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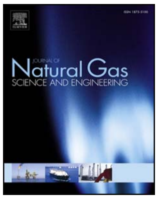

# Techno-economic and life cycle assessments of the natural gas supply chain from production sites in Canada to north and southwest Europe

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## ABSTRACT

In recent years, the need for energy security strategies through liquefied natural gas (LNG) import has occupied an unprecedented spot in the European Union's foreign policy agenda. The availability of abundant natural gas resources in Western Canada, making this region a potential supplier, has, therefore, received significant attention. In order to ensure a competitive spot in the global natural gas market, it is important for Canada to supply its natural gas both at a competitive price and with lower emissions. In this study, a comparative assessment of the delivered costs and life cycle greenhouse gas (GHG) emissions of the natural gas supply chain from production sites in Canada to north and southwest Europe is conducted through the development of techno-economic and life cycle analyses models. Two possible supply chain routes to Europe were explored, one from the west coast and the other via the east coast of Canada, and included recovery, processing, transmission, liquefaction, shipping, and re-gasification. Two sources of Canadian natural gas reserves, Montney and Horn River, are investigated. The results show that the delivered cost ($/GJ) of Canadian LNG (including recovery, processing, transmission, liquefaction, and shipping cost) to Europe is 8.9–12.9, depending on the resources and pathway. The total well-to-port (WTP) GHG emissions (including emissions from recovery, processing, transportation, liquefaction, shipping and re-gasification at the destination port) from the Canadian production sites to Europe is 22.9–42.1 g-$CO_2$eq/MJ, depending on the resources and pathway followed. The costs and GHG emissions values reported in the literature for the delivery of natural gas from the major exporting countries were lower than those for the Canadian LNG supply chain. Finding other sources of natural gas in Eastern Canada might provide a cheaper and less GHG-intensive alternative to the Canadian LNG supply chain.

## 1. Introduction

Over the past decade, the imperative of emerging strategies on energy security through liquefied natural gas (LNG) import has occupied an unprecedented spot in the foreign policy agenda of European Union. However, the growth of gas imports and the natural gas market diversification in Europe will be influenced by global natural gas market trends. In recent years, the demand structure of natural gas in Europe shows variability; the natural gas consumption reached approximately 400 billion cubic meters (bcm) in 2015 (Kocak and Micco, 2016), with the net import of liquefied natural gas (LNG) increasing by 15.8%–37.6 million tonnes after five years of continuous decline between 2009 and 2014 (King and Spalding, 2016). This increase can be due to the convergence of Asian LNG spot prices and European LNG prices in 2015 (Italian Institute for International Political Studies, 2015) and the decline of domestic natural gas production in Europe. According to the European Commission, the European Union (EU) imported a significant portion of natural gas from Russia, approximately 40% of its imports in 2015 (Kocak and Micco, 2016). This strong dependency dominated by a single supplier can increase the risk of a reliable supply of natural gas, as evidenced by the geopolitical tension between the Ukrainian government and Gazprom (Polishchuk, 2016). Norway is considered a secure supply source of gas to Europe; almost 37% of the EU's import in 2015 were from that country (Kocak and Micco, 2016); however the natural gas supply from reserves like Sleipner and Gullfaks South are now declining due to depletion (Kumar et al., 2011). Söderbergh et al. (2009) showed the limited potential for increased export of Norwegian natural gas to Europe in future with gas production projected to decline by 2030. The North Africa region, particularly Algeria, is facing many challenges in unlocking tapped gas resources due to military and political problems and lack of investment (Chi-Chyong and Kazmin, 2016). Therefore, exploring potential suppliers of LNG, particularly in Canada, through the development of new infrastructures has resulted in unprecedented interest from the European government and industrial leaders.

Natural gas is a vital source of energy in Europe and is expected to

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**Acronyms**

| | |
|---|---|
| bcfd | Billion cubic feet per day |
| EU | European Union |
| GHG | Greenhouse gas |
| LCA | Life cycle assessment |
| LNG | Liquefied natural gas |
| mmscfd | Million metric standard cubic feet per day |
| MTPA | Millions tonnes per annum |
| tcf | Trillion cubic feet |
| WCSB | Western Canada Sedimentary Basin |
| WTP | Well-to-port |
| WTW | Well-to-wire |

remain as clean and key source of energy supply in future. The Netherlands, Spain, German, Italy, the United Kingdom, and France account for three-quarters of European gas consumption, imported either by pipeline or LNG carriers to import terminals (Jones et al., 2015). The re-gasification capacity of Europe's 23 major LNG import terminals was 201 bcm/yr in 2014, which could supply 41% of Europe's natural gas demand if fully used (Council of European Energy Regulators, 2016). However, the use rate of LNG import terminals in 2014 was only 19% (Council of European Energy Regulators, 2016). This provides a huge opportunity for Canadian LNG, which can supply 81% of the total capacity of the regasification facility, equivalent to 163 bcm. Apart from this, the European Union is highly interested in considering LNG an important source of their energy security, as evidenced by the adoption of the Energy Security Strategy in 2014 and Energy Union projects with high priority given to identifying and building new supply routes (Kocak and Micco, 2016), as well as the 20 large-scale LNG import terminals currently planned, mostly in Europe (King and Spalding, 2016). All of these create a new opportunity for Canada to explore further the natural gas supply chain market. In order to understand the full potential of Canadian LNG in European markets, it is necessary to evaluate the delivered costs and life cycle GHG emissions risks of the Canadian natural gas supply chain to Western Europe.

