A Well-to-Wire Life Cycle Assessment of Canadian Shale Gas for Electricity Generation in China

Ratan Raj[1], Samane Ghandehariun[1], Amit Kumar [1], Ma Linwei[2]

[1]10-263 Donadeo Innovation Centre for Engineering, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada, T6G 1H9

[2]State Key Laboratory of Power Systems, Department of Thermal Engineering, Tsinghua-BP Clean Energy Center, Tsinghua University, Beijing 100084, China

Abstract

China relies heavily on coal for power generation, and the demand for coal in a country of this size makes China the world's largest carbon dioxide emitter; hence China is pursuing greener pathways for power generation. Importing shale gas in the form of LNG from Canada is one such pathway. It starts with the recovery of shale gas in Canada and its export to China. This paper quantifies well-to-wire (WTW) greenhouse gas (GHG) emissions per kilowatt hour (kWh) of Canadian shale gas-fuelled electricity in China through models. WTW emissions include emissions from recovery, processing,

[1]Corresponding author. Tel.: +1-780-492-7797.
E-mail address: Amit.Kumar@ualberta.ca (A. Kumar).

transmission, liquefaction, marine shipping, re-gasification, power plant operations, and electricity transmission and distribution. Four Canadian shale gas reserves - Montney, Horn River, Liard, and Cordova - are considered. The results show that the WTW GHG emissions of Canadian shale gas-fired combined cycle technology range from 567-610 gCO_2/kWh (57-62% of the GHG emissions from China's present coal-fired electricity), and total well-to-port (WTP) GHG emissions (emissions from recovery, processing, and transmission to a liquefaction facility) range from 7.68 to 13.4 gCO_{2e}/MJ. Sensitivity analysis results show that venting emissions during raw gas processing, flaring rates during well completion, and lifetime productivity of the gas significantly influence WTP emissions.

Keywords: Shale gas; life cycle assessment; electric power generation; liquefaction; natural gas.

Nomenclature

DEA	Diethanoamine
$E_{d,low}$	Minimum diesel energy consumption per unit distance drilled, MJ/m
$E_{d,high}$	Maximum diesel energy consumption per unit distance drilled, MJ/m
d	Measured well depth (horizontal and vertical), meters
H	Heat duty of the reboiler in gas sweetening unit, MJ/h
Q	Circulation rate of DEA, m^3/min
p	Suction pressure of pumps, kPa
P_{BP}	Power requirement of booster pump, kW
P_{CP}	Power requirement of circulation pump, kW
P_{AC}	Power requirement of aerial cooler, kW
P_{RP}	Power requirement of reflux pump, kW
H	Heat duty of the regenerator in gas dehydration unit, MJ/h
q	Glycol to water ratio, m^3/kg

1. Introduction

Demand for energy in Asian countries is growing rapidly. These countries are net importers of energy, and natural gas import is a key component of their energy import portfolio. It is expected that by 2030, Asia's energy consumption (per capita) will grow to approximately 84 Gigajoules (GJ) per year [1, 2]. According to the United States Energy Information Administration (US EIA), future natural gas markets in Asia will be highly bullish and much of this natural gas will be used as a substitute for coal-fired power generation [3]. The opportunity to exploit Canada's vast reserves of unconventional natural gas has received significant attention of the industry and government. This opportunity has led to plans to develop a new industry in liquefied natural gas (LNG) with the main intention of exporting natural gas in the form of LNG to overseas markets, particularly Asia [4]. The strategy is to extract western Canadian natural gas (shale gas) from unconventional fields for its export to Asia. This gas, after processing, would be transported via pipelines to Canada's west coast, where it would be liquefied by proposed liquefaction plants before export.

China is the world's largest producer of power and has a 22% share in global electricity generation [5, 6]. It is also the world's largest emitter of carbon dioxide [7]. These emissions are primarily due to China's extreme reliance on coal-based power. Coal accounted for around 75% of the country's electricity power generation in 2010 [6], whereas natural gas accounted for less than 2% in the same year [7]. Emissions from coal power plants can be significantly mitigated in China by substituting coal with natural gas-based power generation. Due to monitoring from environmental protection agencies and the urgent demand for energy infrastructure optimization, China has proposed policies that encourage the diversification of gas supplies and increase imports from overseas markets [8]. These policies have led to the building and operation of LNG re-gasification terminals in Shenzhen, Fujian, and Shanghai [8].

Despite the advantages of huge shale gas reserves in Canada and growing gas demand in China, exporting LNG to China from Canada is still challenging. One of the key challenges is the growing social and environmental concerns associated with shale gas extraction (hydraulic fracturing), which includes land use emissions, induced seismicity, huge water consumption, and contamination from flow-back water [9]. Midstream (processing and liquefaction) and downstream operations (LNG shipping, re-gasification, combustion) contribute to GHG emissions. Therefore, in order for Canada and China to formulate a policy on exporting LNG, both countries require a comprehensive well-to-wire life cycle assessment to understand the environmental impacts of this LNG chain.

Currently, there is no study in the academic literature that comprehensibly analyzes the life cycle environmental impact of the entire Canada-China LNG supply chain (which considers various processes such as natural gas extraction, processing, pipeline transport, LNG shipping, re-gasification, and combustion) using process modeling. There are some studies that discuss the life cycle analysis of individual processes (predominantly shale gas extraction and processing) of the LNG supply chain. Those studies that do describe the life cycle carbon footprints of extraction and processing of shale gas are based on data from shale gas reserves in the United States [10-16], the UK [17-22], and China [6, 23-28]. Literature on life cycle analyses of shale gas from a Canadian perspective is scarce and, given the significant amount of variation in chemical composition of the shale gas reserves and the processes employed to extract the shale gas from region to region, conducting a life cycle analysis for Canadian shale gas reserves is needed and is novel. Furthermore, existing studies of energy and environmental footprints of shale gas in Canada are qualitative in nature [9] or mainly employ life cycle inventory models [29]. The study conducted by Rivard et al. [9] describing the status of Canadian shale gas exploration and production includes discussions on geological contexts of the main shale formations containing natural gas, water use for hydraulic fracturing, the types of hydraulic fracturing, public concerns, and on-going research efforts but does not quantify the GHG emissions from shale gas extraction from different Canadian unconventional gas reserves. The other study [29] (on energy and environmental footprints of shale gas in Canada) that employs life cycle inventory methods has many limitations, the most significant of which is that it limits the boundaries of the system under analysis [6]. Truncation errors as well as study boundary differences prohibit convincing comparisons with other life cycle analysis results. Because the purpose of this paper is to estimate the life cycle emissions of a system that consists of various processes and sub-processes, defining the boundaries of that system is paramount. Hence, in this paper, the authors employ a process-based life cycle modeling approach to conduct a comprehensive well-to-wire (WTW) life cycle analysis of the entire LNG supply chain. Unlike the inventory approach, a process modeling approach allows us to conduct an uncertainty analysis for individual parameters in each life cycle process. Rahman et al. analyzed transportation fuels derived from North American crude oils through data-intensive process models [30]. The focus of that study was to quantify the life cycle GHG emissions of transportation fuels. The focus of the current study is to quantify the life cycle GHG emissions of Canadian shale gas. The underlying processes, focus, and data used to for these commodities (crude oil and shale gas) are different and hence warrant a different approaches to estimate GHG emissions. The flexibility to change different process parameters and visualize their impact on total GHG emissions is especially important for Canadian shale gas, whose composition and well characteristics vary significantly from one gas reserve to another. For example, the carbon dioxide content of the shale gas in Montney is 0% and in Horn River is 12% [31]. A model is needed in order to guide others in making sound policy decisions. The goal of this paper is to address the gaps and limitations raised above and present novel contributions to the literature by conducting a comprehensive well-to-wire (WTW) life cycle analysis of the entire LNG supply chain through process modeling. The major objectives of this paper are as follows:

- To quantify the well-to-wire (WTW) greenhouse gas (GHG) emissions per kilowatt hour (kWh) of Canadian shale gas-fuelled electricity in China
- To estimate the GHG emissions impact in extraction and production of the four Canadian shale gas reserves, namely the Montney, Horn River, Liard, and Cordova
- To compare the WTW emissions of different electricity generation sources in Canada and China

- To conduct a sensitivity analysis to identify the parameters that significantly influence total GHG emissions

Overall, this paper assesses the GHG emissions impact of BC's LNG export chain from the shale gas wellhead to electricity distribution in China. The results presented can help decision-makers and researchers in Canada and China to better understand the GHG footprints of this LNG supply chain and of imported shale gas-fired electricity in China.

