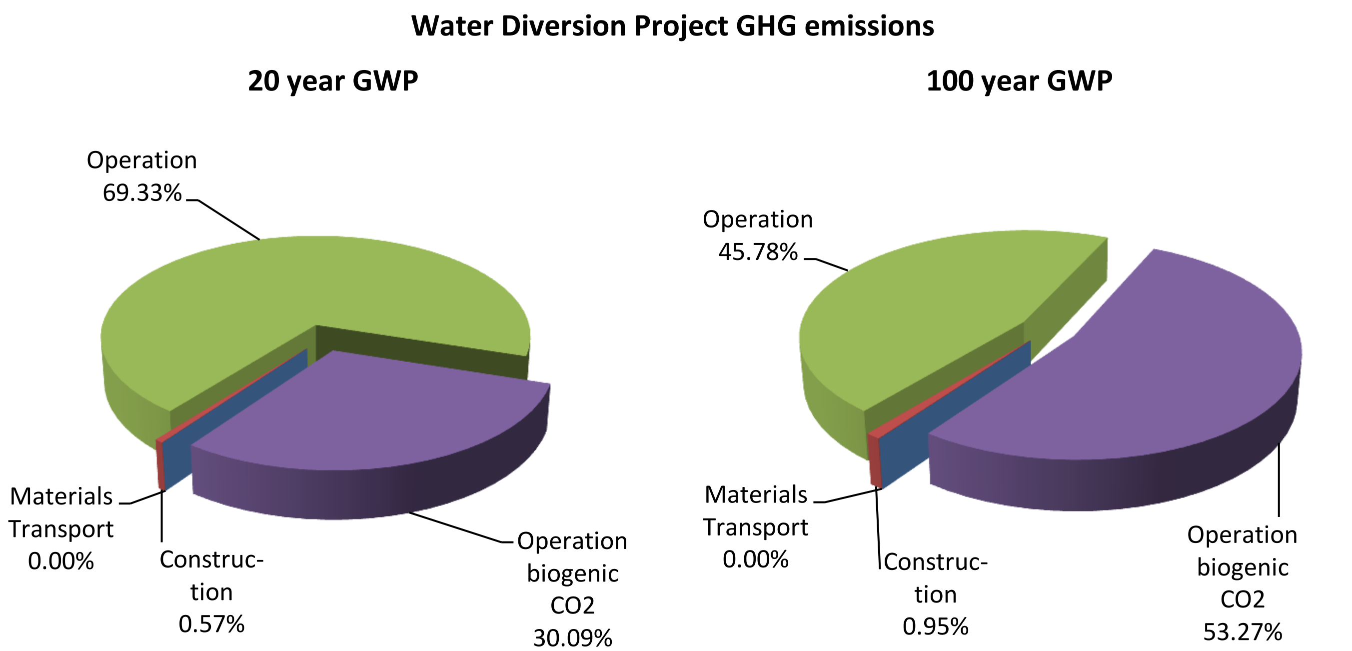


Figure 36. Water Diversion Project GHG emissions (20 and 100 year GWP)

Table 30. Water Diversion Project GHG emissions summary of results – 24 years lifetime

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Biogenic	N_2O	SF_6	CH_4				
Materials Transportation	6.94E-04	0.0000	5.54E-09	3.03E-16	8.35E-07	7.6521E-04	0.00	7.1847E-04	0.00
Construction	0.2917	0.0000	3.93E-05	1.29E-13	3.65E-04	0.3328	0.57	0.3124	0.95
Operation	0.0000	17.4614	11.5771	0.0000	0.4506	57.6924	99.43	32.4669	99.04
Total	**0.2924**	**17.4614**	**0.0090**	**1.29E-13**	**0.4510**	**58.0260**	**100**	**32.7800**	**100**

In order to compare the Water Diversion Project with other hydro options (small hydro and pumped storage), the results were normalized per project life of 65 years. The normalized results are shown in Table 31.

Table 31. Water Diversion Project GHG emissions summary of results – 65 years lifetime

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Biogenic	N_2O	SF_6	CH_4				
Materials Transportation	2.56E-04	0.0000	2.04E-09	1.12E-16	3.08E-07	2.8254E-04	0.00	2.6528E-04	0.00
Construction	0.1077	0.0000	1.45E-05	4.77E-14	1.35E-04	0.1229	0.57	0.1153	0.95
Operation	0.0000	6.4473	0.0033	0.0000	0.1664	21.3023	99.43	11.9884	99.04
Total	**0.1080**	**6.4473**	**0.0033**	**0.0000**	**0.1665**	**21.4255**	**100**	**12.1040**	**100**

4.4 Fixed and Variable Emissions Analysis

The fixed GHG emissions are emissions associated with power plant and infrastructure construction and include raw materials acquisition, transportation, site preparation, and construction of the plant and transmission line. In the diesel, LNG, biomass gasification and waste to energy pathways, the emissions related to diesel, LNG, biomass and MSW transportation are considered variable emissions. The fixed emissions are expressed in tonnes CO_2e per facility, while variable emissions that originate from power plant operations are expressed in kg CO_2e/MWh.

Table 32. Fixed and variable GHG emissions from energy production pathways (20 and 100 year GWP)

Energy Production Pathway	Fixed GHG emissions tonnes CO_2e		Variable GHG emissions kg CO_2e/MWh		Variable GHG emissions (biogenic CO_2 excluded) kg CO_2e/MWh	
	20 year GWP	100 year GWP	20 year GWP	100 year GWP	20 year GWP	100 year GWP
Biomass Gasification	679.1	651.7	769.3	768.9	14.53	14.14
Waste to energy: MSW	7,775	7,496	699.8	687.9	444.4	432.5
Waste to energy: MSW + biomass	7,775	7,496	666.0	654.1	310.1	298.2
Biogas	420.9	404.1	1151.2	1005.8	249.1	103.7
Geothermal	6,647	6,077	0.0230	0.0145	0.0230	0.0145
Wind	3,641	3,499	0.7379	0.7108	0.7379	0.7108
Solar	6,726	6,067	0.1284	0.0988	0.1284	0.0988
Pumped storage	16,294	16,098	18.77	10.56	13.09	4.88
Small hydro	6,704	6,630	17.31	9.77	12.02	4.48
Battery storage	904.5	820.9	0.00	0.00	0.00	0.00
Thermal - Diesel	675.2	649.1	1058.48	950.70	1058.48	950.70
Thermal - LNG	1,065	1,023	1050.09	727.04	1050.09	727.04
New transmission line (170km)	29,498	27,284	0.0324	0.0304	0.0324	0.0304
Water diversion project, 24 years lifetime	237.8	223.2	57.69	32.47	40.23	15.01
Water diversion project, 65 years lifetime	237.8	223.2	21.30	11.99	14.86	5.43

The site specific data for plant construction (e.g. area of land to be cleared, type of dam, excavation area, quantities of construction materials, energy generation technology) was available for wind, solar, geothermal, battery storage, transmission line, diesel, LNG, biomass gasification, biogas, and the water diversion pathway. The power plant construction data in the waste to energy pathway is representative of a North American power plant. Small hydro and pumped storage power plant construction data represents a mix of North American and European small hydro and pumped storage power plants. The plant construction data is obtained per MWh of energy produced; if the emissions data expressed per MWh is converted back to the total GHG emissions from plant construction using the total energy output of the plant over plant's lifetime, it increases the uncertainty of the results. Site specific data on construction material requirements need to be obtained to better understand GHG emissions from power plants construction in these pathways. It is recommended to update the fixed GHG emissions of waste to energy, small hydro and pumped storage when site and technology specific data become available.

4.5 Sensitivity Analysis

A sensitivity analysis was performed to determine the effect of changing parameters and assumptions on the final results. As it was discussed earlier in section 3.4.1, a number of uncertainties in the life cycle inventory data are identified. For example, materials and equipment manufacturing locations are not known in the wind and battery storage pathways. However, it is expected that the equipment and materials manufacturing location will greatly affect the results of the study, since the GHG emissions originate mainly from the upstream life cycle stages in these pathways. The effect of these and other uncertainties (e.g. CHP plant efficiency, LNG combustion emission factors, and transmission line capacity) on the results of the study is assessed in this section. The results are presented below.

4.5.1 Wind

The wind pathway results presented in the section 4.3.5 are for a 3 turbine wind plant. The modelled wind turbines are Vesta V80 2 MW turbines manufactured in Denmark.

An alternative scenario was modelled to present results for an average mix of wind technologies currently in use in the U.S. This scenario assumes that 55% of wind turbine components are manufactured in China and then transported to Canada by sea freighter and truck. The remaining 45% of wind plant materials and components come from the U.S. Four (4) wind turbines with a capacity of 1.5 MW each are installed. The results of this scenario are shown in Figure 37 below.