According to National Energy Board (National Energy Board 2016), the Western Canada Sedimentary Basin (WCSB)[1] has tremendous natural gas potential with 855 trillion cubic feet (tcf) of remaining gas reserves in 2014, from which 14.7 billion cubic feet per day (bcf/d) were produced; production is projected to increase to 17.9 bcf/d by 2040. With advanced technology in fracturing and well drilling, natural gas production continuously exceeds domestic consumption and is expected to continue to do so in future. Canada's surplus natural gas production needs to find potential customers through the best possible route to Western Europe, in order to trade competitively. For European countries, Canada's stable political system is attractive, especially when the expected reliable supply of natural gas from Russia, Algeria, etc., is at risk because of geopolitical tension. The long-term natural gas export market can build consistent energy security that provides both a reliable supply of natural gas to Europe and a new market opportunity for Canada. Meanwhile, the U.S., Canada's only natural gas export market, has increased the supply risk and left Canada with no option but to explore a potential alternative gas market. The rapid development of the shale gas boom in the U.S. has lowered demand for Canadian natural gas (Medlock, 2012). Thus, exploring the potential market of Canadian LNG to Europe deserves significant research attention. In this paper, the delivered costs and environmental impacts of the Canadian LNG supply chain through all the possible routes to European countries are evaluated.

There are limited studies in the published literature evaluating the techno-economic and life cycle impact of the Canadian LNG supply chain to Western Europe. Previous research on techno-economic analyses of LNG supply chains is quite widespread and mostly focused on individual assessments of the processes involved in the supply chain such as gas processing (dehydration, gas sweetening, and natural gas liquid recovery in an LNG plant), shipping and gas production. Some efforts have been made to conduct an economic analysis of natural gas processing with different technologies (Netusil and Ditl, 2011; Peters et al., 2011), and other authors (Baron et al., 2015; Hureau and Jordan, 2015) investigated the shipping cost of LNG, albeit with limited approaches of fundamental engineering principles. Javanmardi et al. (2006) studied the cost of liquefying natural gas and transporting it from the South-Pars gas field in Iran to the potential natural gas market worldwide. Other research studies are focused on a life cycle analysis of extraction and processing shale gas using data from the shale gas reserves in the U.S. (Howarth et al., 2011; Hultman et al., 2011; Jiang et al., 2011; Stephenson et al., 2011). The studies carried out by Raj et al. (2016a, b and c) focused on the delivery costs and well-to-wire (WTW) life cycle GHG emissions of Canadian LNG to China. Although there is great interest from Canada and Europe in exploring the potential natural gas market, the minimum supply chain costs and the life cycle GHG emissions of the Canadian LNG supply chain in the delivery of LNG to Western Europe are still unknown. . Therefore, as an extension of Raj et al. (2016a, b and c), this study aims to address such gaps through the development of TEA and LCA models. The overall objective of this study is to develop the data intensive techno-economic models to evaluate the delivered costs of Canadian LNG to north and southwest Europe. In addition, the environmental impact associated with the Canadian LNG supply chain to north and southwest Europe is addressed. The goals of this study can be summarized as follows:

- To conduct a comparative assessment of the delivery costs of Canadian LNG supply chain routes (one from west coast and the other via the east coast of Canada) to north and southwest Europe through the development of data-intensive techno-economic models.
- To quantify the well-to-port (WTP) and well-to-wire (WTW) greenhouse gas emissions of the Canadian shale gas (Montney/Horn River) supply chain to Europe.
- To compare the delivery costs and life cycle GHG emissions of the Canadian LNG supply chain with the major suppliers of natural gas to Europe.

## 2. Method

Fig. 1 provides an overview of the two natural gas supply chain routes from Canada to Europe. Canadian shale gas is first recovered from Horn River or Montney and processed in a surface processing facility, then transported by pipeline to liquefaction facilities in Canaport (east coast) or Kitimat (west coast), where the natural gas is liquefied and loaded into an LNG tanker to be shipped to a destination port in Europe (France, Greece, Italy, Spain, Turkey, the Netherlands, or the UK). The LNG is re-gasified before it is delivered to the end user (natural gas-fired power plant).

For the base case, Montney reserve is considered, since the shale gas reserve contains less $CO_2$ content in the gas. Supply chain costs are defined as the costs of delivering natural gas to the respective country and include production, pipeline transportation of natural gas, liquefaction, and shipping costs. Re-gasification and natural gas-fired power generation are thus excluded from the supply chain costs but included in the life cycle GHG emissions estimation.