2. Methodology

In this paper, a life cycle assessment (LCA) approach has been used to estimate GHG footprints, following the LCA methodology described in ISO 14040/44 [32, 33]. GHG emissions from carbon dioxide, methane, and nitrous oxide are included. The emissions are converted to carbon dioxide equivalents based on the 100-year global warming potential factors reported by the IPCC's Fourth Assessment Report, 2007 [34].

2.1 Goal and scope of the study

The goal of the study is to estimate the life cycle environmental impacts of producing electricity in China from imported Canadian shale gas and to compare them with the life cycle environmental effects of other forms of electricity generation in China. Shale gas would be extracted from Canada, particularly from the shale gas reserves (Horn River, Montney, Cordova, Liard) in the Western Canadian Sedimentary Basin (WCSB), transported by pipeline to an LNG facility in the Port of Kitimat, British Columbia (BC), where it would be compressed and loaded onto an LNG tanker, transported to an LNG port in China, re-gasified, and then transported to a natural gas power plant (see Figure

1). It is assumed that both simple and combined cycle natural gas plants in China would be used to generate electricity. Since it is not clear at this stage what the imported shale gas would replace, the shale gas is compared to the following current electricity options in China:

- Domestic shale gas-fired power plants
- Coal-fired power plants
    - Subcritical
    - Supercritical
    - Ultra super critical pulverized coal
    - Integrated gasification coal combined cycle

The scope of this study for electricity from shale gas is from "well to wire" (see Figure 2). The scope is described in more detail in the following sections.

2.2. System description, data and assumptions

2.2.1. Shale gas life cycle

The first unit operation in the life cycle of shale gas is its recovery from the gas well. This operation encompasses various unit operations such as drilling pad construction, vertical and horizontal drilling, hydraulic fracturing, well completion, and gas production. Energy is consumed during the drilling process by diesel-powered or electric equipment. In this paper, it is assumed that this power requirement would be met by engines powered by diesel. Unlike conventional sources of natural gas, shale gas, an unconventional source, requires horizontal drilling as well. This is because most shale gas resources (Horn River, Montney, Liard, and Cordova) in the WCSB are located 1800-3200 meters or more below ground level and are relatively thin (for example, the Montney shale gas formation is between 30 and 300 meters thick) (see Table 1 for properties of shale gas reserves). Therefore, a horizontal well, by allowing the borehole to be in contact with the relatively thin shale interval over significantly long distances and surface areas compared to a vertical borehole, enhances the recovery of shale gas.

Following vertical and horizontal drilling, hydraulic fracturing is done to increase the permeability of the shale reservoirs and in turn facilitate the gas flow toward the well. This is achieved by perforating the steel casing of the well and injecting pressurized fracturing fluid with the help of diesel engines. The Horn River Basin shales are primarily fracked with slickwater (a mixture of water, sand, friction reducers, and chemical additives), whereas Montney's liquid-rich shales are fracked with foam (a mixture of water and gas) [9]. BC fracking regulations are available in the public domain [35]. After hydraulic fracturing, well completion begins. Emissions in the well completion stage are caused by venting/flaring of the shale gas that comes out during well development. The emissions during the well completion stage are considered episodic emissions in that they are not part of the daily, steady state of well operations. Gas production begins after the well is completed. From this point, the life cycle stages for shale gas are the same as conventional gas. The gas from the wellhead is sent for surface processing, where it is sweetened, dehydrated, and compressed for pipeline transmission. Then the gas is liquefied at the LNG facility at the Port of Kitimat and sent to LNG re-gasification ports in China by LNG carriers. After re-gasification, the gas is sent to natural gas power plants to generate power. These stages are described in further detail below. The analysis is based on Canada- and China-specific data wherever possible, and we have drawn on data from the literature and in discussion with experts.

2.2.2. Shale gas recovery

The first unit operation in shale gas recovery is gas well pad construction. Well pads are the area from which drilling operations are conducted. Influenced hugely by economic factors, oil and gas operators have transitioned from constructing single wells on single pads to multiple wells on single pads [36]. Multi-well pads significantly reduce the costs of demobilizing and moving a drill rig from one pad to another [36, 37]. The number of wells per pad varies depending on the properties of the shale reservoir, geographical location, and economic considerations. For example, the number of well pads constructed for Canadian shale gas extraction ranges from 1 (Liard) to 20 (Montney) [31]. GHG emissions from well pad development are those associated with road and well pad construction as well as the loss of carbon due to clearing a vegetative area [12].

After well pads are built, gas wells are drilled. As discussed before, diesel-powered drill rigs meet the drilling energy requirement. To estimate the energy consumption by drill rigs during the drilling process, empirical relationships established earlier were used [38]. These relationships, based on Canadian well drilling data, show an exponential relationship between energy consumption and gas well depth (see Equations 1 and 2, supplementary information). Both the vertical and horizontal lengths of the wells are taken into account to estimate the energy consumption. Well depth for each shale reservoir can be found in Table 1. The energy required to drill a well is amortized over the lifetime productivity of the well. Emissions are calculated from the ratio of energy required to drill a well to the lifetime productivity of the well in terms of energy and emission factors for diesel combustion [39]. The lifetime gas production of different Canadian shale reserves and the related well drilling data are reported in Table 1. The unbracketed numbers in Table 1 are the base case values, and the bracketed numbers give the range for a particular parameter.

The next unit operation after well drilling is hydraulic fracturing. The major energy consumption in this process is from pumping the fracking liquid into the gas well. Canadian shales are fracked mostly by slickwater or gel/foam. Emissions from this process are estimated using the pumping energy capacity, pumping time, and emission factor for the pump's diesel engine [39]. The pumping energy capacity (25 MW) was adapted from [12] and pumping time for fracking each shale reserve was calculated using the amount of fracking fluid pumped per stage, number of stages, and the pump rate (see completion data in Table 1). Extensive water consumption occurs during the slickwater hydraulic fracturing process. Water quantities required for hydraulic fracturing depend mainly on the geology of the shale gas reserves [9]. Water consumption for all four shale gas reserves considered in this paper is presented in Table 1. Due to the lack of Canada-specific data on GHG emissions associated with water use, these values have been adapted from Jiang et al. [12]. Emissions from flaring the shale gas produced during well completion are a function of the initial gas production rate of gas wells, flaring time, and the flaring rate of the gas [15]. Since these variables are prone to uncertainties, a sensitivity analysis is conducted to cover a wide range of flaring rate times to capture the uncertainty. According to the Canadian Association of Petroleum Producers (CAPP), the sources of emissions for natural gas production are wells, gathering systems, and batteries. Gas wells are sources of fugitive emissions due to gas leaks in valves and fittings on the wellhead. The emissions from these sources are taken from CAPP inventory [40] and are summarized in Table 2. These emissions values are based on the reported natural gas production of 155 million tons of natural gas.