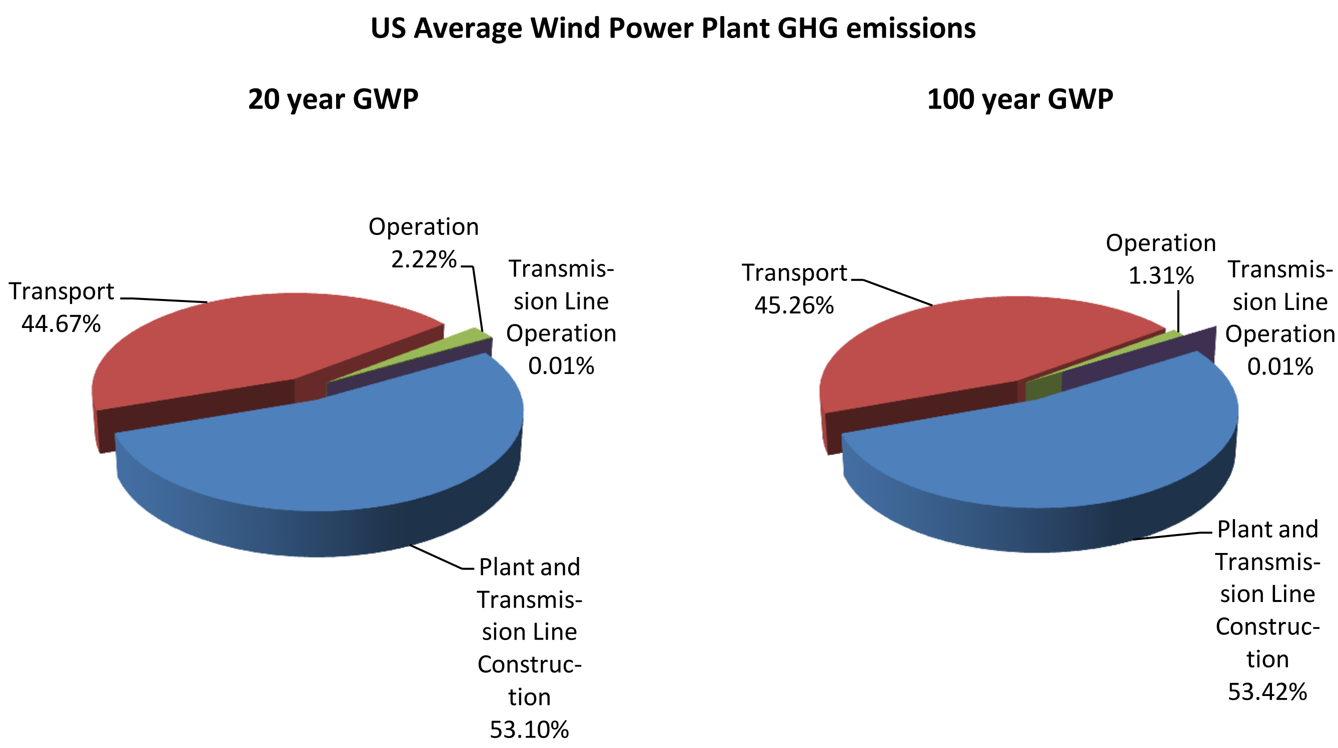


Figure 37. U.S. Average Wind Power Plant GHG emissions (20 and 100 year GWP)

Table 33. U.S. Average Wind Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh				Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	N_2O	SF_6	CH_4				
Plant and Transmission Line Construction	10.1515	3.03E-05	7.84E-10	4.05E-04	10.3069	53.10	10.2087	53.42
Materials Transportation	8.6400	7.15E-07	0.0014	3.67E-04	8.6710	44.67	8.6505	45.26
Operation	0.1440	6.17E-05	9.30E-11	0.0032	0.4315	2.22	0.2507	1.31
Transmission Line Operation	0.0013	1.71E-07	4.71E-12	1.59E-06	0.0014	0.01	0.0014	0.01
Total	**18.9367**	**9.29E-05**	**0.0014**	**0.0040**	**19.4109**	**100.00**	**19.1112**	**100.00**

As it can be seen from Tables 34, the total GHG emissions are significantly higher in the average U.S. wind plant scenario compared to the Vesta turbines manufactured in Denmark. This is due to the higher GHG emissions from transportation and turbine components manufacturing in China. The choice of the turbine manufacturer should be carefully considered when selecting wind turbines for the project, as wind turbines manufactured in Asia tend to have higher environmental impact.

Table 34. Wind scenarios comparison (100 year GWP)

Wind Plant	**Total GHG, kg CO_2e/MWh (100 yr GWP)**	Plant and Transmission Line Construction	Materials Transportation	Operation (plant and transmission line)
Baseline scenario 3 Vesta V80 2 MW turbines	10.33	6.49	3.09	0.71
Average U.S. wind plant Four 1.5MW turbines	19.11	10.21	8.65	0.25

4.5.2 Battery Storage

Two batteries from different manufacturers – UltraLife Corporation and SAFT Batteries were evaluated. A 1,000-kWh lithium-ion battery manufactured by SAFT is currently installed at the Wind and Storage Demonstration project site in the Cowessess First Nations, Saskatchewan[43]. A specific power density of different batteries varies significantly from one manufacturer to another. The UltraLife Corporation's battery has a specific power density of 149 W/kg and the SAFT Batteries' specific power density is 60 W/kg.

The effect from the number of batteries required for a 20-year plant lifetime was also modelled. The baseline scenario (UltraLife battery) described in the previous section assumes that 1.5 batteries are

[43] Natural Resources Canada. (2016). Wind and Storage Demonstration in a First Nations Community, Cowessess First Nation. http://www.nrcan.gc.ca/energy/funding/current-funding-programs/cef/4983

needed. The sensitivity scenario assessed the effect of battery's lifetime of 10 years. In this case, two batteries are required. The results for the 100 year GWP are presented in Table 35 below.

Table 35. Battery storage sensitivity analysis results (100 year GWP)

Battery manufacturer	Battery lifetime, years	Number of batteries	GHG, kg CO_2e/MWh (100 yr GWP)
UltraLife (baseline scenario)	15	1.5	14.66
Ultralife	10	2	19.44
Saft	15	1.5	35.64
Saft	10	2	47.48

A significant increase in GHG emissions from one type of the battery to another is observed. The Saft battery's specific power density is only 60 W/kg. This means that the weight of a 8MW battery (132 tonnes) is much higher compared to the UltraLife battery with the specific power density of 149 W/kg (53.6 tonnes). This results in higher GHG emissions from battery manufacturing and transportation life cycle stages.

4.5.3 Biomass Gasification

An alternative scenario for biomass gasification was modelled. It assumes that only 1,283 MWh of heat per year will be delivered and consumed in Haines Junction compared to 8,059 MWh_{th}/yr in the baseline scenario. Table 36 presents GHG emissions from this scenario. The total GHG emissions are 1,678.26 kg CO_2e/MWh based on the 100 year GWP. The GHG emissions are significantly higher compared to the baseline scenario where more heat is utilized. This scenario has lower overall plant efficiency and thus, higher emissions.

Table 36. Biomass Gasification Power Plant GHG emissions summary of results

Life Cycle Stage	Emissions, kg/MWh					Total, kg CO_2e/MWh (20 year GWP)	%	Total, kg CO_2e/MWh (100 year GWP)	%
	CO_2	CO_2 Biogenic	N_2O	SF_6	CH_4				
Materials Acquisition	1.7673	0.0000	9.29E-06	2.71E-13	0.0008	1.8388	0.11	1.7928	0.11
Materials Transportation	1.2247	0.0000	9.77E-06	5.36E-13	1.47E-03	1.3511	0.08	1.2685	0.08
Biomass Transportation	5.4245	0.0000	0.0001	2.37E-12	0.0065	5.9921	0.36	5.6268	0.34
Operation	0.0000	1669.57	0.0000	0.0000	0.0000	1669.57	99.45	1669.57	99.48
Total	**8.4165**	**1669.57**	**0.0001**	**3.18E-12**	**0.0088**	**1678.75**	**100**	**1678.26**	**100**

A comparison of the two scenarios is shown in Table 37 below. The GHG emissions in the sensitivity analysis scenario are more than 2 times higher than in the baseline scenario. This is due to the lower efficiency of the CHP plant since only a small portion of produced heat is utilized.

Table 37. Biomass gasification scenarios comparison

Scenario	**Total GHG, kg CO_2e/MWh (100 yr GWP)**	Materials Acquisition	Materials Transportation	Biomass Transportation	Operation
Baseline scenario (65% electrical and heat production efficiency)	771.97	1.7928	1.2685	5.6268	763.28
Sensitivity analysis scenario (only 1,283 MWh of heat is utilized in Haines Junction)	1,678.26	1.7928	1.2685	5.6268	1,669.57

4.5.4 LNG Combustion Emissions

GHG emissions from LNG combustion are estimated based on emissions factors, not specific operating data that was not available at the time of the study. The emissions factor is derived from GHGenius 4.03 that is based on the US EPA non-road model for large natural gas engines. A sensitivity analysis is performed to better understand an effect of different emissions factors on the results.

Two different LNG combustion emissions factors are selected for the sensitivity analysis:

1. Canadian Energy Partnership for Environmental Innovation, CEPEI (Pembina, 2013):
    a. CO_2 emission factor – 49,300 ng/J NG combusted (4-stroke lean burn)
    b. CH_4 emission factor – 537 ng/J NG combusted (4-stroke lean burn)
2. 2016/2017 B.C. Best Practices Methodology for Quantifying Greenhouse Gas Emissions, Ministry of Environment, May, 2016. Stationary fuel combustion emission factors are based on Environment Canada (2014). National Inventory Report: Greenhouse Gas Sources and Sinks in Canada 1990-2012., and British Columbia (2014). British Columbia Greenhouse Gas Inventory Report 2012.
    a. CO_2 emission factor – 1.926 kg/m^3
    b. CH_4 emission factor – 0.000037 kg/m^3
    c. N_2O emission factor – 0.000035 kg/m^3

The results are presented in Table 38.

Table 38. LNG combustion emissions

Scenario	**kg CO_2e/MWh (20 yr GWP)**	**kg CO_2e/MWh (100 yr GWP)**
Baseline scenario, US EPA	846.86	574.23
CEPEI, Pembina 2013	734.06	500.24
2016/2017 B.C. Best Practices	390.49	390.08

The emissions factors selected for the baseline scenario are in the upper range of emissions and therefore conservative. Actual natural gas engine GHG emissions would likely be lower and will be based on actual operating conditions of the unit. The direct measurement of emissions from the unit is recommended to determine the precise emissions factor.

4.5.5 TRANSMISSION LINE CAPACITY

The GHG emissions from transmission line pathway are modelled using 80%, 60% and 40% transmission line capacity. The baseline scenario assumes that the transmission line operates at 100% of reliable capacity. It is expected that the actual transmission line capacity will vary over the life time of the transmission line. The results are presented in Table 39 below.

Table 39. 170 km transmission line capacity modelling

Scenario	GWh/yr	kg CO_2e/MWh (20 yr GWP)	kg CO_2e/MWh (100 yr GWP)
Baseline scenario, 100% reliable capacity	3880.7	0.1706	0.1582
80% capacity	3104.5	0.1784	0.1631
60% capacity	2328.4	0.2380	0.2175
40% capacity	1552.3	0.3561	0.3254

5 CONCLUSIONS AND RECOMMENDATIONS

The use of an LCA allows decision makers to better understand the impacts on human health and the environment that may not be traditionally seen when selecting an energy source. The results of this study illustrate the vast differences in GHG emissions generated by various energy resource technologies. Careful consideration is crucial in determining the most amenable resource option in light of current policies and climate change strategies. Cost, long-term access to the resources, land availability, and energy demand forecasts must be examined in conjunction with the LCA results. The LCA results provide a means to more fully understand the impacts of choices among energy options, including those impacts that occur outside the project location, which can ultimately lead to a more balanced approach.