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[1] WCSB includes B.C., Alberta, Saskatchewan and Manitoba.

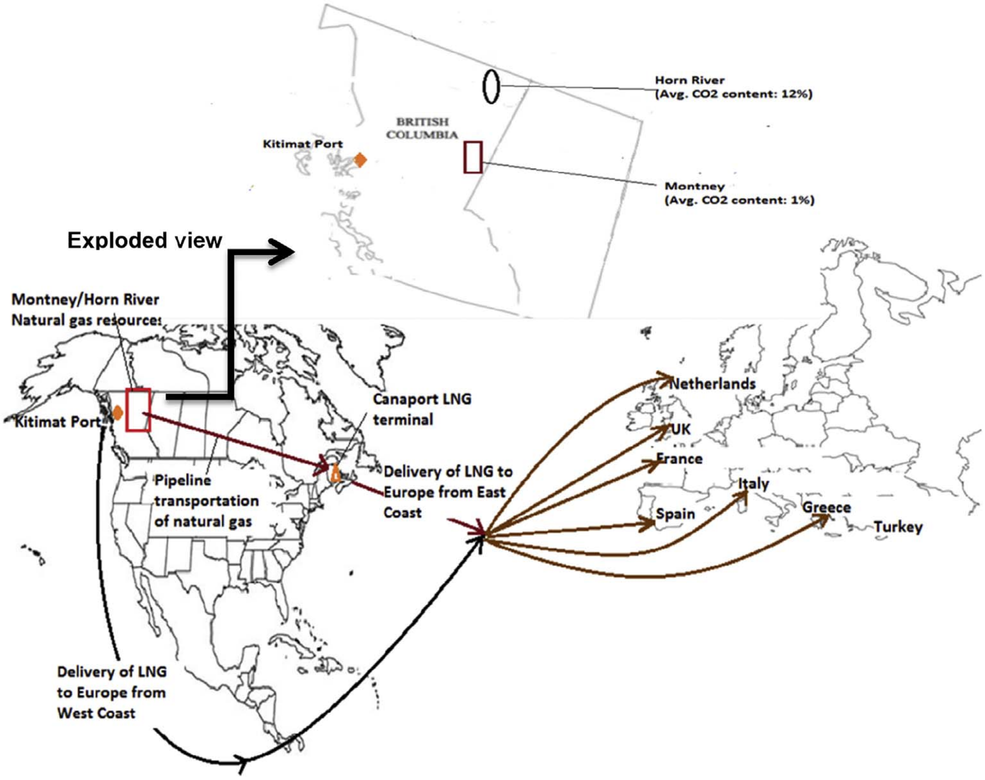

**Fig. 1.** Map overview of the natural gas supply chain route from Canada to Europe.

### 2.1. Goal and scope definition

The main purpose of the TEA and the LCA models is to evaluate the delivery costs and WTP and WTW life cycle GHG emissions of the Canadian LNG supply chain to north and southwest Europe from two supply chain routes, Canada's east and the west coasts. The costs and GHG emissions results from the two pathways are compared with the aim of identifying their relative environmental sustainability and economic viability. This work provides a comprehensive baseline data to stakeholders involved in the LNG supply chain to understand the full potential of Canadian LNG in European markets to help them make informed decisions.

This study evaluates the GHG emissions released during the operation phases. Fugitive, flaring and venting GHG emissions from each stage of the operations are included. Other life cycle impact categories like land and water use, human health, and infrastructure construction are beyond the scope of this work. The costs associated with liquefaction include investment and operational costs. The pipeline transportation costs cover the charge based on tariff system and the shipping costs incorporate fuel cost, hiring cost, and port and passage fees.

#### 2.1.1. System boundary

Fig. 2 shows the main systems considered for the TEA and LCA approaches. The LCA includes the full life cycle starting from recovery, gas processing, gas transmission through pipeline, liquefaction, re-gasification, and/or final use. Power generation and re-gasification are beyond the scope of the TEA modelling. For the base case, a pipeline transportation distance of 650 km is assumed to deliver the produced natural gas from the reserve to the Kitimat port and approximately 5150 km is assumed to transport natural gas to Canaport in the east coast of Canada. The pipeline transportation of natural gas from re-gasification port to natural gas power plant is not included here because this study is project-specific and relevant to the destination country where natural gas is delivered.

All the input and output requirements in each pathway are matched with the functional unit, which is 1 MJ electricity generation from LNG at the natural gas-fired power plant. For the TEA, all the life cycle costs in US$ from the production, pipeline transportation, liquefaction, and shipping of natural gas per 1 MJ are estimated.

The main unit operations considered in each stage of the LNG life cycle are discussed as follows.

**Recovery**: The operations both at Montney Play and Horn River Basin typically include horizontal and vertical drilling, well pad construction, hydraulic fracturing, well completion, and production. Diesel is the main energy input for these operations. Drilling and hydraulic fracturing equipment are the major consumers.