2.2.3. Shale gas surface processing

When shale gas comes to the surface from the gas well, it contains impurities such as hydrogen sulfide and carbon dioxide that must be treated to produce pipeline quality gas (95-98% methane). This unit operation, surface processing, is the stripping out of those impurities and other hydrocarbon fluids. Of the four shale gas reservoirs considered in this paper, the Horn River Basin has high CO_2 content (around 10-12%) (see Table 1). The Montney reserve has negligible CO_2. The raw gas from the wellhead is first sent to an inlet gravity separator to separate gas and water. This separator uses chemical additives with small environmental concerns but since no fuel is consumed in this process, it is not a significant source of GHG emissions. After the inlet separator, the gas is treated in a gas sweetening unit and a glycol dehydrator. In this paper, di-ethanolamine (DEA) is used as a gas sweetening chemical solvent, as this leads to fewer losses in the hydrocarbon content of the natural gas [37]. The DEA circulation rate is calculated using the amount of acid gases in the shale gas reservoirs (see Table 1). The types of equipment that consume energy in this process are amine reboiler, booster pump, circulation pump, aerial cooler, and reflux pump. The heat duty calculations for the reboiler and power calculations for various pumps are given in Equations (6)-(11) [41] (see supplementary information). In this paper, it is assumed that this equipment is powered by natural gas.

The next step in gas processing is to remove the water from the gas. This is done in the dehydration unit. Reboiler heaters and pumps are the major energy-consuming units in this process. The reboiler heat duty can be calculated from the amount of water removed and the regenerator duty, which is illustrated by Equation (3). In this paper, it has been assumed that 0.72 grams of water are removed per cubic meter natural gas in the gas dehydrating unit [14]. Apart from combustion emissions, the gas processing plants, where gas is sweetened and water removed, are also significant sources of fugitive emissions. These emissions mostly depend on the acid gas content of the feed gas that is being processed. The fugitive emissions from a Canadian natural gas plant processing gas with 3% CO_2 content are 1159.21 g CO_{2eq}/GJ [29].

2.2.4. Domestic pipeline transport

After the shale gas is processed, it is sent to a liquefaction facility via gas pipeline. The three major and proposed gas transmission pipelines from the WCSB to BC's coast are listed in Table 3.

In this paper, a pipeline transmission distance of 650 km is considered for the base case. This pipeline is assumed to have an expected service life of 25 years (2018-43) and a capacity of 5 billion cubic feet per day [42]. The major combustion emission sources in this transmission process are the compressor stations and include combustion emissions from gas turbine compressors. The emissions are calculated using the compressor's exhaust flow rates, its acid gas concentration, and fuel combustion rates. Parameters associated with a typical gas turbine compressor are given in Table 4. Meter stations, which are used to monitor the amount of gas in a pipeline, do not contain any combustion sources. Fugitive emissions mainly arise from components such as compressor seals, valves, and piping connectors, whereas venting and flaring emissions are associated with standard practices and maintenance activities. We estimated fugitive and venting emissions by adapting emission factors (based on pipeline length and compressor and meter station) from *Greenhouse gas emission estimation guidelines for natural gas transmission and storage* [43].

2.2.5. Liquefaction facility

In this paper, a two-train LNG plant, each train with an annual liquefaction capacity of 5 million tons, was considered in the base case to estimate GHG emissions. It is assumed that the liquefaction plant will process approximately 1.43 billion cubic feet of natural gas per day (estimated from the annual liquefaction capacity of the plant) and operate for at least 25 years. The CO_2 mole percent of the feed gas is assumed to be around 0.8%, as this is the CO_2 gas content in the Canadian pipelines that transfers the natural gas to a liquefaction plant [29]. The major power-consuming equipment in a liquefaction train are the natural gas-fuelled turbines and acid gas incinerators. It was assumed that each liquefaction train consists of two natural gas-fuelled turbines and one acid gas incinerator. The purpose of the incinerators is to burn acid gases that are removed from the feed gas. Each natural gas turbine would be operated at a maximum load of 99.3 MW. The specific parameters for the gas turbines are summarized in Table 5. Cryogenic heat exchangers, which provide large surface areas to transfer heat from the feed gas, do not consume significant amounts of energy.

GHG emissions from the gas turbines are estimated based on each equipment's specific fuel consumption rates, emission factors, and operation duration. Fuel consumption rates are calculated from the heat rate of the gas turbine, and Canada-specific CO_2 emissions factors are estimated using earlier estimates [44]. The emissions from acid gas incinerators, flaring, and venting emissions are adapted from a report by Banholzer et al. [45].

2.2.6. LNG shipping via LNG carriers

Natural gas would be shipped as LNG to Chinese re-gasification ports via LNG carriers. Energy consumption and hence GHG emissions from LNG shipping would primarily depend on the propulsion system and fuel used. In this paper, marine engines powered by natural gas and heavy fuel oil (HFO) were considered. The data for GHG emissions in this process are presented in Table 6. It has been assumed in this paper that the boil-off gas during the voyage is consumed (gas-based propulsion) or re-liquefied (HFO based).

2.2.7. Power plant operations and electricity transmission

Burning shale gas as a fuel in the power plant for electricity generation is the last unit operation in the life cycle analysis conducted in this paper. Emissions from both simple and combined cycle natural gas plants were considered in this model. The difference between the two cycles is that in the combined cycle natural gas plant, the excess heat during the combustion of natural gas is directed to produce steam and turn a steam turbine. This leads to greater plant efficiency. The details of both types of plants are presented in Table 7 below. Carbon capture and sequestration (CCS) technology were not considered because there is no large-scale CCS use in China [6].

3. Results

3.1. Well-to-port GHG emissions

As shown in Figure 2, the well-to-port (WTP) system boundary includes the emissions from shale gas recovery, surface processing, and pipeline transport to the liquefaction facility. Figure 3 shows the WTP emissions associated with the four types of shale gas reservoirs considered in this paper. Emissions range from 7.68gCO_{2e}/MJ to 13.4gCO_{2e}/MJ depending on the shale gas reserve. Horn River has the highest WTP emissions followed by Liard, Cordova, and Montney. As evident from Figure 3, venting emissions during shale gas processing (acid gas removal) are the largest contributor (at more than 30%) to GHG emissions for every shale reservoir except Montney. At Montney, which is a sweet gas reserve, venting emissions form only 18% of WTP emissions. The average CO_2 gas content in the Horn River Basin is around 12% (see Table 1), which makes the emissions from this shale reserve the highest of the reserves considered. These emissions can be greatly reduced by building a carbon capturing and sequestration (CCS) plant near the gas processing plant. One such pilot plant, the Fort Nelson Carbon Capture and Storage Feasibility Project (FNCCS), has been proposed by Spectra Energy [46]. The proposed project is an initiative that aims to significantly reduce CO_2 emissions at Spectra Energy's Fort Nelson Gas Plant (FNGP) in northeast British Columbia. The FNGP processes unconventional natural gas from Horn River, Liard, and Cordova shale gas reserves. According to Spectra Energy, the proposed plant is expected to remove up to 2.2 megatons/y of GHG emissions from the atmosphere [46]. If implemented and successful, this CCS project can significantly reduce the recovery GHG emissions from the Horn River, Liard, and Cordova shale gas reserves. Combustion emissions from the re-boilers in gas sweetening and dehydrating units are negligible compared to the venting emissions. Well completion emissions, which are episodic emissions, are highest for the Liard Basin, as Liard has the highest initial gas production rate. Since the GHG emissions of each unit operation in this stage are divided by the eventual overall or lifetime gas production of shale gas wells to obtain an estimate of GHG emissions per unit of gas produced, higher lifetime productivity of the wells will make recovery emissions less significant. Therefore, a sensitivity analysis is conducted to cover a wide range of potential lifetime gas productivity amounts. The emissions from pipeline and compressor operations also significantly contribute to WTP emissions.