This analysis provides insight into the estimated GHG emissions from several renewable and non-renewable energy resources. Key conclusions from this analysis are summarized below.

- The overall results indicate that the biogas pathway is the greatest GHG emitter with over 1,000 kg CO_2e/MWh of GHG emitted for both time horizons, if biogenic CO_2 is included. The next highest emitters are diesel and LNG pathways with 1,059 and 1,051 kg CO_2e/MWh emitted for the 20 year time horizon, respectively, and 951 and 728 kg CO_2e/MWh emitted for the 100 year time horizon, respectively. The smallest GHG emitters for both time horizons are solar (approximately 40 kg CO_2e/MWh), followed by pumped storage, small hydro, water diversion, battery storage, wind, and geothermal (all with less than 25 kg CO_2e/MWh). The 170 km of new transmission line produces 0.17 kg CO_2e/MWh for the 20 year and 0.16 CO_2e/MWh for the 100 year time horizon.
- Renewable energy resources (hydro, solar, wind and geothermal) produced significantly less amounts of GHG emissions per MWh. This may ultimately lead to the replacement of fossil thermal energy generation (diesel and LNG) in the long term, especially when these sources are coupled with battery storage technology and supported by hydro power. However, this must be considered in combination with a cost-benefit analysis.
- The application of 20 year and 100 year GWPs did not significantly change the results except for diesel, biogas, LNG and hydro options. This is due to the higher amounts of methane emissions since methane's GWP is three times higher in the 20 year time horizon scenario than it is for the 100 year time horizon. Methane emissions in biogas pathway originate mainly from anaerobic digestion and waste storage processes, while in the diesel pathway they originate from crude oil extraction. Methane emissions in hydro energy pathways come from biomass decomposition after land inundation. Wind, solar, geothermal, battery storage, transmission line, biomass gasification, and waste to energy produce emissions that are almost the same for both time horizons.
- The GHG emissions from biomass gasification, MSW conventional combustion, and MSW and biomass conventional combustion pathways strongly depend on the CHP plant efficiency and are reduced significantly (per MWh) when plants operate at higher efficiencies and all heat produced is utilized.
- Operations are the highest contributing life cycle stages to GHG emissions across all energy resources, except solar, wind, transmission line, battery storage and geothermal pathways

where materials acquisition, transportation, and plant construction (upstream life cycle stages) are the highest contributors. Diesel and LNG thermal plants also had notable GHG emissions contributions from upstream (fuel extraction and production) life cycle stages. Transmission line had 19% of GHG emissions from operation due to fuel consumption for yearly land clearing.

- Biogenic CO_2 emissions are reported separately as these emissions are considered carbon-neutral. The resource options that comprise biogenic emissions are biogas (902 kg biogenic CO_2/MWh), MSW (255 kg biogenic CO_2/MWh), combined MSW and biomass (356 kg biogenic CO_2/MWh), biomass gasification (755 kg biogenic CO_2/MWh), small hydro (5.29 kg biogenic CO_2/MWh), pumped storage (5.68 kg biogenic CO_2/MWh), and water diversion (17.46 kg biogenic CO_2/MWh and 6.45 kg biogenic CO_2/MWh for the 24 and 65 years lifetime, respectively).
- While GHG emissions from fossil sources are quite small for biogas and biomass gasification energy resources, waste to energy scenarios (MSW and MSW with biomass combustion) have notable fossil GHG emissions.
- The sensitivity analysis reveals that the choice of the technology and location of the manufacturing facilities (e.g. in North America versus oversees) can significantly impact the total life cycle emissions in the case of renewable energy sources where upstream life cycle stages are the largest contributors to the total life cycle GHG emissions.
- The technology pathways that may have a good potential to support other energy generation options such as small hydro are geothermal, as well as wind and solar coupled with battery storage. Hydro options, in turn, make it feasible to utilize other renewable sources. Pumped storage offers operational flexibility, since it can immediately respond to fluctuations in the demand for electricity. The flexibility and storage capacity of hydro options make then efficient and economical in supporting the use of intermittent sources of renewable energy, such as solar and wind, especially if these energy options are not coupled with battery storage. The waste to energy option has a potential to displace some fossil fuel-based sources, such as diesel and LNG, especially if produced heat is utilized to make the technology economically viable. However, the waste to energy pathway was found to produce a significant amount of fossil GHG emissions due to MSW combustion.
- The fixed GHG emissions originate from the plant construction (materials acquisition, transportation, components manufacturing, site clearing, etc.), while variable emissions come from the operation life cycle stage. The fixed emissions remain constant; however, variable emissions vary with power plant energy output. If power plant runs only occasionally (e.g. diesel and LNG power plants), the variable emissions are minimal.
- Site specific data on construction material requirements need to be obtained to better understand fixed GHG emissions from power plants construction in the waste to energy, small hydro, and pumped storage pathways. It is recommended to update fixed GHG emissions in these pathways when site and technology specific data become available.

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APPENDIX A: LIFE CYCLE INVENTORY – SUPPORTING INFORMATION

A.1 Scenario 1: Biomass Gasification

Table 1.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Concrete Steel Aluminum	Athena, 2005 GaBi Professional database (region: Canada)
Available biomass	Wood residues, spruce (left at the landing, in the harvest block and standing dead) – 5,600 tonnes/yr Sawmill residues – 2,000 tonnes/yr	Stantec, 2013[44]
Required biomass (based on net energy production)	Oven dry tonnes – 3,000 tonnes/year With 15% moisture content – 3,789 tonnes/year • Forest harvesting residues: 1,603 tonnes/year • Sawmill residues – 2,190 tonnes/year	Stantec, 2013
Biomass collection	Diesel consumption: 2.37 L/tonne Average collection distance is 100 km	Jones et al. 2010[45]
Size reduction by mobile wood chipper (roadside chipping)	Diesel consumption: 1.7 L/tonne of biomass	Jones et al., 2010
Transport of wood residues to the plant	Forest harvesting residues – 70km, truck, 9t payload Sawmill residues – 50 km, truck, 9t payload	Stantec, 2013
Transport of construction materials	2,400 km by truck, 22t payload	
Plant construction	No site preparation included – brownfield site 37.4 x 36.4 pre-engineered building (steel) +foundation (concrete) 2 x 250 kVA wood gasification generators Plant Materials Requirements: • Concrete: 6.2387 kg/MWh electricity produced • Steel: 1.7345 kg/MWh electricity produced	Stantec, 2013 Yukon Energy, 2016a[46] Stantec, 2016a[47]

[44] Stantec. (2013). Front End Engineering Design (FEED) Study. Yukon Bioenergy Demonstration Project in Haines Junction, Yukon. Final FEED Report. June 7, 2013.

[45] Jones, G., Loeffler, D., Calkin, D. and Chung, W. (2010). Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and energy return. *Biomass and Bioenergy* 34, 737 – 746.

[46] Yukon Energy. (2016a). Personal communication with Marc Andre Lavigne, Resource Planner, Yukon Energy.

[47] Stantec. (2016a). Basis of Design (BOD). Thermal Energy Plant Study. Stantec Consulting LTD. June 2, 2016.

Process	Assumptions	Source
Biomass drying and gasification	Annual energy production (net): • 2,585 MWh_e -682 kWh_e/tonne of biomass • 8,059 MWh_{th} – 2,127 kWh_{th}/tonne of biomass	Stantec, 2016[49]
	Gasification and Energy Production GHG emissions (based on Nexterra Energy gasifier)[48] • CO_2 biogenic – 1,495.63 kg/tonne of biomass • CH_4 – trace only • N_2O – trace only	Chan et al. (2008)[50]

A.2 Scenario 2: Municipal Solid Waste Combustion

Waste volumes potentially available to a WTE facility are presented in the Table below.

Table 2.1 Waste volumes potentially available to a WTE facility in Whitehorse[51]

Waste Stream	Current Diversion Rate		
	Annual Heating Value (GJ/yr)	Annual Waste Flow (tpy)	Weighted HHV (GJ/tonne)
MSW Generated within the City of Whitehorse	337,409	23,595	14.3
MSW Generated outside Whitehorse	35,231	2,669	13.2
Tires	8,970	299	30.0
Waste Oil	8,891	239	37.2
Abattoir Waste	500	250	2
Totals	*391,000*	*27,052*	*14.45**

** Annual Average HHV*

[48] Nexterra's gasifier emissions factors were used instead of the Community Power Corporation's (CPC) gasifier emissions factors. CPC couldn't be reached.

[49] Stantec. (2016). Biomass Technology Updated. January 15, 2016.

[50] Chan, B., Chan, B., and Young, C. (2008). Wood Pellet for UBC Boiler Replacing Natural Gas Based on LCA. UBC. April 11, 2008.

[51] Morrison Hershfield (2011). Waste to Energy Business Case Analysis (Final). Summary Report. Whitehorse, Yukon. September 6, 2011.

The City of Whitehorse MSW composition and heating values are shown in the Table 2.2.

Table 2.2. City of Whitehorse Waste Composition[52]

Material	Waste Composition Weighted Average (%)	Weight, Tonne/Year	Heat Content, Million BTU/Tonne
Paper	13.5	3545.64	6.7
Glass	1.3	341.43	0
Metal	6.7	1759.69	0
Plastic	9.1	2147.15	20.45
Organics	17.1	4491.14	5.2
Composite	9.3	2442.55	18.1
Wood Waste	15.3	4018.39	9.96
Inert Materials	2.3	604.07	0
Gypsum Wallboard	6.3	1654.63	0
Textiles	2.8	735.39	13.8
Rubber	0.4	105.06	26.86
Carpet and Underlay (PVC)	2.2	577.81	16.5
Electronic Waste	3.2	840.45	0
Personal Hygiene Products	2.5	656.60	7.51
Hazardous Waste	1.6	420.22	18.1
Biomedical Waste	0.5	131.32	18.1
Pet Waste	1.2	315.17	9.7
Fines	0.3	78.79	18.1
Fiberglass Insulation (Glass)	0.6	157.58	0
Other	3.7	971.77	18.1
MSW Total		**25994.86**	
Tires		299.00	
Waste Oil		239.00	
Abattoir Waste		250.00	
Total		**26782.86**	

Paper, wood waste, and organics are assumed to contribute to the biogenic CO_2 emissions. All other groups of waste contribute to fossil CO_2 emissions.