**Gas processing**: The raw gas impurities, mainly in the form of hydrogen sulfide, carbon dioxide, water, and other hydrocarbon fluids, are removed in a gas sweetening and a glycol dehydrator unit. The main kinds of equipment included in the gas processing stage are heat exchangers, absorber tower, stripper or regeneration column, pressure vessels, condensers and reboiler (Peters et al., 2011). The amount natural gas consumed in the reboiler heaters, pumps (in the dehydrator unit), booster, reflux and circulation pumps, amine reboiler, and aerial cooler (in the gas sweetening unit) is considered. Consistent with the work from Raj et al. (2016c), four gas sweetening units with a flow rate of 359 million metric standard cubic feet per day (mmscfd) per unit and five parallel units for each LNG train of 5 million tonnes per annum (MTPA) with four towers in each dehydration unit were considered.

**Pipeline transportation**: The transportation cost of natural gas by pipeline is based on tariff systems. For the pipeline transportation of natural gas to the west coast, a pipeline of distance 650 km with an expected pipeline lifetime of 25 years and a capacity of 5 billion cubic feet per day (bcfd) is taken into account for the default case (TransCanada, 2014); and an approximate distance of 5150 km is assumed for the transportation of natural gas to the east coast. Natural gas is the main fuel used in the compressor station for the pipeline transportation of natural gas.

**Liquefaction**: In this process unit, natural gas is liquefied by cooling it to a cryogenic temperature of about −155 °C in a pre-cooled

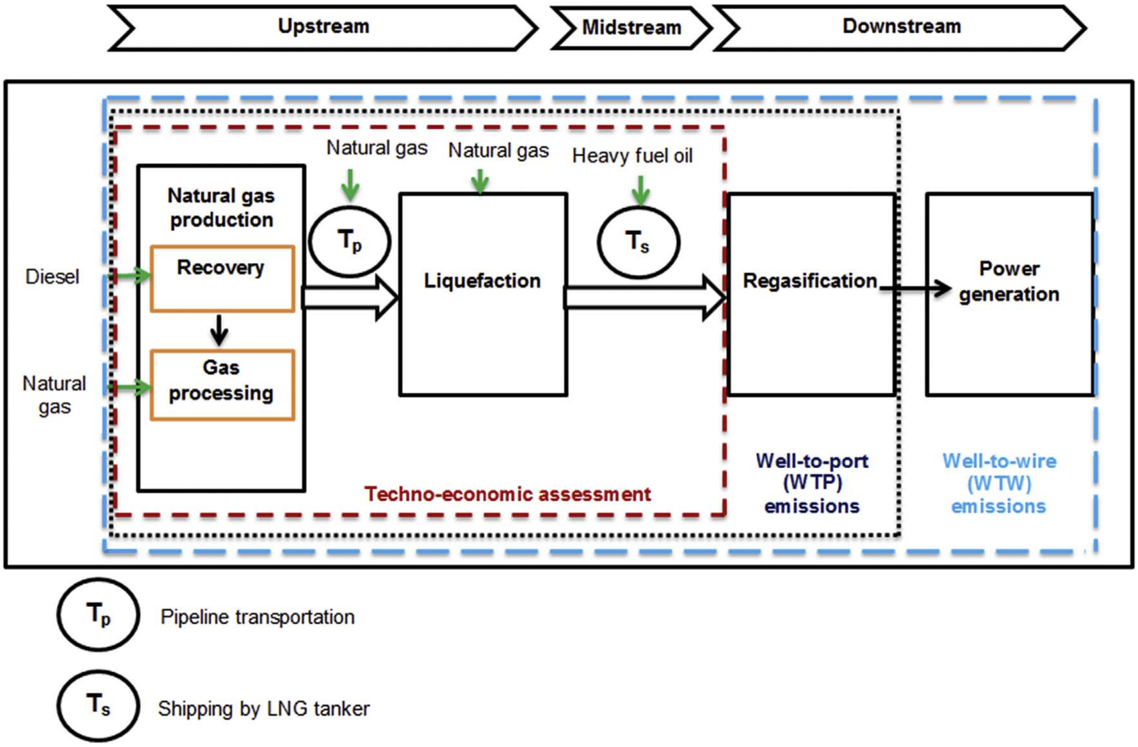

**Fig. 2.** Scope of the natural gas supply chain from Canada to Europe.

refrigerant cycle. The liquefaction cost and the GHG emissions are directly affected by the liquefaction technology. There are various technologies available for this operation, but this study considered the most widely used propane pre-cooled mixed refrigeration (APCI C3MR) process. The cryogenic heat exchangers, compressors, and gas turbines are the major equipment in the liquefaction unit. Natural gas-driven turbines and acid gas incinerators are the major energy consumer units. Two LNG plant trains, each with a capacity of 5 million tonnes per annum, were considered in this study (Raj et al., 2016c).

