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A well-to-wire life cycle assessment of Canadian shale gas for electricity generation in China

Ratan Raj [a], Samane Ghandehariun [a], Amit Kumar [a, *], Ma Linwei [b]

[a] 10-263 Donadeo Innovation Centre for Engineering, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta T6G 1H9, Canada
[b] State Key Laboratory of Power Systems, Department of Thermal Engineering, Tsinghua-BP Clean Energy Center, Tsinghua University, Beijing 100084, China

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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, 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 to 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.

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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

* Corresponding author.
E-mail address: Amit.Kumar@ualberta.ca (A. Kumar).

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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

(hydraulic fracturing), which includes land use emissions, induced seismicity, huge water consumption, and contamination from flowback 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

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