3.2. Port-to-wire and well-to-wire GHG emissions

In this section, port-to-wire emissions are discussed. These include emissions resulting from natural gas liquefaction, LNG shipping by marine carriers, re-gasification at Chinese ports, power plant operations, and electricity transmission. The emission results for liquefaction facilities show that 0.35 tons of CO_{2e} are released into the atmosphere to produce one ton of an LNG product. The total emissions in this stage are estimated on a reference flow of per ton of LNG output. Natural gas turbines are the largest source of emissions (around 70% of a liquefaction plant's GHG emissions), followed by acid gas incinerators. Venting and flaring emissions contribute to approximately 7% and 2% of the total emissions, respectively. It should be noted that after the processing phase, the life cycle of shale gas is similar to that of conventional natural gas. Both gas-fuelled and HFO-fuelled marine engines are considered. LNG carriers burning natural gas as fuel emit around 28% fewer emissions than HFO-burning LNG carriers. Re-gasification and electricity transmission emissions data were adapted from Skone and James [14]. Results show that the natural gas-fired power plant is the biggest GHG emitter in the entire LNG supply chain. These emissions can be reduced significantly by implementing CCS projects at the plant site. Emissions from all the previous stages are normalized to the functional unit of kWh of energy produced in the natural gas power plant and are presented in Table 9.

The well-to-wire (WTW) GHG emissions from burning Canadian shale gas in China for power generation are presented in Figure 4 below. Life cycle GHG emissions from Canadian shale range from 538 gCO_2/kWh (Montney) to 640 gCO_2/kWh (Horn River). Natural gas combustion at the power plant for electricity generation in China and natural gas liquefaction in BC constitute about 70% and 10% of the total emissions, respectively. The remaining 20% are from the recovery, processing, and transportation processes of natural gas or LNG. Implementing CCS technologies near the power plant can significantly reduce emissions at the power plant. Life cycle GHG emissions from the Horn River Basin are the highest among the shale reserves studied, mostly because of the fugitive emissions during processing. The Liard Basin has GHG emissions similar to Horn River but has the highest recovery emissions of the shale reserves studied. Due to Horn River's high initial gas production rate, its well completion emissions are considerably high. The Montney shale reserve has the lowest emissions due to its low acidic content compared to the others. Port-to-wire emissions, which include LNG shipping, re-gasification, power plant operations, and electricity transmission and distribution are same for all the shale reserves.

Since it is not yet clear which power generation option the imported LNG from Canada would replace in China, the calculated life cycle emissions of Canadian shale gas for electricity generation were compared to life cycle emissions of other power generation sources in China. The comparison is presented in Figure 5 below. The life cycle emissions for different coal technologies and shale gas-powered generation were adapted from Chang et al. [6]. Canadian shale gas is more competitive than coal for power generation in China in terms of GHG emissions mitigation potential. When we evaluate solely on GHG emissions from electricity generation, Canadian shale gas is at a little disadvantage over Chinese shale gas. This is mainly due to the added emissions from liquefaction (and re-gasification) and marine shipping in the Canadian shale LNG supply chain. Nonetheless, Canadian shale gas may give tough competition to Chinese shale gas for two reasons. First, the shale gas industry in China is in its nascent phase due to high production costs [47]. Moreover, for gas-fired power plants to operate regularly, they must have a continuous supply of gas. Although some may argue that China has huge reserves of shale [6, 48], large-scale shale gas production requires advanced drilling and hydraulic fracturing techniques as well as development and investment in re-gasification and pipeline infrastructure. These developments are still in their nascent phase in China and require both investment and strategic policy formulation from the Chinese government [6, 48].

3.3. GHG abatement cost calculation

GHG abatement cost assessments help to evaluate GHG mitigation and the economics of an energy system and to make sound policy decisions. In this section, the GHG abatement cost of electricity generation from two sources of fuel (imported shale gas from Canada and Chinese coal) is estimated. The abatement cost is a function of the cost of fuel (imported shale gas and coal) used in the power plant and the life cycle emissions of both the fuels. The data required to estimate the abatement cost are provided in Table 10. Results show that the GHG abatement cost is around \$117/ton CO_{2e}. The sensitivity of this result is illustrated in Figure 6. As is clear from the figure, GHG abatement costs are most sensitive to life cycle GHG emissions of coal and shale gas.

3.4. Sensitivity analysis

In the sensitivity analysis, various key variables pertaining to shale gas recovery and processing operations were altered using a parameterized model. This modeling allowed us to identify variables that have the greatest effect on GHG emissions. The sensitivity analysis was conducted by varying each variable within its acceptable range. A Monte Carlo simulation was performed using ModelRisk by simulating one million trials. Since the base case value refers to the likeliest value, parameters were assumed to follow a triangular distribution. Parameters whose range was not available were varied by ±50%. The results of the sensitivity analysis are presented in Figure 7.

It is clear from the analysis that the carbon dioxide content in the shale gas has the greatest impact on recovery and processing emissions. This is due to the venting of carbon dioxide directly into the atmosphere. GHGs can be mitigated significantly by implementing CCS technologies at the processing plant. The second most impactful parameter is the flaring rate of shale gas during well completion. The flaring rate in the sensitivity analysis was varied from 0-98% based on values reported in published literature (discussed in section 2.2.2). Since the total emissions from each unit operation are divided by the energy produced by the shale gas wells in their lifetime to obtain the emissions per unit of energy, the lifetime productivity of gas wells is also a very sensitive parameter. Increasing the lifetime productivity of a gas well would reduce the impact of GHG emissions and decreasing it would amplify this impact. Based on estimates by Stephenson et al., the lifetime productivity of shale gas is 1200-1500 times the initial gas production rate per day [15]. The methane content of the Horn River Basin varies from

80-98% (see Table 14). The methane content of the gas, along with reservoir depth, re-boiler duty and efficiency, and hydraulic fracturing pumping time have little impact on recovery and processing emissions.

4. Conclusion

There are abundant supplies of shale gas in Canada and they have doubled Canada's natural gas reserve base; with exploration, the amount available could increase. However, shale gas development is still in early stages. The results reported in this paper have demonstrated that altering various key parameters gives a wide range of life cycle environment impacts of power generation in China with Canadian shale gas. The findings of the well-to-wire emissions from Canadian shale gas show that the combustion stage is the major contributor to emissions, and the emissions may be considerably worse depending on the amount of acid gas concentration in the raw gas and the estimated lifetime productivity of the well, among other factors. Moreover, the choice of flaring or venting the gas during well completion also has a tremendous effect on life cycle emissions. The development of technologies to ensure the reasonable capturing of gas that would otherwise be flared or vented would significantly reduce one of the largest sources of emissions from shale gas recovery and processing.