[52] Waste Composition Weighted Averages source: Walker & Associates (2010). City of Whitehorse Solid Waste Composition Study. Draft Report. Prepared for the City of Whitehorse.
Heat Content: Energy Information Administration (2007). Methodology for Allocating Municipal Solid Waste to Biogenic and Non-Biogenic Energy. U.S. Department of Energy, May 2007.

Table 2.3 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Concrete Steel Aluminum	Athena, 2005[53] GaBi Professional database (region: Canada)
Municipal Solid Waste and Biomass requirements	2015 feedstock: 16,100 tonnes MSW + 7,650 tonnes biomass 2035 feedstock: 23,750 tonnes MSW	Morrison Hershfield, 2012[54]
Biomass collection	Diesel consumption: 2.37 L/tonne Average collection distance is 100 km	Jones et al. 2010
Size reduction by mobile wood chipper (road side chipping)	Diesel consumption: 1.7 L/tonne of biomass	Jones et al., 2010
Transport of wood residues to the plant	Forest harvesting residues – 70km, truck, 9t payload Sawmill residues – 50km, truck, 9t payload	Stantec, 2013
Transport of MSW to plant	16km, truck, 9t payload	Morrison Hershfield, 2012
Transport of construction materials	Assumed 2,400 km by truck, 22t payload	GaBi database (region: Canada)
Plant construction	No site preparation included – brownfield site (2 ha) Plant Materials Requirements • Concrete: 22.3 kg/MWh electricity produced • Steel: 8.341 kg/MWh electricity produced • Aluminum: 0.065 kg/MWh electricity produced • Iron: 0.097 kg/MWh electricity produced	Morrison Hershfield, 2012 Spath and Mann, 1997[55]
Electricity Generation	Annual electricity production (net): 9,975 MWh_e/year Annual heat production (net): 23,700 MWh_{th}/year Energy production (net): • 420 kWh_e per tonne of MSW or MSW+biomass • 998 kWh_{th} per tonne of MSW or MSW+biomass The heat content of different groups of waste (Table 2.2) and the IPCC, 2006 MSW combustion emission	Morrison Hershfield, 2012

[53] Athena Institute. (2005). Cement and Structural Concrete Products: Life Cycle Inventory Update #2. Prepared by Athena Sustainable Materials Institute, Ottawa, Canada, 2005.
[54] Morrisson Hershfield. (2012). Waste to Energy Updated Design Basis and Business Case Analysis. April 24, 2012.
[55] Spath, P.L. and Mann, M. K. (1997). Life Cycle Assessment of a biomass Gasification Combined-Cycle System. NREL. December 1997.

Process	Assumptions	Source
	factors were used to estimate GHG emissions from waste combustion. MSW combustion emission factors Emissions factors, kg/TJ — CO_2 / CH_4 / N_2O Waste oil — 73300 / 30 / 4 MSW non biomass — 91700 / 30 / 4 Wood waste — 112000 / 30 / 4 Biomass — 100000 / 30 / 4	IPPC, 2006[56]

A.3 Scenario 3: Biogas Plant

The feedstock is residential and commercial organic waste collected in Whitehorse.

Organic waste characteristics are based on WSP, 2016[57].

Feedstocks	%TS	%VS	M³ Biogas/T VS	Density (KG/L)	Methane (% CH_4)
SSO from residential collection	36%	82%	600	0,9	60%
Green yard waste	31%	81%	380	0,8	55%
Dry yard waste	44%	86%	100	0,8	55%
SSO from ICI	23%	83%	600	0,9	60%

Note: %TS and %VS come from Wisconsin laboratory results and the other parameters come from the consultant's database.

TS – Total solid concentration, expressed as a fraction of the wet mass of the prepared feedstock.

VS – Volatile solid concentration, expressed as a function of the total solid mass.

Table 3.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Concrete Steel	Athena Institute, 2005
Collection and transport of organic waste	Organic waste transportation 16 km, truck, 9t payload 3.6144 tonnes of waste/MWh	WSP, 2016 (Based on mass balance - 2016)
Transport of construction materials	2,400 km by truck, 22t payload	Estimated

[56] IPPC. (2006). Incineration and Open Burning of Waste. Chapter 5. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
IPPC. (2006). Stationary Combustion. Chapter 2. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
[57] WSP (2016). Biogas Plant in Whitehorse. Feasibility Study. January 2016.

Process	Assumptions	Source
Plant construction	No site preparation included – brownfield site Plant construction (includes Anaerobic digester (AD) and CHP plant construction): Concrete: 21.4044 kg/MWh Steel: 5.2628 kg/MWh	EcoInvent, 2007[58] Whiting and Azapagic, 2014[59] Stantec, 2016a
Organic waste anaerobic digestion and electricity generation	Electric output: 56kWe (33kW$_e$ in April and 100 kW$_e$ in August) Thermal output: 64 kWt (37 kW$_t$ in April and 114 kW$_t$ in August) Total electricity produced (net): 885.9 MWh$_e$/yr Biogas heating value: 22 MJ/Nm^3 1 m^3 biogas = 2.135 kWh (electrical conversion efficiency = 35%) AD plant emissions CO_2 fossil 18.78 kg/MWh CH_4 (from AD plant) 2.58 kg/MWh N_2O 0.0282 kg/MWh Biogas combustion emission factors (CHP) CO_2 biogenic 1.926 kg/m^3 CH_4 0.000037 kg/m^3 N_2O 0.000035 kg/m^3	EcoInvent, 2007 Fusi et al., 2016[60] Ministry of Environment, BC (2016)[61]

[58] EcoInvent. (2007). Life Cycle Inventories of Bioenergy. Swiss Centre for Life Cycle Inventories.

[59] Whiting, A. and Azapagic, A. (2014). Life Cycle Environmental Impacts of Generating Electricity and Heat from Biogas Produced by Anaerobic Digestion. *Energy 70*, 181-193.

[60] Fusi, A., Bacenetti, J., Fiala, M. and Azapagic, A. (2016) Life Cycle Environmental Impacts of Electricity from Biogas Produced by Anaerobic Digestion. Fontiers in Bioengineering and Biotechnology, March 11, 2016.

[61] Ministry of Environment, BC. (2016). 2016/2017 B.C. Best Practices Methodology for Quantifying Greenhouse Gas Emissions. Including Guidance for Public Sectors Organizations, Local Governments and Community Emissions. Victoria, B.C., May, 2016.

A.4 Scenario 4: Geothermal Power Plant

A binary Organic Rankine Cycle (ORC) plant uses the high temperature steam and/or water from the production wells (called "geofluid") to heat a binary fluid, which most often is a hydrocarbon, with a low boiling point in a heat exchanger. The hydrocarbon fluid evaporates, producing the high-pressure vapour that is then expanded through a turbine. The turbine drives a generator to produce electric power.

Binary cycle power plants are closed-loop systems, and virtually nothing (except water vapor) is emitted to the atmosphere. The process diagram is shown in the Figure A.1.

After the geothermal fluid has heated the hydrocarbon fluid in the heat exchanger, it is reinjected into the reservoir through a reinjection well.

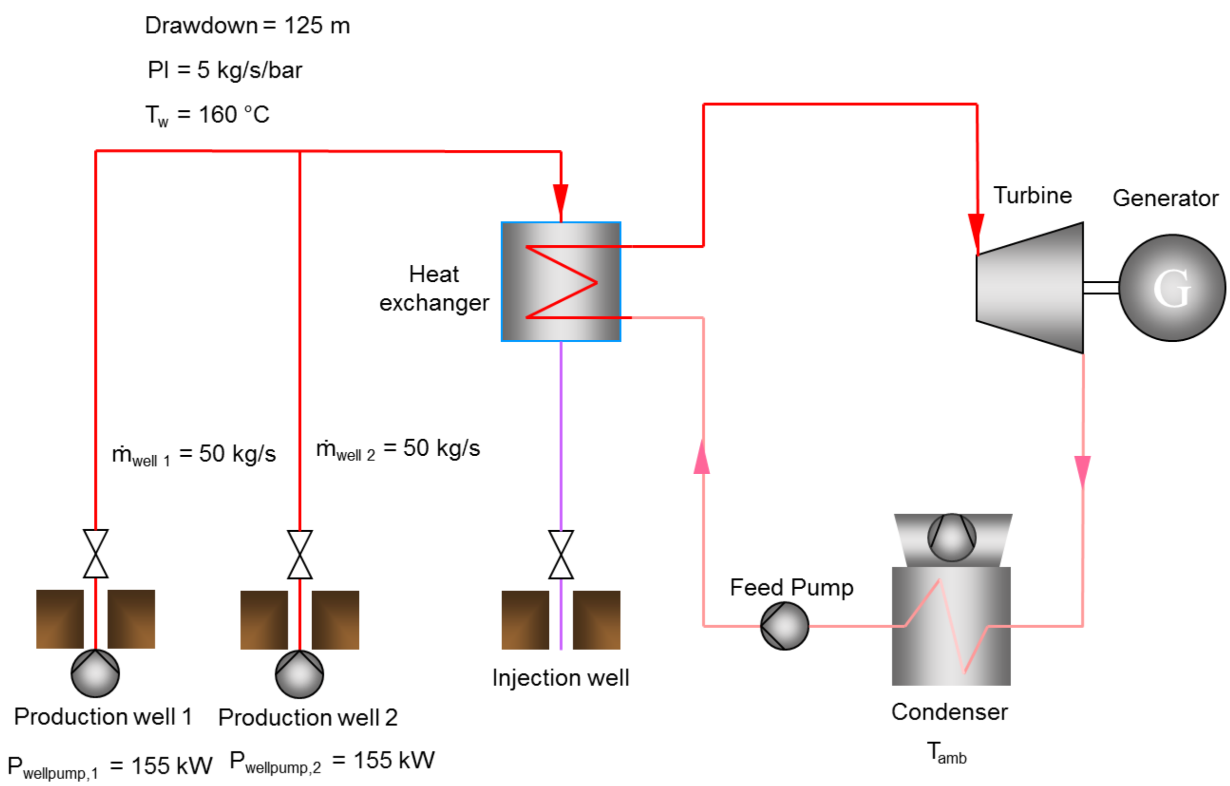

Figure A1. Organic Ranking Cycle Flowchart[62]

[62] KGS Group. (2016). Geothermal Review and Site Inventory. KGS Group, Winnipeg, Manitoba, May 2016.