**Shipping:** The liquefied gas is then loaded in an LNG tanker and shipped to the destination port. An LNG carrier (Q-Flex) of 210,000 $m^3$ capacity is considered (Sinha and Nik, 2012). The GHG emissions and shipping costs vary with propulsion type and fuel. A pure HFO-burning propulsion system, which uses heavy fuel oil (HFO) as the main fuel to power the marine engines, is assumed. It is also assumed that the boil-off gas during the voyage is re-liquefied. Average nautical distances of 3400 nautical miles (6296.8 km) and 9300 nautical miles (17223.6 km) are approximated for east coast and west coast to Europe, respectively. The calculation is based on averaging the distances from the Canadian ports to all the major LNG import terminals in Europe (see SI, Table S1). The data are taken from the Portworld Distance Calculator (S&P Global Platts, 2016).

**Re-gasification:** After LNG reaches the destination port in Europe, it is re-gasified. In this operation, LNG is converted to natural gas by providing vaporizing heat through fuel combustion. The volume of fuel for combustion is used to estimate the GHG emissions.

**Power generation:** To evaluate WTW life cycle GHG emissions, we assumed that natural gas is used in natural gas-fired power generation plant. The efficiency of natural gas-fired power generation varies, depending on the type of power plant (open cycle gas turbine, combined cycle gas turbine, steam turbine). This work considers the use of combined cycle gas turbine because of its higher efficiency.

## 2.2. Life cycle inventory analysis

The life cycle inventory data for natural gas production, pipeline transportation, liquefaction, shipping, re-gasification, and power generation are shown in Table 1. A wide range of data has been presented because of the sparsely available data, particularly for Canada, due to the infancy of Canadian shale gas operations, like drilling and completion, gas composition, and flow back water treatment, as well as the amount of gas vented during the processing phase and the lifetime productivity of the reserves. Depending on the natural gas resources, and transportation distance (pipeline and shipping), the data are likely to vary from one pathway to other.

## 2.3. Life cycle impact assessment

### 2.3.1. Techno-economic assessment

The TEA of the liquefaction facility is based on discounted cash flow analysis (DCFA). The major cost evaluation is in terms of investment and operations cost (Raj et al., 2016c). The natural gas production cost has two components, the well head price of gas and pipeline transportation costs. The well head costs of the Montney and Horn River resources are taken from an earlier study by Macquarie Private Wealth (2012). The pipeline transportation cost was estimated based on the tariff system. The shipping cost followed the time charter method in which the charter pays the fuel cost, hiring cost, and port and passage fee. All the costs estimated in this study are for the year 2015.

### 2.3.2. Life cycle GHG emissions

The GHG emissions presented in this study are based on the Intergovernmental Panel on Climate Change (IPCC) 100-year global warming potential factors (Intergovernmental Panel on Climate Change, 2013). Carbon dioxide, methane, and nitrous oxide are the three major GHG emissions accounted. The ISO framework and guidelines for LCA are followed in evaluating the life cycle GHG emissions (ISO, 2006).

**Table 1**
LCI data inventory for natural gas production, pipeline transportation, liquefaction, shipping, re-gasification, and power generation.

| | GHG emissions (g-CO$_2$eq/MJ) | | | Costs (US$/GJ) | | |
|---|---|---|---|---|---|---|
| | Range | Default | Comments/Source | Range | Default | Comments/Source |
| **Natural gas production** | | | | | | |
| Montney | 5.86–11.45 | 5.86 | Include the combined emissions from recovery and gas processing taken from Raj et al. (2016b) | 2.63–3.74 | 2.63[a] | (Macquarie Private Wealth 2012) |
| Horn River | | 11.45 | | | 3.74[a] | |
| **Pipeline transportation** | | | | | | |
| West coast[b] | 1.82–1.96 | 1.82[d] | Calculated using combustion, fugitive and venting emissions | 0.84–1.00 | 0.84 | Based on tariff system (Macquarie Private Wealth 2012; TransCanada PipeLines Limited, 2017) |
| East coast[c] | 14.46–14.60 | 14.46[d] | | 3.66–3.82 | 3.66 | |
| **Liquefaction** | | | | | | |
| Propane pre-cooled mixed refrigeration (APCI C3MR) | | 8.35 | (Raj et al., 2016b) | 4.33–4.36 | 4.33 | (Raj et al., 2016c) |
| **Shipping** | | | | | | |
| From east coast[e] | 2.04–4.40 | 3.22 | Calculated for pure HFO-burning propulsion system | 0.55–0.87 | 0.67 | Calculated for pure HFO-burning propulsion system and is based on time charter method[g]. |
| From west coast[f] | 6.58–10.01 | 9.01 | | 1.61–1.88 | 1.71 | |
| **Re-gasification** | | 2.63 | (Skone et al., 2014) | | | |
| **Power generation** | | | | | | |
| Natural gas-fired power generation | | 51.12[h] | (Taglia and Rossi, 2009) | | | |

[a] This costs represent the break-even well head costs.
[b] The pipeline transportation distance to the Kitimat port (west coast) is assumed 650 km approximately.
[c] The pipeline transportation distance to the Canaport (east coast) is assumed an approximate distance of 5150 km.
[d] These values include fugitive and venting emissions calculated based on pipeline distance and compressor and meter station from Greenhouse gas emission estimation guidelines for natural gas transmission and storage (Interstate Natural Gas Association of America, 2005).
[e] Shipping distance of approximate 3400 nautical miles (6296.8 km) is considered.
[f] Approximate shipping distance of 9300 nautical miles (17223.6 km) is considered.
[g] The time charter is a method in which charterer leases the tanker for certain time period and pays fuel cost, hiring cost, and port and passage fee.
[h] The value represents the emission from combined cycle natural gas power plant.