The well-to-port emissions for Canadian shale gas range from 7.68 to 13.4 gCO_{2e}/MJ. This range is primarily driven by the amount of gas vented during the processing phase and the lifetime productivity of the reserves. It must be noted that since Canada-specific data, like drilling and completion emissions, gas composition, flow back water treatment, are still sparse owing to the early stage of the development of shale gas extraction in Canada, many parameters have uncertainty. Therefore, a sensitivity analysis was conducted to assess the impact of these variables on total life cycle emissions.

To estimate power plant operation emissions, we used Chinese natural gas power plant data in this paper. It was found that for a power plant in China with 51% efficiency on a low heating value (LHV) basis fuelled by a Canadian shale gas, the WTW emissions range from 567 to 610 gCO_2/kWh, depending on the assumptions. Implementing CCS technologies can significantly reduce power plant emissions.

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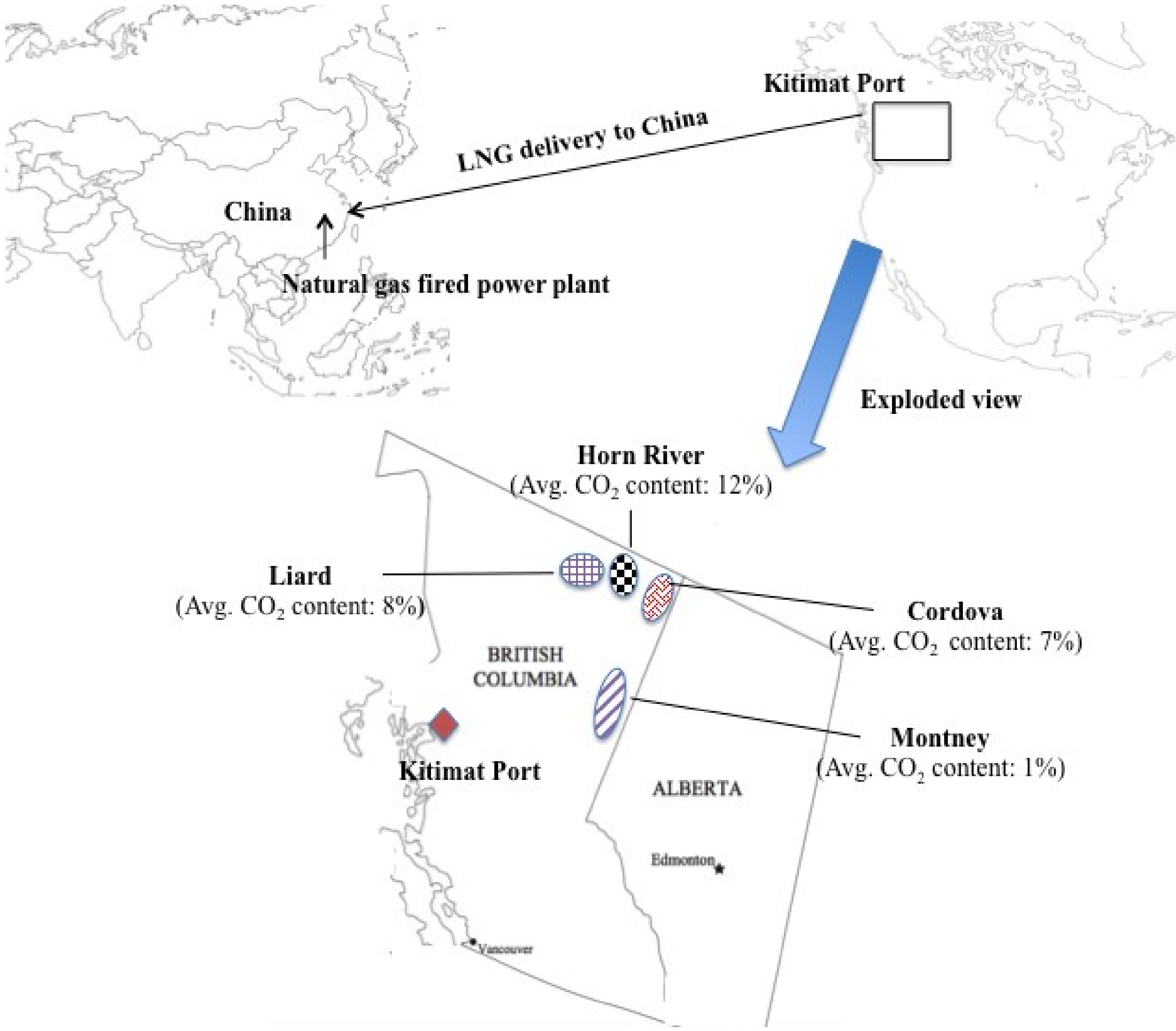

Figure 1: Map overview of Kitimat Port and different shale reserves in Western Canada

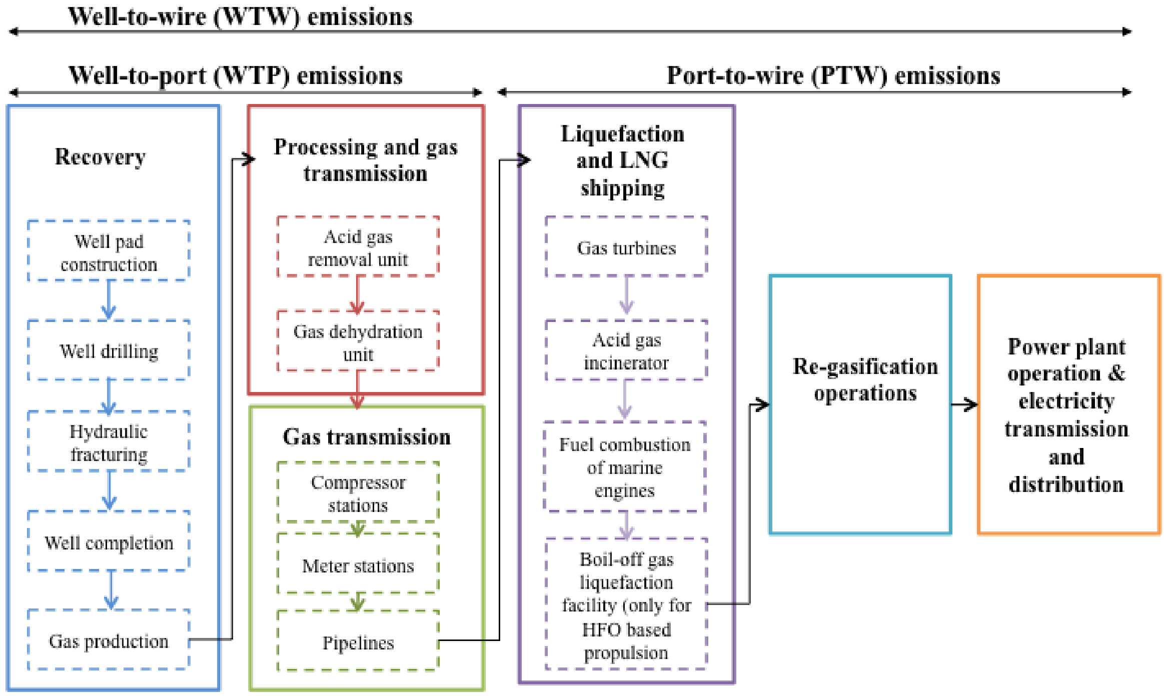

Figure 2: System boundary and unit operations involved in well-to-wire GHG emissions assessment.