Table 4.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum, cast iron)	Athena, 2005 GaBi Professional database (region: Canada)
Transport of construction materials	2,400 km by truck, 22t payload	
Plant and transmission line construction	Wells construction and installation (1.5km wells, including an exploration well) Two production wells and one injection well would be located approximately 1 km apart. One exploration well will be drilled. • Steel, pipe welded: 0.566 kg/MWh • Cement: 0.373 kg/MWh • Diesel: 0.333 kg/MWh Plant construction and installation • Aluminum: 0.240 kg/MWh • Concrete: 2.385 kg/MWh • Cast Iron: 0.0222 kg/MWh • Steel, pipe welded: 1.200 kg/MWh • Diesel: 0.113 kg/MWh Pipeline construction and installation (1,000m of piping) • Diesel: 0.00162 kg/MWh • Steel, pipe welded: 1.85 kg/MWh • Cement: 0.456 kg/MWh Greenfield site: Site preparation and access gravel road construction Access road construction: • Diesel: 0.000232 kg/MWh • Gravel: 0.611 kg/MWh Site preparation: • Diesel: 800 L/km Transmission line construction (42 km of 138kV line)[63]	NETL, 2012[64] Sullivan et al., 2010[65] Yukon Energy, 2016[66]

[63] Refer to Scenario 12: Transmission Line for more information on line construction and operation.
[64] NETL. (2012). Role of Alternative Energy Sources: Geothermal Technology Assessment. National Energy technology Laboratory. U.S. Department of Energy. August 28, 2012.
[65] Sullivan, J.L., Clark, C.E., Han, J. and Wang, M. (2010). Life-Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems. Argonne National Laboratory, Energy Systems Division, U.S. Department of Energy. August 2010.

Process	Assumptions	Source
Electricity Generation	Binary Organic Ranking Cycle (ORC) geothermal plant with 70% efficiency. Net electricity production: 48.2 GWh_e/yr	

A.5 Scenario 5: Wind Power Plant

The wind farm has a total capacity of 6 MW. Two different scenarios were modelled:

1. 4 wind turbines with a capacity of 1.5 MW each (sensitivity analysis scenario)
    a. Based on average wind farm technology used in the U.S.
    b. 55% of components are manufactured in China. The remaining 45% come from the U.S.
2. 3 wind turbines with a capacity of 2 MW each
    a. Based on Vesta V80 2 MW turbine manufactured in Denmark

Table 5.1 Data sources and assumptions for processes in the system boundaries – Scenario 1 – The U.S. average wind turbine

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum, cast iron)	NETL, 2012a[67]
Transport of construction materials	It is assumed that 55% of wind farm components are manufactured oversees (China). The remaining 45% come from the US. Transmission line components are transported 2,400km by truck.	NETL, 2012a Estimated
Plant and transmission line construction	<u>Manufacture of Turbine Components</u> *Rotor (turbine rotor diameter 63m)* • Blades Glass fibers – 2,713 kg Carbon fibers – 399 kg Resin glue – 598kg Steel – 279 kg Electricity – 15,958 MJ • Hub Cast iron – 10,082 kg Electricity – 44,675 • Spinner, nose cone Glass fibers – 309.8 kg Resin glue – 464.7 kg	NETL, 2012a

[66] Yukon Energy. (2016). Diesel consumption for land clearing information provided by Shannon Mallory. July 2016.
[67] NETL. (2012a). Role of Alternative Energy Sources: Wind Technology Assessment. National Energy Technology Laboratory. U.S. Department of Energy. August 30, 2012.

Process	Assumptions	Source
	Electricity – 8,542 MJ *Nacelle* • Main Shaft and bearings Cold rolled steel – 5,241 kg Electricity – 445,491 MJ • Generator Cold rolled steel – 665 kg Copper – 3,574 kg Silicate – 1,759 kg Electricity – 1,361,570 MJ • Main frame Cast iron – 5,376 kg Cold rolled steel – 3,584 kg Electricity – 27,690 MJ • Nacelle cover Glass fibers – 2,153 kg Resin glue – 538.5 kg Electricity – 30,046 MJ *Tower* Cold rolled steel – 117,787 kg Electricity – 103,652 MJ Plant construction • Gravel road Diesel – 0.741 kg/m of gravel road Gravel – 2319.5 kg/ m of road • Switchyard and transformer Transformer – 105,000 kg/switchyard Mineral oil – 28,800 kg/switchyard Circuit breaker – 14,400 kg/switchyard Concrete – 690,000/ kg/switchyard Greenfield site: Site preparation • Diesel: 800 L/km Transmission line construction (7.6 km of 138kV line)	Yukon Energy, 2016
Electricity Generation	Net electricity production: 14.558 GWh_e/yr Operation Diesel – 0.000759 kg/MWh Lubrication oil – 0.0730 kg/MWh	NETL, 2012a

Table 5.2 Data sources and assumptions for processes in the system boundaries – Scenario 2 – Vesta V80 2 MW wind turbine

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum, cast iron) Manufacturing of turbine in Denmark	Elsam, 2004[68]
Transport of construction materials	Turbine transport by sea – 5,578 km (Denmark – Montreal) Turbine transport by road – 5,560 km (Montreal – Whitehorse) Emissions from turbine transport CO_2 g/kWh CH_4 g/kWh N_2O g/kWh Transmission line components are transported 2,400km by truck.	Estimated
Plant and transmission line construction	Manufacture of Turbine Components Steel 223,140 kg/turbine Stainless steel 13,328 kg/turbine Cast iron 20,688 kg/turbine Glass fiber 21,507 kg/turbine Plastic 3,088 kg/turbine Cobber 2,816 kg/turbine Aluminum 1,678 kg/turbine Zinc 203 kg/turbine Concrete 805,000 kg/turbine Emissions from manufacturing CO_2 6.1 g/kWh CH_4 3.55E-03 g/kWh N_2O 2.06E-04 g/kWh Greenfield site: Site preparation • Diesel: 800 L/km Transmission line construction (7.6 km of 138kV line)	Elsam, 2004 Yukon Energy, 2016
Electricity Generation	Net electricity production: 14.558 GWh_e/yr Operation CO_2 0.69 g/kWh CH_4 4.83E-04 g/kWh N_2O 2.22E-05 g/kWh	Elsam, 2004

[68] Elsam. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. Elsam Engineering A/S. October 20, 2004.

A.6 Scenario 6: Solar Power Plant

Table 6.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum, cast iron)	NETL, 2012b[69]
Transport of construction materials	Transport of solar panels Fukuyama, Japan to Vancouver, BC – 7,664 km by sea Vancouver to Whitehorse – 2,400 km by truck, 22t payload	Estimated
Plant construction	Panasonic 330W panels; panel weight – 19 kg. Brownfield, no site preparation or access road construction is included • Plant construction and installation • PV module, array support, foundation, inverter, other components manufacturing and construction	NETL, 2012b Ito (2011)[70] Fthenakis and Kim (2010)[71]
Electricity Generation	Operations Diesel for fire pump engines and emergency generators – 0.02019 kg/MWh Gasoline for maintenance vehicles – 0.1005 kg/MWh Net electricity production: 5.2 GWh_e/yr	NETL, 2012b

[69] NETL (2012b). Role of Alternative Energy Sources: Solar Thermal Technology Assessment. National Energy Technology Laboratory. U.S. Department of Energy. August 28, 2012.

[70] Ito, M. (2011). Life Cycle Assessment of PV systems, Crystalline Silicon - Properties and Uses, Prof. Sukumar Basu (Ed.), ISBN: 978-953-307-587-7, InTech, http://www.intechopen.com/books/crystalline-silicon-properties-and-uses/life-cycle-assessment-of-pv-systems

[71] Fthenakis, V.M. and Kim, H.C. (2010). Photovoltaics: Life-cycle Analyses. *Solar Energy* 85, 1609-1628.

A.7 Scenario 7: Pumped Storage Hydro Power Plant

Table 7.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum, cast iron)	Athena, 2005 GaBi Professional database (region: Canada)
Transport of construction materials	2,400 km by truck, 22 t payload	Estimated
Plant construction	<u>Greenfield site with inundation area of 354.2 ha</u> GHG emissions from inundation are estimated using IPPC, 2003 Tier 1 methodology: 5.68 kg CO_2/MWh 0.1466 kg CH_4/MWh 0.0029 kg N_2O/MWh <u>Plant Construction</u> Cement 3.42 g/kWh Gravel 29.8 g/kWh Reinforcing steel 0.06 g/kWh Steel for equipment 0.06 g/kWh Steel for tubes and anchors 0.14 g/kWh Copper 0.0099 g/kWh Explosives 0.02 g/kWh Diesel 0.0467 g/kWh Transmission line construction (2.6 km of 138kV line)	IPCC, 2003[72] Flury and Frischknecht, 2012[73]
Electricity Generation	Net electricity production: 54 GWh_e/yr	IEA, 2002[74]

Intergovernmental Panel on Climate Change Tier 1 approach to estimate GHG emissions from reservoirs (IPPC, 2003).

The IPCC has developed guidelines for estimating GHG emissions from flooded lands. The Tier 1 approach provides a simplified method for estimating GHG emissions. Only the first 10 years post-inundation are considered to be at the level estimated by the following equations. After 10 years, emissions are assumed to be negligible.