## 3. Results and discussion

### 3.1. Supply chain cost of Canadian LNG to Europe

Fig. 3 shows the supply chain costs in the delivery of Canadian LNG to major LNG import terminals in north and southwest Europe through two supply chain routes. For default case, the delivery of Canadian LNG through pathway 1 (via east coast) supply chain costs are US$ 10.94–12.93, while pathway 2 (via west coast) costs are US$ 8.91–11.33, depending upon the destination country. Pathway 1 clearly has higher supply chain costs. This is mainly because of the pipeline transportation costs in the delivery of natural gas to the Canaport terminal in pathway 1 (east coast), which are 30–32% of the total supply chain costs, depending on the natural gas source. The wide range of values for the delivery of Canadian LNG is due to the differences in resources (Montney/Horn River), pipeline transportation, and shipping costs. Fig. 4 shows the detailed breakdown of the delivered costs of natural gas from two supply chain routes to European countries.

The supply chain costs were also compared in the delivery of Canadian LNG to Europe with the estimated border prices of natural gas from the main exporting countries (Norway, Russia, and Algeria). The estimated border prices of natural gas are for the first quarter of 2015 and taken from the report by the European Commission (European Commission, 2015). The prices show wide variation and are very

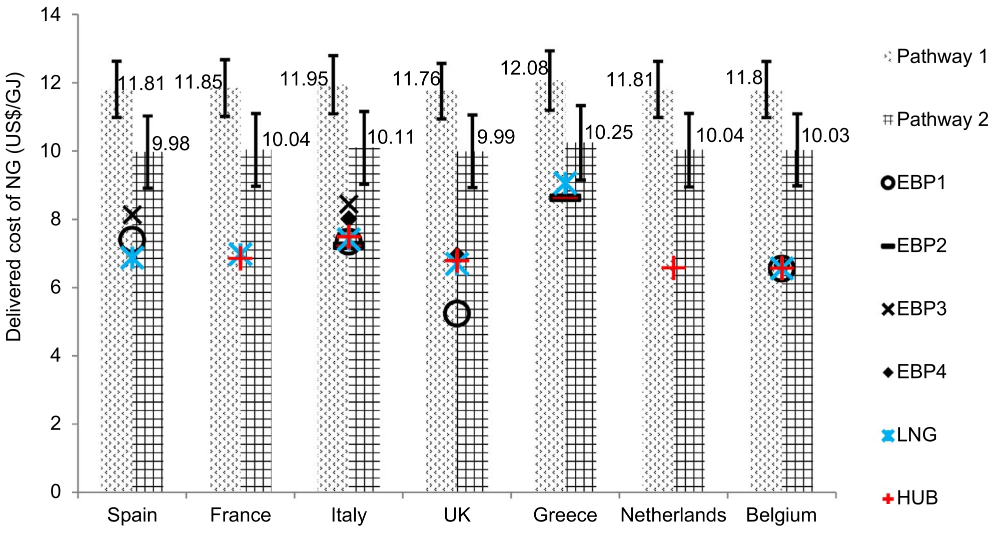

**Fig. 3.** Comparison of the delivered costs of LNG. Pathway 1 is the delivered costs of Canadian LNG through the east coast route. Pathway 2 is the delivered costs of Canadian LNG through the west coast route. EBP1 is the estimated border price for gas supply from Norway, January–March 2015 (European Commission, 2015). EBP3 is the border price for gas from Algeria, January–March 2015 (European Commission, 2015). LNG prices from Belgium, Spain, France, and the UK are the landed prices for January–March 2015 (European Commission, 2015). LNG prices for Greece and Italy are estimated based on customer data reported to ESTAT COMEXT for January–March 2015 (European Commission, 2015). EBP2 is the border price for gas from Russia, January–March 2015 (European Commission, 2015). EBP4 is the estimated border price of gas from the Netherlands, January–March 2015 (European Commission, 2015). HUB is a trading location (virtual or physical) within the grid where volumes of gas are exchanged, and it represents the gas price based on market value (Petrovich, 2013).