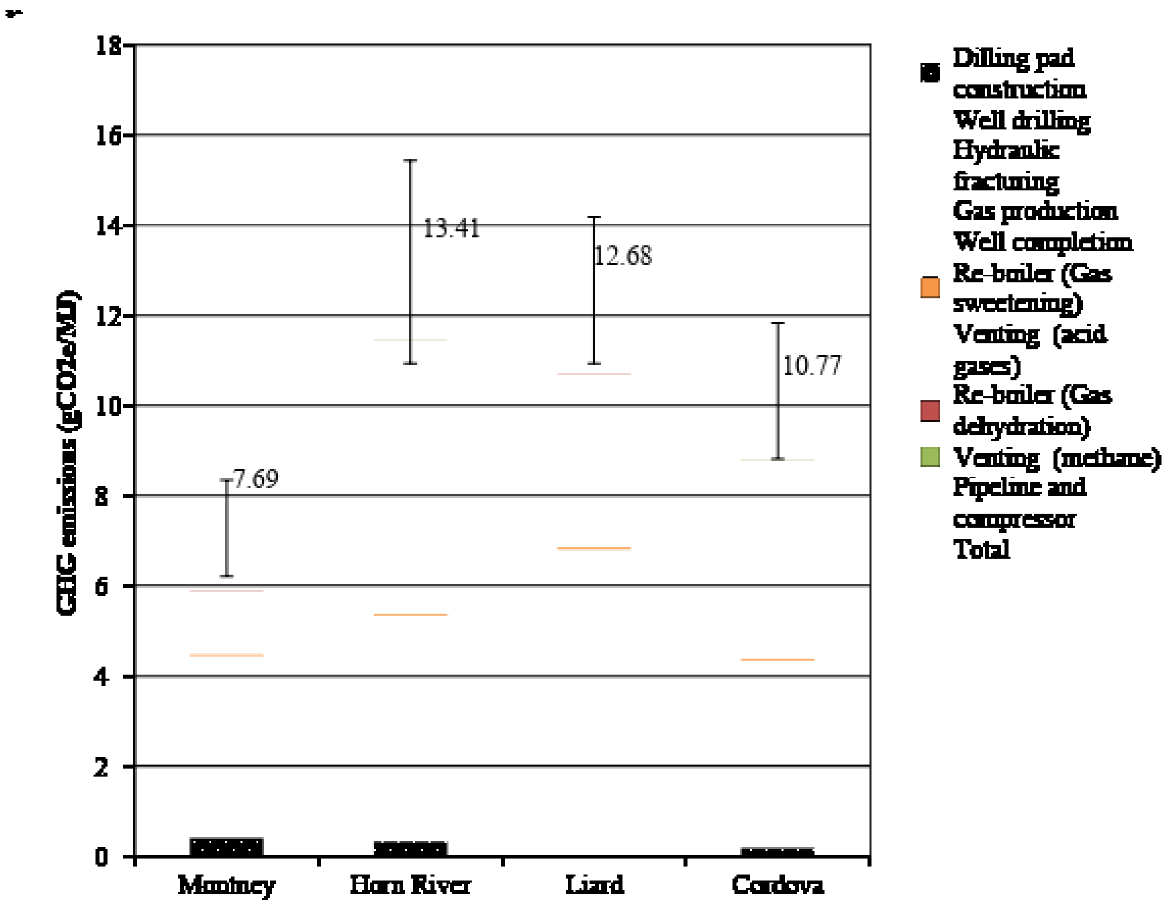

Figure 3: Well-to-port GHG emissions for different Canadian shale gas reserves

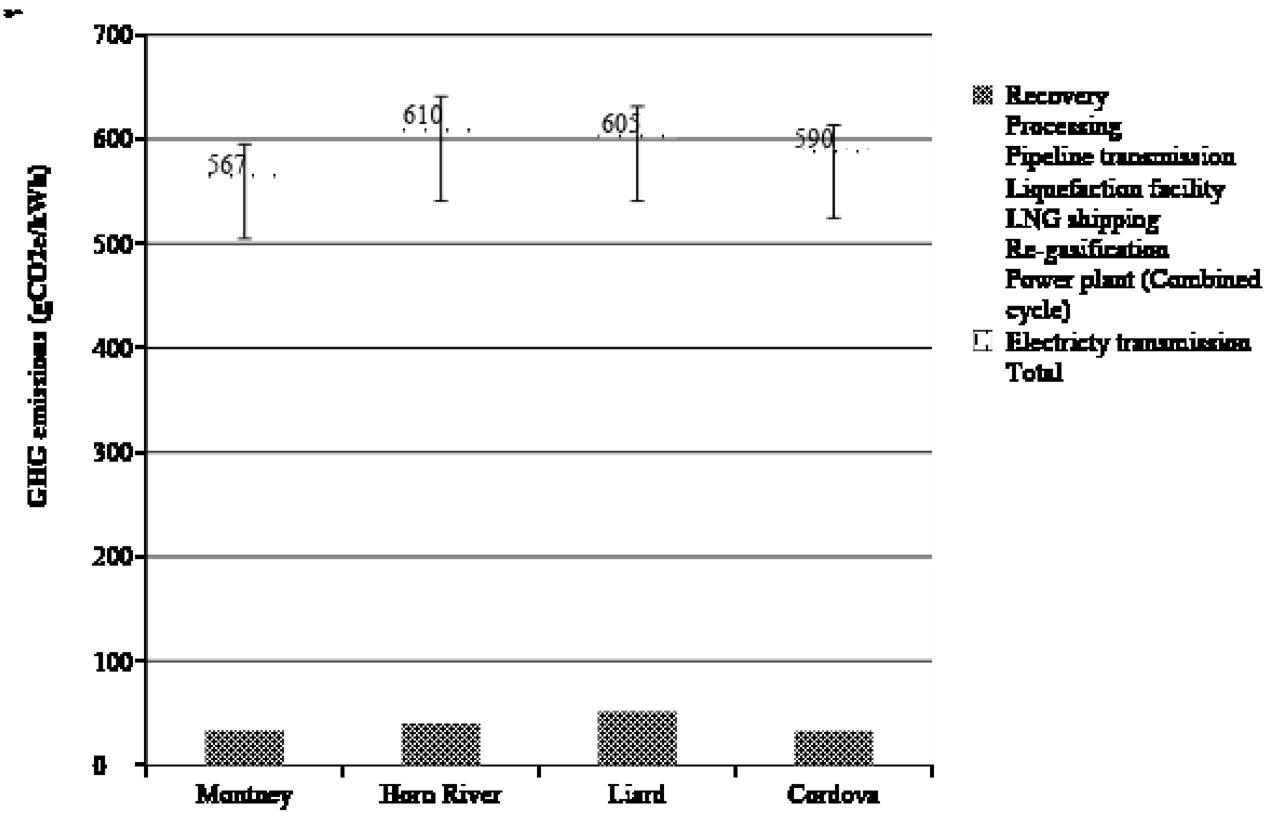

Figure 4: Well-to-wire GHG emissions for different Canadian shale gas reserves

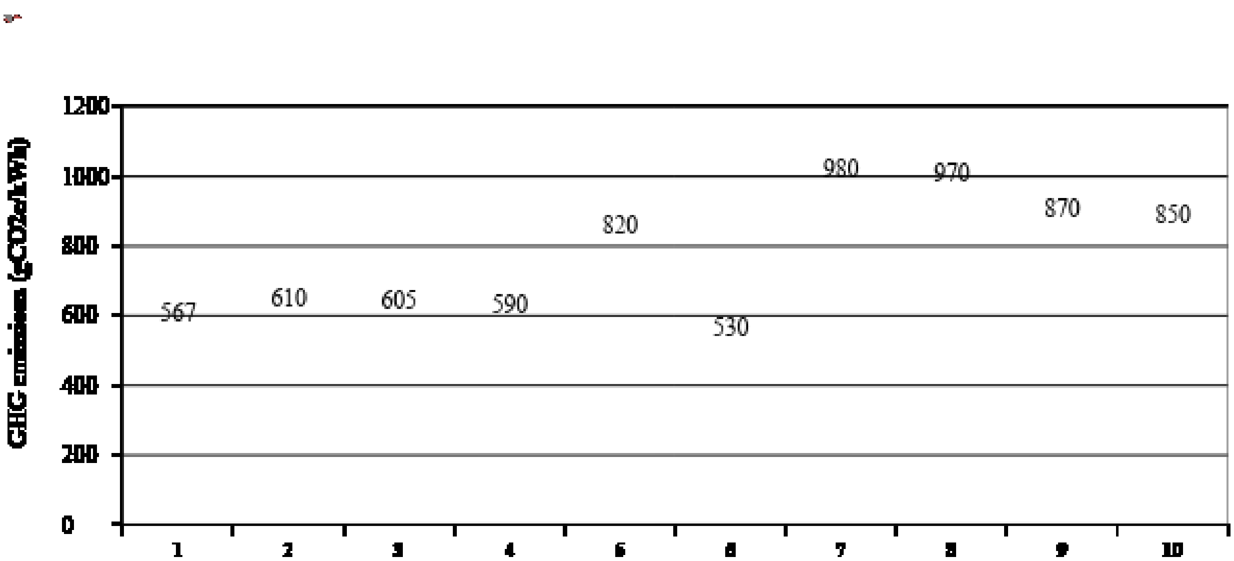