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[72] IPPC (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. J. Penman, M. Gytarsky, T. Hiraishi, T. Krug and D. Kruger (eds.). Institute for Global Environmental Strategies (IGES). 944 pp.

[73] Flury, K. and Frischknecht, R. (2012). Life Cycle Inventories of Hydroelectric Power Generation. ESU- Services. Commissioned by Öko-Institute e.V.

[74] IEA. (2002). Environmental and Health Impacts of Electricity Generation. A comparison of the Environmental Impacts of Hydropower with those of other Generation Technologies. The International Energy Agency – Implementing Agreement for hydropower Technologies and Programmes.

Equation 1: Tier 1 CO_2 Emissions from Flooded Lands

$$CO_{2\,emissions} = P * E(CO_2)_d * A_r$$

Where:

$CO_{2\,emissions}$ = total CO_2 emisisons from flooded lands, kg CO_2/yr;

P = period of emissions, usually 365 days for annual inventory estimates, d/yr;

$E(CO_2)_d$ = averaged daily diffusive emissions, with a default value of 15.5 kg CO_2 / ha /day;

A_r = total flooded surface area, ha.

Based on Equation 1, the Tier 1 CO_2 emissions for 354.2 ha of flooded area are 1,993,703 kg CO_2/yr or 5.68 kg CO_2/MWh.

Equation 2: Tier 1 CH_4 Emissions from Flooded Lands

$$CH_{4\,emissions} = P * E(CH_4)_d * A_r + P * E(CH_4)_b * A_r$$

Where:

$CH_{4\,emissions}$ = total CH_4 emisisons from flooded lands, kg CH_4/yr;

P = period of emissions, usually 365 days for annual inventory estimates, d/yr;

$E(CH_4)_d$ = averaged daily diffusive emissions, with a default value of 0.11 kg CH_4 / ha /day;

$E(CH_4)_b$ = averaged bubbles emissions, with a default value of 0.29 kg CH_4 / ha /day;

A_r = total flooded surface area, ha.

Based on Equation 2, the Tier 1 CH_4 emissions for 354.2 ha of flooded area are 51,450.4 kg CH_4/yr or 0.1466 kg CH_4/MWh.

Equation 3: Tier 1 N_2O Emissions from Flooded Lands

$$N_2O_{emissions} = P * E(N_2O)_d * A_r$$

Where:

$N_2O_{emissions}$ = total N_2O emisisons from flooded lands, kg N_2O/yr;

P = period of emissions, usually 365 days for annual inventory estimates, d/yr;

$E(N_2O)_d$ = averaged daily diffusive emissions, with a default value of 0.008 kg N_2O / ha /day;

A_r = total flooded surface area, ha.

Based on Equation 3, the Tier 1 N_2O emissions for 354.2 ha of flooded area are 1,029 kg N_2O/yr or 0.0029 kg N_2O/MWh.

A.8 Scenario 8: Small Hydro Power Plant

Table 8.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum, cast iron)	Athena, 2005 GaBi Professional database (region: Canada)
Transport of construction materials	2,400 km by truck, 22 t payload	Estimated
Plant construction	Greenfield site with inundation area of 190 ha GHG emissions from inundation are estimated using IPPC, 2003 Tier 1 methodology: 5.2168 kg CO_2/MWh 0.1346 kg CH_4/MWh 0.0027 kg N_2O/MWh	IPCC, 2003
	Plant Construction Concrete 17.9 g/kWh Gravel 14.3 g/kWh Steel 0.6689 g/kWh Aluminum 0.000345 g/kWh PE 0.117 g/kWh PVC 0.0251 g/kWh Cast iron 0.350 g/kWh Copper 0.00268 g/kWh Diesel 0.000687 MJ/kWh Transmission line construction (0.5 km of 138kV line)	Flury and Frischknecht, 2012
Electricity Generation	Net electricity production: 31.7 GWh_e/yr	IEA, 2002

A.9 Scenario 9: Battery Storage

A lithium ion battery with an 8MW capacity and 5 hours discharge time was studied. The battery is a lithium iron phosphate cathode (hydrothermal) battery.

Lithium iron phosphate (LiFePO4) is a cathode material for lithium-iron batteries. It can be prepared hydrothermally or through a solid state technique. The hydrothermal pathway is selected (Dunn et al, 2014)[75].

Specific power density of different batteries varies significantly from one manufacturer to another. Two batteries from different manufacturers – UltraLife Corporation and SAFT Batteries were evaluated. The UltraLife Corporation's battery has a specific power density of 149 W/kg and the SAFT Batteries' specific power density is 60 W/kg.

Table 9.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum, lithium iron phosphate, etc.) Battery lithium iron phosphate cathode (hydrothermal) battery <u>Battery manufacturing and assembly</u> Lithium iron phosphate ($LiFePO_4$) production CO_2 3.56 kg/kg $LiFePO_4$ CH_4 8.52 g/kg $LiFePO_4$ N_2O 76.06 mg/kg $LiFePO_4$ Battery production and assembly CO_2 4.36 kg/kg battery CH_4 9.21 g/ kg battery N_2O 81.25 mg/ kg battery CF_4 14.89 mg/ kg battery C_2F_6 2.05 mg/ kg battery 1 MW battery weight: 6,700kg (Ultalife)[76] 1 MW battery weight: 16,500kg (SAFT Batteries)[77]	GREET, 2015[78] Dunn et al., 2014
Transport of construction materials	<u>Battery transport</u> California to Alaska by sea – 3,226 km Alaska to Whitehorse -1,133 km by truck, 22t payload	Estimated

[75] Dunn et al. (2014). Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries. ANL/ESD/14/10.
[76] UltraLife Corporation https://www.ultralifecorporation.com/
[77] SAFT Batteries www.saftbatteries.com/
[78] GREET. (2015). GREET Model. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model. Argonne National Laboratory https://greet.es.anl.gov/

Process	Assumptions	Source
Plant construction	Site preparation The site preparation includes clearing of 0.42 ha (4,200 m^2) area • Diesel: 800 L/km	Yukon Energy, 2016
Electricity Generation	Battery lifetime is 10-15 years. It's assumed that 1.5 batteries are required. Net electricity production: 2,780 MWh_e	

Lead Acid and Lithium-Ion Batteries Comparison

Lead acid and lithium ion batteries are two of the most popular energy storage technologies available, but have a significant impact on the environment. The environmental performance is primarily dependent on its lifetime durability and efficiency[79].

Lead acid batteries have been widely used for approximately 150 years and have proven to be a robust technology. However, extraction and processing of lead require significant amounts of energy and produce large amounts of pollution. Lead is a toxic substance, but the manufacturing and packaging technologies make the risk to humans insignificant. Fortunately, close to 98% of lead acid batteries are recycled in the United States[80]. Nevertheless, lead acid batteries include hazardous, flammable and explosive materials that present serious environmental risks[81,82]. In one study, analysis of a lead acid battery grid-connected to a photovoltaic system revealed that the overall climate change impact of the battery had a comparable CO_2e/year effect as driving over 4,000 km per year in a typical gasoline car. The overall conclusion was that there was a significant environmental impact[83]. Moreover, lead acid batteries are known for limitations in their useable capacity and number of charging cycles causing the need for early replacement. Their charging time can take longer compared to other battery types, and they have limited charging efficiency in that they may not store the full amount of power, which is problematic when charging using certain energy resources such as solar, where storing as much energy as possible is desirable before nightfall or cloud coverage. Another inefficiency of lead acid batteries is voltage sag, where lead acid batteries slowly lose their charge over time regardless of power use[84].

In the last few decades, lithium ion batteries have increased in use worldwide. They are known to perform better in colder climates, charge more quickly, can be charged more often before they reach

[79] Messagie, M., Oliveira, L., Rangaraju, S., Fomer, J.S., and Rivas, M.H. (2015). Rechargeable Lithium Batteries. From Fundamentals to Applications. Woodhead Publishing Series in Energy. pp. 303-318. doi:10.1016/B978-1-78242-090-3.00011-0

[80] http://www.batterycouncil.org/

[81] Zhanga, J., Chena, C., Zhangb, X., and Liua, S. (2016). Study on the environmental risk assessment of lead-acid batteries. Procedia Environmental Sciences 31: 873 – 879.

[82] Zhu, X., Li, L., Sun, X., Yang, D., Gao, L., Liu, J., Vasant Kumar, R., and Yang, J. (2001). Preparation of basic lead oxide from spent lead acid battery paste via chemical conversion. Hydrometallurgy.117:24-31.

[83] McKenna, E., McManus, M., Cooper, S., and Thomson, M. (2013). Economic and environmental impact of lead-acid batteries in grid-connected domestic PV systems. Applied Energy. 104: 239-249.

[84] Albright, G., Edie, J., and Al-Hallaj, S. (2012). A comparison of lead acid to lithium ion in stationary storage applications. AllCell Technologies. http://www.altenergymag.com/content.php?post_type=1884

their end of life, and have a longer lifespan compared to lead acid batteries[85,86]. Additionally, they can more easily deliver their full rated capacity of power and weigh about one-third to one-half of a standard lead acid battery, thus making them easier to transport. However, lithium ion technology does have its own environmental challenges[87]. Lithium ion batteries are comprised primarily of mined lithium carbonate, iron ore, aluminum and copper. Lithium mining is resource intensive, but lithium itself is only a small fraction of the battery. Therefore, the production and processing of the aluminum, copper and iron ore contribute more significantly to the overall environmental impacts. Additionally, compared to lead acid batteries, lithium ion batteries have a low recycling rate. However, it is expected that as the recovery and recycling technology matures, the battery materials will be recovered at rates comparable to lead acid batteries.