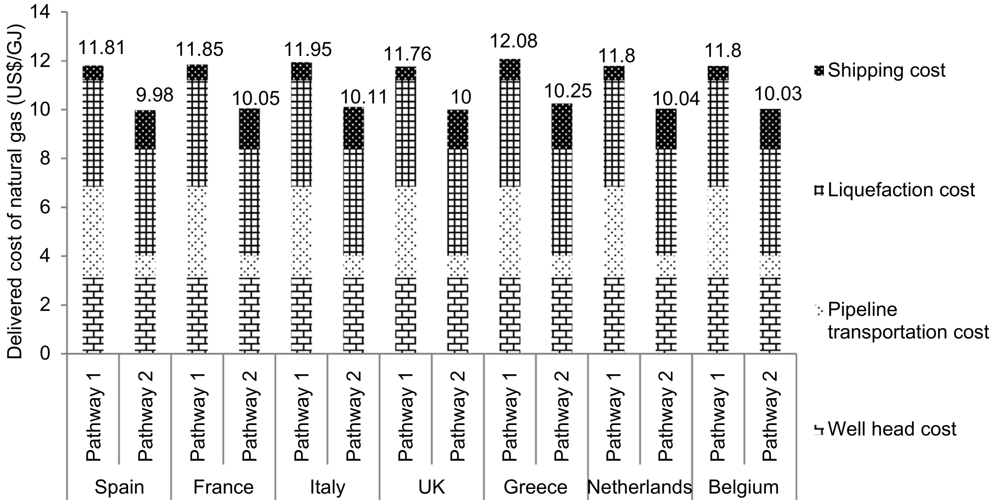

**Fig. 4.** Breakdown of delivered costs of natural gas from two supply chain routes to European countries.

susceptible to oil-indexed prices. The delivered costs of natural gas from these countries are lower than Canadian LNG. The main reason is the shorter distance for pipeline transportation and shipping of natural gas.

### 3.2. Total WTP life cycle GHG emissions

Figs. 5 and 6 show the total LC WTP GHG emissions in the delivery of Canadian LNG to different countries in Europe for two supply chain routes from the Montney and Horn River reserves, respectively. For the base case, the results show that the LC WTP GHG emissions for pathway 1 are 28.51–38.45 g-$CO_2$ eq/MJ and 22.94–30.15 g-$CO_2$eq/MJ for pathway 2. Pathway 1 is clearly more GHG intensive than pathway 2; this is because of the additional emissions in the transportation of natural gas to the east coast. The wide range of GHG emissions (including fugitive, flaring, and venting emissions) shows the uncertainty in each stage of operations. For the default case, the emissions from the transportation of natural gas by pipeline make up 35–43% of the total WTP GHG emissions, depending on the shale gas reserves, for pathway 1, which is 29–36% more than the transportation emissions from pathway 2. The LC WTP emissions from Horn River are higher than Montney's because of the high $CO_2$ content (approximately 12%) in Horn River's gas.

The LC WTP GHG emissions in the delivery of Canadian LNG to Europe were compared with the gas imported to Europe either by pipeline in gaseous form or as LNG by LNG tanker (particularly from Russia to Germany and the United Kingdom, Qatar and Libya to Italy, and Algeria and Trinidad to Spain as shown in Fig. 5). Uncertainties exist in the GHG emissions values obtained in the delivery of natural gas or LNG from these countries due to differences in study system boundaries, methodologies, and technologies considered in the each stage of operation. However, the average GHG emissions of natural gas imported to Europe reported in the study by Taglia and Rossi (2009) was 12.32 g-$CO_2$eq/MJ with emissions up to 18 g-$CO_2$eq/MJ (+45% variation) from Russia to Germany. The overall LC WTP GHG emissions from the Canadian LNG supply chain to Europe are comparatively higher because of the additional GHG emissions from both the long pipeline transportation of natural gas (for the east coast route) and the long shipping distance (for the west coast route).

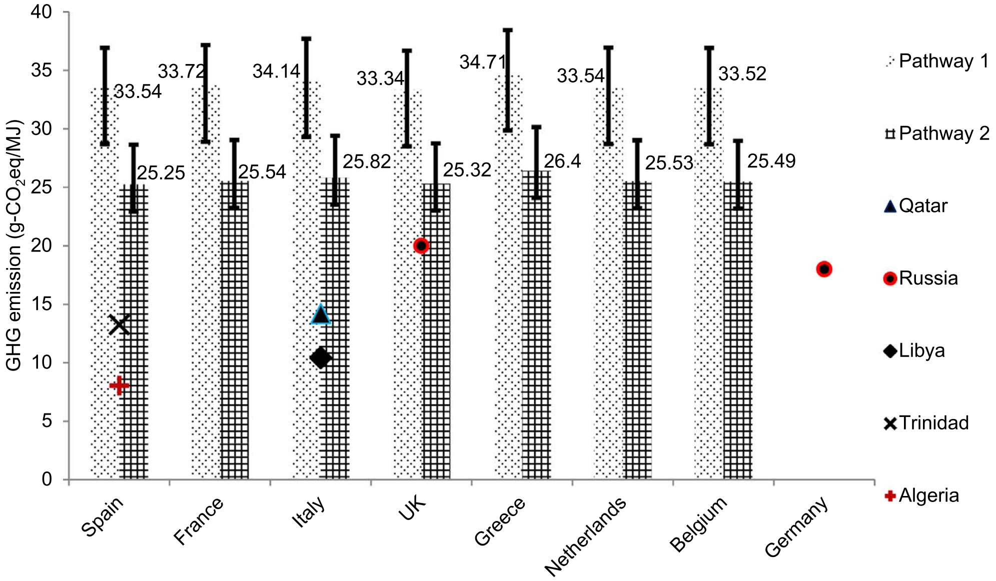

**Fig. 5.** LC WTP GHG emissions of two supply chain pathways of Canadian LNG from the Montney reserve. Note: Currently, there is no LNG import terminal in Germany, so only the GHG emission value in the delivery of natural gas by pipeline from Russia is reported.