Figure 5: Comparison of well-to-wire emissions of different electricity generation sources in Canada and China

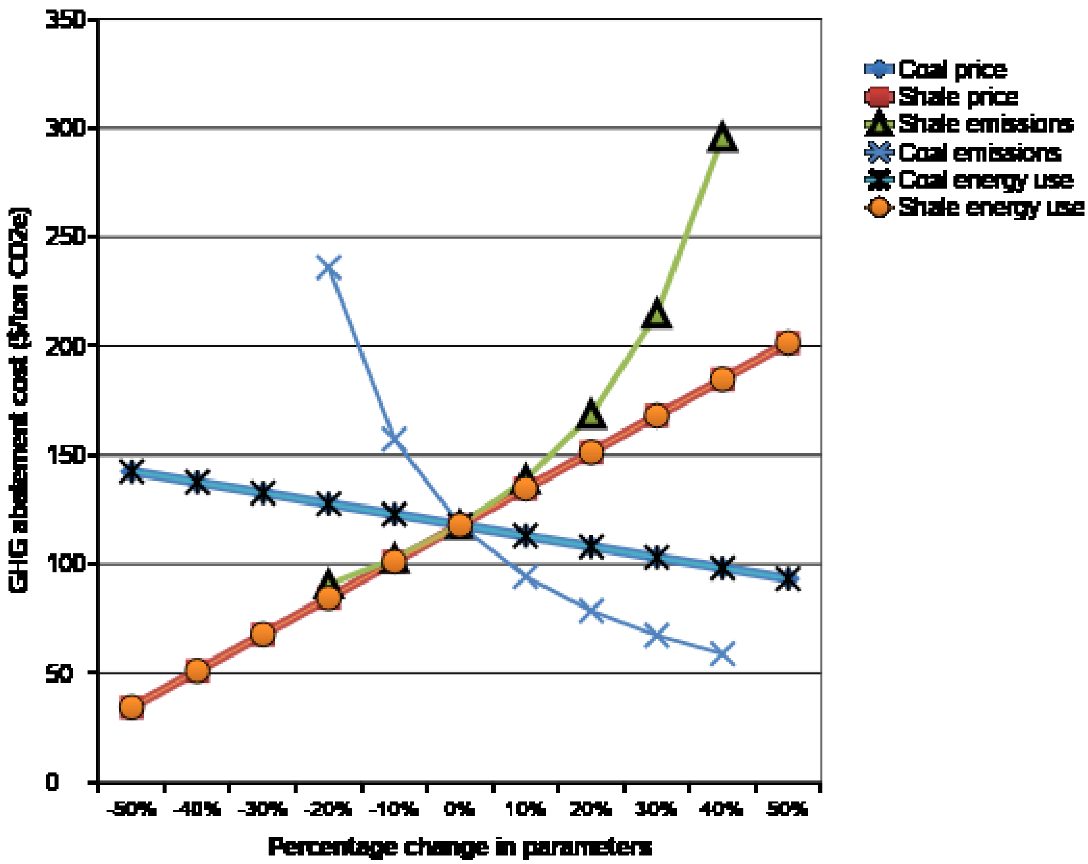

Figure 6: Sensitivity analysis for GHG abatement cost

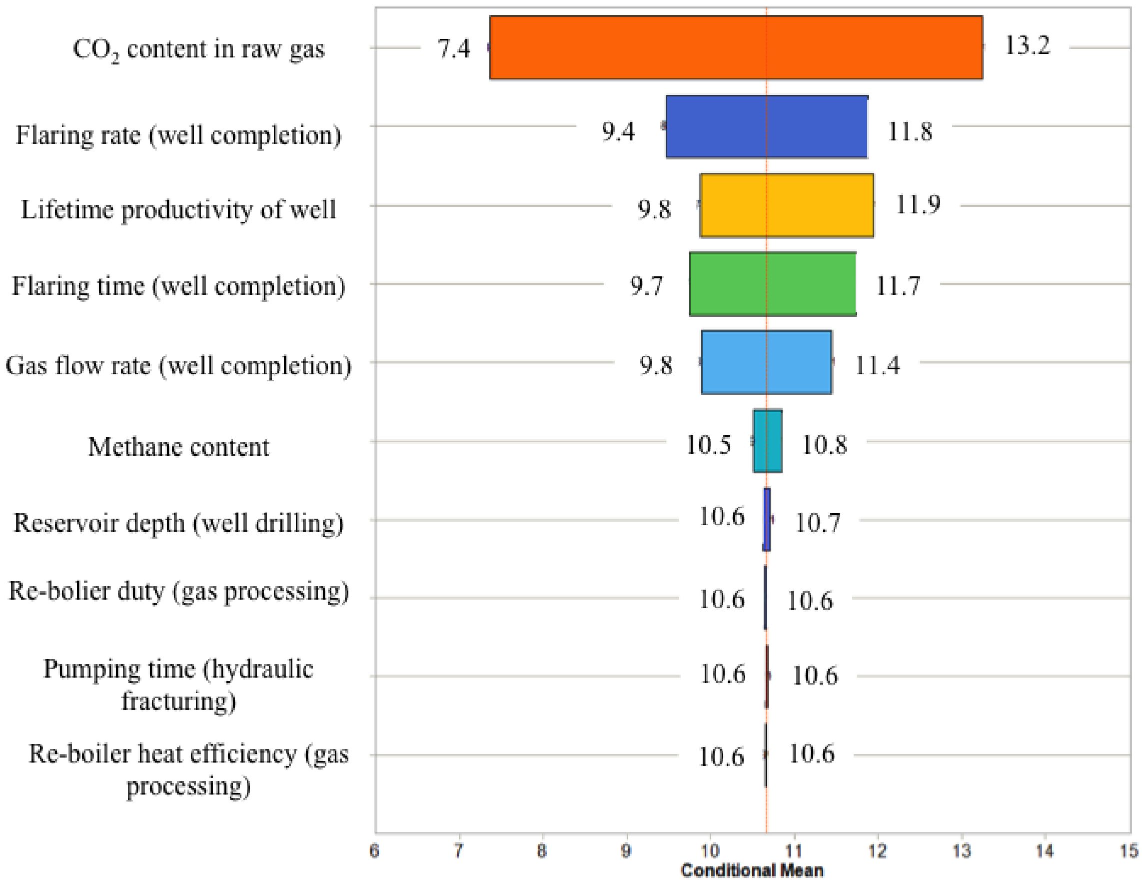

Figure 7: Impact of parameters on GHG emissions from recovery and processing of shale gas (Horn River)