A.10 Scenario 10: Thermal Diesel Power Plant

Table 10.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum)	Athena, 2005 GaBi Professional database (region: Canada)
Crude oil extraction	Crude oil is extracted from Alaska's North Slope and Alberta (includes drilling and crude extraction)	Pembina, 2013 S&T[2], 2014
Crude oil processing	Crude oil is processed at Puget Sound refinery in the U.S.	GHGenius v4.03
Transport of construction materials, crude oil and diesel	<u>Construction materials transport</u> 2,400 km by truck, 22 t payload <u>Crude oil transport</u> Crude oil is transported to Puget Sound refinery via ocean vessel <u>Diesel transport</u> Ocean transport to Skagway - 1734 km (one way) Truck transport to Whitehorse - 354 km (round-trip)	Estimated GHGenius v4.03 NREL LCI Database
Plant construction	<u>Site preparation</u> The site preparation includes clearing of 5 ha area • Diesel: 800 L/km <u>Plant construction</u>	Yukon Energy, 2016 Stantec, 2016a

[85] Zubi, G., Dufo-López, R., Pardo, N, and Pasaoglu, G. (2016). Concept development and techno-economic assessment for a solar home system using lithium-ion battery for developing regions to provide electricity for lighting and electronic devices. Energy Conversion and Management. 122:439-448.

[86] Krieger, E.M., Cannarella, J., and Arnold, C.B. (2013). A comparison of lead-acid and lithium-based battery behavior and capacity fade in off-grid renewable charging applications. Energy. 60:492-500.

[87] Notter, D.A., Gauch, M., Widmer, R., Wäger, P., Stamp, A., Zah, R., and Althaus, HJ. (2010). Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles. *Environ. Sci. Technol.* 44: 6550–6556.

Process	Assumptions	Source
	• Concrete: 0.8423 kg/MWh electricity produced • Steel: 0.2825 kg/MWh electricity produced	Yukon Energy, 2016a
Electricity Generation	Net electricity production: 39.42 MWh_e/yr	S&T[2], 2014

A.11 Scenario 11: Thermal LNG Power Plant

Table 11.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum)	Athena, 2005 GaBi Professional database (region: Canada)
Natural gas extraction	Natural gas is extracted from conventional gas fields predominantly in Northeast BC and some from NW Alberta	Pembina, 2013 S&T[2], 2014
Natural gas processing	LNG is treated to remove impurities and liquefied at the Fortis BC Tillbury facility	GHGenius v4.03 S&T[2], 2014
Transport of construction materials, natural gas and LNG	Construction materials transport 2,400 km by truck, 22 t payload Natural gas transport Natural gas is delivered to the Fortis BC Tillbury facility from Spectra at Huntington Gate by pipeline LNG transport LNG is transported 5,440 km round trip by truck	Estimated GHGenius v4.03 Pembina, 2013 (LNG truck transport)
Plant construction	Site preparation The site preparation includes clearing of 6.5 ha area • Diesel: 800 L/km Plant construction • Concrete: 1.3932 kg/MWh electricity produced • Steel: 0.3208 kg/MWh electricity produced	Yukon Energy, 2016 Stantec, 2016a Yukon Energy, 2016a
Electricity Generation	LNG is vapourized and combusted to produce power in a Jenbacher generator operating at 46.3% efficiency (47% @ 90% load). Net electricity production: 39.42 MWh_e/yr	S&T[2], 2014 GHGenius v4.03

Methane Emissions from Natural Gas Life Cycle

Natural gas has been touted as a more environmentally friendly fuel. However, the extraction, processing and transportation of natural gas are not without concern. Fugitive, vented and flared methane emissions are present throughout the process, and the uncertainty surrounding the amount of emissions is disconcerting[88]. In order to fully understand the advantages of using natural gas, all emissions, from extraction to delivery and use, must be considered.

Fugitive emissions related to natural gas production and processing consist of (in this study, these emissions are included in the extraction of resources and fuel production life cycle stages):

- Emissions from venting and flaring of natural gas, waste gas, and vapour streams during production or processing;
- Emissions unrelated to venting and flaring, which are comprised of gas wellheads, well servicing, gas transportation, disposal activities, gas processing, storage, and combustion of fossil fuels that do not generate usable heat or electricity.

The key emission assessment issues are: (a) use of simple production-based emission factors is susceptible to excessive errors; (b) use of rigorous bottom-up approaches requires expert knowledge to apply and relies on detailed data which may be difficult and costly to obtain; and (c) measurement programmes are time consuming and very costly to perform.

The reported data for fugitive methane emissions vary widely[89]. This is due to the following key factors: 1) where the measurements are taken, 2) the method by which the measurement is taken, and 3) the implementation of measurement programmes is both costly and time consuming, and requires expert knowledge[90]. If there is an emission "hot spot" which has a higher-than-normal methane release, such as due to pipe or equipment failure, the reported data will not be representative of the entire gas stream. Conversely, if data are collected in an area that always has little to no leakage, fugitive emissions will be under-reported. As a result, there is a high degree of uncertainty in the available data on fugitive emissions[91].

Two different methods to collect fugitive emissions data are used. However, both of these also produce varying results. The first is a "bottom-up" approach. In this case, emissions are measured at a particular source, such as along a pipeline or the home that the fuel is being supplied to. While this provides a very accurate picture of a particular location, this method may miss critical components of the system that may lead to an inaccurate estimate. The second approach is "top-down" which measures methane concentrations at a pre-determined height (such as from an airplane or tall building) above a particular area. This method ensures that both high-emitting and low-emitting areas

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[88]Greenhouse Gas Institute. (2016). Methane emissions from the oil and gas industry: is the world getting it right? http://ghginstitute.org/2016/07/18/methane-emissions-from-the-oil-and-gas-industry-is-the-world-getting-it-right/?utm_source=July+Newsletter+2016&utm_campaign=July+Newsletter+2016&utm_medium=email

[89] Zavala-Araiza et al. (2015). "Reconciling divergent estimates of oil and gas methane" *Proc Natl Acad Sci*. http://www.pnas.org/content/early/2015/12/03/1522126112.abstract

[90]IPCC. "Fugitive emissions from oil and natural gas activities." http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/2_6_Fugitive_Emissions_from_Oil_and_Natural_Gas.pdf

[91] NREL. (2015). Estimating U.S. Methane Emissions from the Natural Gas Supply Chain: Approaches, Uncertainties, Current Estimates, and Future Studies. http://www.nrel.gov/docs/fy16osti/62820.pdf

are accounted for. However, methane emissions unrelated to natural gas extraction are also included, thus giving higher concentrations. Additionally, this method does not identify specific troublesome areas since the measurements do not pinpoint which particular area contributed most to the measured methane levels[92]. To address this, some researchers have developed predictive models to determine which wells, or other emissions sources, may be at the greatest risk for releasing higher methane levels.

The difference in reported CH_4 emissions estimates can be seen when considering the available data in the 2015 and 2016 U.S. GHG inventories by the EPA[93,94]. The 2015 inventory reports data from 2012 that includes 23.3 MMT CO_2e from petroleum systems, and 154.4 MMT CO_2e from natural gas systems. However, the 2016 submission estimates emissions from 2012 to be 58.4 MMT CO_2e from petroleum systems, and 172.6 MMG CO_2e from natural gas. These comparisons are shown in Figure A.2 below.

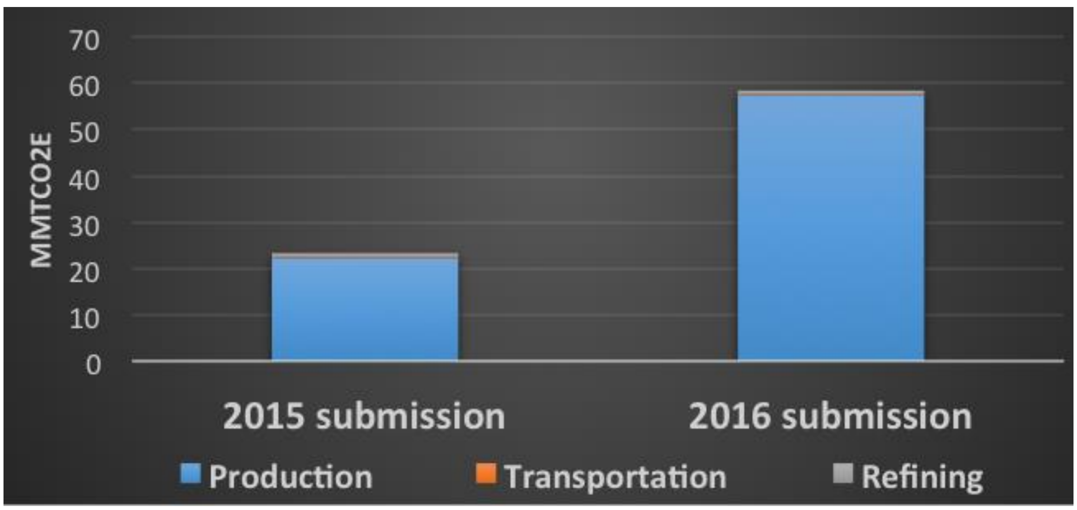

Figure A.2. Methane emissions from petroleum systems for the year 2012 in the 2015 and 2016 inventory submissions (Adapted from GHG Institute, 2016)

[92] EPA. Comparing top-down & bottom up estimates of oil & gas CH4 emissions: A spatially-resolved emission inventory for the Barnett Shale Region. (2015). https://www.epa.gov/sites/production/files/2015-09/documents/lyon_pres.pdf

[93] EPA. (2015). https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf

[94] EPA. (2016). https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html

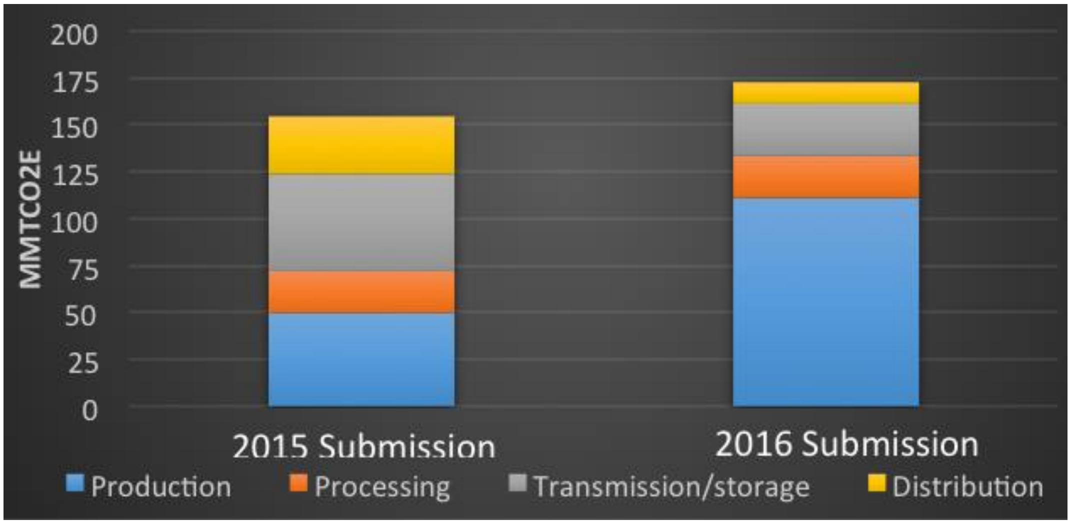

Figure A.3. Comparison of 2015 and 2016 inventory submissions for 2012 estimates of GHG emissions from natural gas (Adapted from GHG Institute, 2016)[95]