Table 1: Various parameters of Canadian shale gas reservoirs [30]

Parameters[1]	Montney	Horn River	Liard	Cordova	Units
Depth range	2300 (1400-3200)	2500 (1900-3100)	4350 (3900-4800)	1900 (1500-2300)	m
Gross thickness	165 (30-300)	210 (140-280)	150 (100-200)	95 (70-120)	m
Average H_2S	0.08(0-0.15)	0.035 (0-0.07)	0.002	0.00004	%
Average CO_2	2.5 (0-5)	11 (10-12)	7	8	%
Water saturation	25	25	18 (15-20)	25	%
Drilling data					
Wells per pad	11 (Up to 20)	8 (Up to 16)	1	5 (1-9)	
Average horizontal length	1652 (1545-1760)	2350.00	1200.00	1765.00	
Fracking fluid	slickwater, gel/foam (<2000)	slickwater	slickwater	slickwater	
Average water	9000	64000	23000	43000	m^3/well
Average sand	1300	3700	1500	4100	t/well

Completion data					
Average fluid amount pumped per stage	870 (550-1190)	3456	2043.00	3050	m^3
Average number of stages	13 (10-16)	23 (15-31)	10 (7-13)	15 (8-12)	
Pump rate	8.5 (2-15)	12 (8-16)	13 (10-16)	13 (10-16)	m^3/min
Production data					
Initial production rate of gas well	106	184	533	71	10^3m^3/day
Number of wells drilled	1897	374	6	36	
Total cumulative production	6.51E+10	1.70E+10	2.55E+08	5.66E+08	m^3
Lifetime productivity	1.36E+08	1.81E+08	2.27E+08	1.13E+08	m^3/well

Table 2: Emissions from natural gas production (kilo tons CO_2 equivalent) [39]

Source	Combustion	Flaring	Venting
Wells	65	0	487
Gathering systems	7225	153	3171
Batteries	2401	102	6670

Table 3: Proposed gas transmission pipelines from the WCSB to BC's coast

	Pacific Trail Pipeline [41]	**Coastal GasLink Pipeline [42]**	**Prince Rupert Gas Transmission Project [43]**	
From	Summit Lake, B.C	Dawson Creek, B.C	Hudson's Hope, BC	
To (LNG facility)	Kitimat LNG	LNG Canada	Pacific Northwest	
Pipeline specifications				
Pipeline length (land)	463	650	780	km
Pipeline length (marine)			120	km
Diameter (land)	36	48	48	inch

Diameter (marine)	-	-	36	inch
Initial design capacity	1	1 to 5	2	bcf
Construction material	High quality steel			
Pipeline wall thickness	18 to 30			mm

Table 4: Parameters for a typical gas turbine compressor[1]

	Compressor	Unit
Net power output	32.2	MW
Load factor	90	%
Heat input	74.60	MW
Efficiency	38.6	%
Fuel consumption rate	171000	1000 m^3/d
Exhaust mass flow rate	89.9	kg/s
CO_2 concentration in exhaust gas	1-5	% volume
CO_{2e} emission rate	4.28	kg/sec

[1]Parameters are based on a GE LM2500+G4 compressor that is widely used in offshore oil and gas operations [45].

Table 5: Parameters for gas turbines[1]

Parameter	Value	Unit

Power output	99.3	MW
Heat rate	7875	kJ/kWh
Efficiency	45.7	%
Pressure ratio	40	
Exhaust flow	205.6	kg/sec
Turbine speed	3000-3600	rpm
Exhaust temperature	417	C
CO_{2e} emission rate:	10.28	kg/sec
Exhaust temperature	417	C

[1] Parameters are based on GE LMS100 gas turbine [46].

Table 6: Parameters for estimating GHG emissions from LNG shipping operations

Parameters	**Gas-based**	**HFO-based**	**Unit**
Installed power (main engine and auxiliary engine)[1]	42.7	42.7	MW
CO_2 emission factor[2]	446	577	g/kWh
Re-liquefaction plant specific power requirement[1]	-	2719	kW/kg/sec
Main engine specific fuel consumption[1]	171	169	g/kWh
Auxiliary engine specific fuel consumption[1]	181	181	g/kWh
Sailing time[3] (China)	264	264	hours
Number of vessel visits per year[4]	150	150	

[1]Power rating, emission factors, and specific fuel consumption data are based marine engine manufacturer MAN 6S70ME-C (HFO burning) and 6S70ME-GI (gas burning) engines. Project guides are available at [49] and [50].

[2]Liquefaction plant specific power requirement data from [51].

[3]Sailing time estimated using a sailing distance of 5116 nautical miles [52] and average LNG carrier speed of 20 knots [53].

[4]Average number of LNG shipments expected to arrive at Kitimat LNG facility at Port of Kitimat [54].

Table 7: Energy use and GHG emissions from shale-gas fired power plants

	Simple cycle (SC)	Combined cycle (CC)	Unit	Reference
Energy use	10.9	7.05	MJ/kWh	[6, 55]
GHG emissions	606	392	gCO_{2e} /kWh	[6, 55]
Efficiency	33	51	%	[56]

Table 8: Percentage share of each operation with respect to total WTP GHG emissions

	Montney	Horn River	Liard	Cordova
Drilling pad construction	5.2	2.4	0.2	1.7
Well drilling	1.2	0.9	1.2	0.8
Hydraulic fracturing	2.8	5.6	2.0	5.5

Gas production	31.6	18.1	19.2	22.6
Well completion	17.0	12.7	31.1	9.7
Re-boiler (gas sweetening)	0.5	0.3	0.3	0.3
Venting (acid gases)	17.9	45.3	30.5	41.0
Re-boiler (gas dehydration)	0.1	0.1	0.1	0.1
Venting (methane)	0.0	0.0	0.0	0.0
Pipeline and compressor	23.7	14.6	15.5	18.2

Table 9: Port-to-wire (PTW) GHG emissions

Unit operation		GHG emissions (gCO_2/kWh)	Source/Comments
Liquefaction plant		63	Calculated
LNG shipping	Gas-based	29.38	Calculated
	HFO-based	38.02	Calculated
Re-gasification		20	[58]
Natural gas power plant		392 (CC), 606 (SC)	Table 7
Electricity transmission		3.4	[58]

Table 10: Parameters for calculating GHG abatement cost

	Chinese Coal	**Imported Shale Gas**
Price	$ 48.1/ton [6]	$ 9.28 /GJ [60]
Primary energy use in power plant (MJ/kWh)	9.63 [6]	7.05 [6]
Life cycle GHG emissions (gCO2e/kWh)	980 [6]	588.5