Improvements in reported estimates of GHG emissions are expected as new data and modelling techniques become available. In some estimates, only partial data sets are available when the inventory is performed, with the foreknowledge that they will be updated in the next inventory. In other instances, data may be extrapolated or recalculated based on more recent emission factors. Therefore, changes in the reported data are not surprising and are evidence of an industry and regulatory bodies working hard to determine emission impacts. This is a positive sign that suggests an evolving area of science attempting to keep abreast of the demands of climate change initiatives. However, this also signals that the accuracy of estimated emissions and the ability to carefully track the data is of concern. As a result, the 2006 IPCC Guidelines suggests a range of +/-100% uncertainty when applying their values to estimate natural gas methane emissions.

The application of correct emissions factors in order to estimate emissions is challenging. Many emissions in the oil and gas industry are unintentional and do not necessarily correlate with default emission factors; rather, they are dependent on the operation and condition of the specific equipment itself. When emission factors are unavailable, studies and assessments are forced to use generic emissions factors, regardless of the range of uncertainty. Therefore, understanding the inherent uncertainty is key to applying emissions factors in life cycle assessments.

Fugitive Emissions and Choice of Emission Factors

Significant differences can exist among data reported for fugitive emissions. The method in which data are collected, various modelling techniques, and the location where the data are collected contribute to the variability. Data on GHG emissions from natural gas extraction, transport and processing used in the LCA study of LNG pathway by Pembina Institute (Pembina, 2013) was extracted from CAPP, 2004[96]. While somewhat dated, the advantage is that the data are from Canadian sources.

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[95] Production means natural gas extraction.

[96] CAPP. (2004). A National Inventory of Greenhouse Gas (GHG), Criteria Air Contaminant (CAC) and Hydrogen Sulphide (H_2S) Emissions by the Upstream Oil and Gas Industry.

The current standard in GHG accounting and reporting is to apply methodologies and emissions factors from the 2009 Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry developed by the American Petroleum Institute (API). This report included very specific data on fugitive emissions for equipment, components used in the natural gas field, facility use, onshore and offshore production, processing, transmission and storage equipment, stations and pipe material. However, close examination revealed that their source data was from the 1990s. Specifically, three reports from the EPA[97,98,99] are frequently referenced. The flare data for developed countries in the API 2009 Compendium came from a 2006 IPCC report.

The province of British Columbia published a Ministry of Environment Information Note (File: 280-30, CLIFF/tracking #: 197083) to address the amount of methane deliberately and/or accidentally vented into the atmosphere[100]. The emission intensity of CH_4 for the actual vented amount, according to the table below, is 0.00226 kg CH_4/m^3 of natural gas.

Table 11.2. Methane emissions into the atmosphere in BC in 2010 and 2011

Year	NG Production	Methane mass density	Methane amount	CO_2e amount if all released into Atm.	Actual Venting	% Vented out of Total Production	GWP
	m^3	kg/m^3	t CH_4	Mt CO_2e	Mt CO_2e		100 yr
2010	34,991,762,000	0.678	23724415	498.21	1.97	0.40%	21
2011	41,441,414,000	0.678	28097279	590.04	1.97	0.30%	21

The most updated fugitive emissions information come from a publication by Argonne National Laboratories dated 2015 that uses the GREET model[101]. The data used in the report originates from several sources, including data from the 1990s up to at least 2011. The model also included site-specific data and measurements from processing plants, urban distribution systems and natural gas gathering facilities. The reported data is shown in the Table 11.3 below.

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[97] Harrison, M.R., L.M. Campbell, T.M. Shires, and R.M. Cowgill. (1996). Methane Emissions from the Natural Gas Industry, Volume 2: Technical Report, Final Report, GRI-94/0257.1 and EPA-600/R-96-080b. Gas Research Institute and U.S. Environmental Protection Agency, June 1996.

[98] Campbell, L.M., M.V. Campbell, and D.L. Epperson. (1996). Methane Emissions from the Natural Gas Industry, Volume 9: Underground Pipelines, Final Report, GRI-94/0257.26 and EPA-600/R-96-080i. Gas Research Institute and U.S. Environmental Protection Agency, June 1996.

[99] Harrison, M.R., T.M. Shires, R.A. Baker, and C.J. Loughran. (1999). Methane Emissions from the U.S. Petroleum Industry, Final Report, EPA-600/R-99-010. U.S. Environmental Protection Agency, February 1999.

[100] B.C. Ministry of Environment. (2013). Ministry of Environment Information Note. p. 8. http://docs.openinfo.gov.bc.ca/D331214A_Response_Package_MOE-2013-00244.PDF

[101] Argonne National Laboratory. (2015). Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET1_2015 Model. https://greet.es.anl.gov/files/fugitive-ch4-2015

Table 11.3. Summary of Methane Emissions in GREET1_2014 and GREET1_2015

Sector	Process	Unit	Conventional GREET1_2014	Shale GREET1_2014	Conventional GREET1_2015	Shale GREET1_2015	Conventional % Change	Shale % Change
Production	Completion	g CH_4/million Btu NG	0.5	12.4	0.5	7.2	0%	-42%
	Workover		0.0	2.5	0.0	1.4	0%	-42%
	Liquid Unloading		10.4	10.4	9.6	9.6	-7%	-7%
	Well Equipment		51.3	51.3	52.2	52.2	2%	2%
Processing	Processing	g CH_4/million Btu NG	26.7	26.7	26.7	26.7	0%	0%
Transmission	Transmission and Storage	g CH_4/million Btu NG	81.2	81.2	84.5	84.5	4%	4%
Distribution	Distribution	g CH_4/million Btu NG	83.1	83.1	88.9	88.9	7%	7%
Distribution	Distribution (station pathway)	g CH4/million Btu NG	63.6	63.6	69.1	69.1	9%	9%
Total		**g CH_4/million Btu NG**	**253.2**	**267.5**	**262.4**	**270.5**	**4%**	**1%**
Total (station pathway)		**g CH_4/million Btu NG**	**233.8**	**248.1**	**242.5**	**250.6**	**4%**	**1%**

According to the API 2009 report, uncertainties in methane emissions can be as high as +/- 200%, therefore, it becomes challenging to compare numbers from one set of calculations to another.

In this study, the Canadian data from CAPP, 2004 and GHGenius v4.03 was used. Emissions due to gas leaks and flares are captured under a separate category ("gas leaks and flares") in GHGenius. This helps to separate these emissions from other GHG emissions resulting from, for example, well exploration, well drilling, well completion, and acid gas removal.

A.12 Scenario 12: Transmission Line

Table 12.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials extraction and processing (steel, concrete, aluminum, cast iron, etc.)	Athena, 2005 GaBi Professional database (region: Canada)
Transport of construction materials	Transmission line components are transported 2,400 km by truck, 22t payload.	Estimated
Transmissions Line construction	Line Construction Steel 1.54E-04 kg/km Concrete 6.01E-04 kg/km Aluminum 5.37E-05 kg/km Cement 2.84E-07 m^3/km Lead 7.80E-06 kg/km Glass 4.58E-06 kg/km Bronze 1.79E-06 kg/km Copper 4.80E-06 kg/km Mineral oil 5.35E-06 kg/km Pp 1.06E-06 kg/km Paper 2.12E-06 kg/km Sand 8.93E-04 kg/km Zinc 3.46E-06 kg/km Cement 8.98E-16 kg/km	Itten et al., 2014[102]
	Land clearing 170 km line, 30m right of way clearing and 68 km x 15m of an existing 34.5kv line (306 ha plus 102 ha of cleared area footprint) Initial vegetation clearing – 800 L of diesel/km Yearly vegetation clearing – 210 L of diesel/km	Yukon Energy Correspondence, 2016
	Diesel emission factors Emissions factors, kg/L: CO_2 / CH_4 / N_2O Diesel fuel: 2.663 / 0.133 / 0.4	WRI, 2010
Electricity Transmissions	Transfer Capacity: 443 MW, 230 kV transmission line	

[102] Itten, R., Frischknecht, R., and Stucki, M. (2014). Life Cycle Inventories of Electricity Mixes and Grid. Version 1.3. treeze Ltd., Switzerland, June, 2014.

A.13 Scenario 13: Water Diversion Project

Table 13.1 Data sources and assumptions for processes in the system boundaries

Process	Assumptions	Source
Construction materials extraction and processing	Raw materials (gravel, sand) are sourced locally.	
Transport of construction materials	Locally sourced materials are used Transport distance: 15 km by truck, 22 t payload	Estimated
Diversion channels and dam construction	Partial greenfield site with inundation area of 220 ha GHG emissions from inundation are estimated using IPPC, 2003 Tier 1 methodology: 17.4614 kg CO_2/MWh 0.4506 kg CH_4/MWh 0.0090 kg N_2O/MWh Channel excavation and dam construction Excavation by a single-bucket excavator Excavation rate: 130 m^3/hr Diesel consumption: 23 L/hr or 0.1769 L/ m^3 Channel excavation quantities 514,000 m^3 Quantities for Dam D (gravel till, impervious till, sand) 234,100 m^3	IPCC, 2003 Estimated AECOM, 2011[103]
Electricity Generation	Net electricity production: 29.7 GWh_e/yr – the project would utilize existing Hydro units.	

[103] AECOM. (2011). Gladstone Diversion Concept Conceptual Design. AECOM, May, 2011.