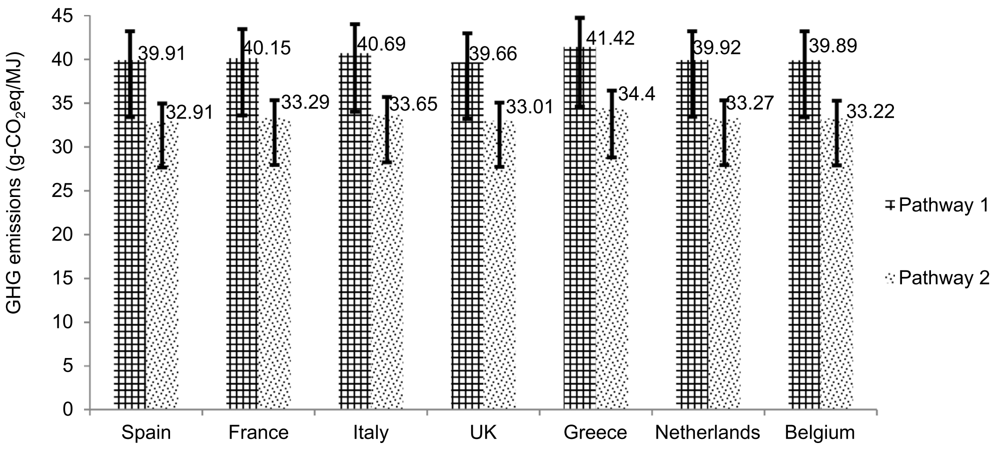

**Fig. 6.** LC WTP GHG emissions of two supply chain pathways of Canadian LNG from the Horn River reserve.

### 3.3. *Well-to-wire life cycle GHG emissions*

The well-to-wire life cycle GHG emissions include upstream (recovery, processing, pipeline transportation, and liquefaction), midstream (shipping), and downstream (re-gasification and power generation plant) emissions. Fig. 7 shows the well-to-wire life cycle GHG emissions (g-$CO_2$eq/MJ) in the delivery of Canadian LNG to north and southwest Europe. The results show that a wide range of uncertainties exist due to the sparsely available data, particularly for Canada, for operations like drilling and completion emissions and gas composition as well as the quantity of gas vented during the processing phase and the lifetime productivity of the reserves, due to the infancy of Canadian shale gas extraction. For the base case, pathway 1 shows a range from 80 to 90 g-$CO_2$eq/MJ and pathway 2 shows a range from 74 to 81 g-$CO_2$eq/MJ for Montney reserve. The natural gas-fired power generation plant is the operation that emits the most emissions; it accounts for 60–67% of the total life cycle emissions of the entire LNG supply chain, depending upon the pathway followed, as shown in Fig. 8. The other operations – recovery (5–6%), processing (2%), pipeline transportation (2–17%), liquefaction (10–11%), shipping (2–10%), and re-gasification (3%) – have considerably less impact on WTW life cycle emissions. The WTW GHG emissions from the Canadian LNG supply chain are comparatively higher than from the main exporter countries like Russia, Qatar, and Algeria, as shown in Fig. 7. An alternative natural gas resource in Eastern Canada might give a cheaper route for Canada.

## 4. Conclusion

Because Canadian shale gas development is still at an infancy stage, there is not much research from an economic or environment impact perspective in the delivery of Canadian LNG to Europe. To respond to this need and the importance of the abundant supply potential of Canadian shale gas being realized, this study evaluated and compared the delivered costs and environmental risks of two supply chain routes to north and southwest Europe. In this work, we developed data-intensive techno-economic and life cycle assessment models to evaluate the supply chain costs and total life cycle GHG emissions of Canadian LNG in the delivery to north and southwest Europe. It was estimated that the delivery of Canadian LNG through pathway 1 (via the east coast) was US$ 10.94–12.93, while pathway 2 (via the west coast) was US$ 8.91–11.33, depending upon the destination country, for the Montney Play as supply reserves. However, with improvements in recovery and liquefaction operations, supply chain costs can be reduced. The border prices of natural gas from the main exporters such as Norway, Russia, and Algeria to European countries show high variation and are very susceptible to oil-indexed prices. The reported border prices in the first quarter of 2015 from these countries are US $5.24–9.1/GJ; however, the Canadian shale gas costs to supply LNG are higher. Thus, other natural gas resources in Eastern Canada might provide a cheaper and more competitive alternative route for Canada.

The life cycle well-to-port (WTP) GHG emissions in the delivery of Canadian LNG to ports in north and southwest Europe are

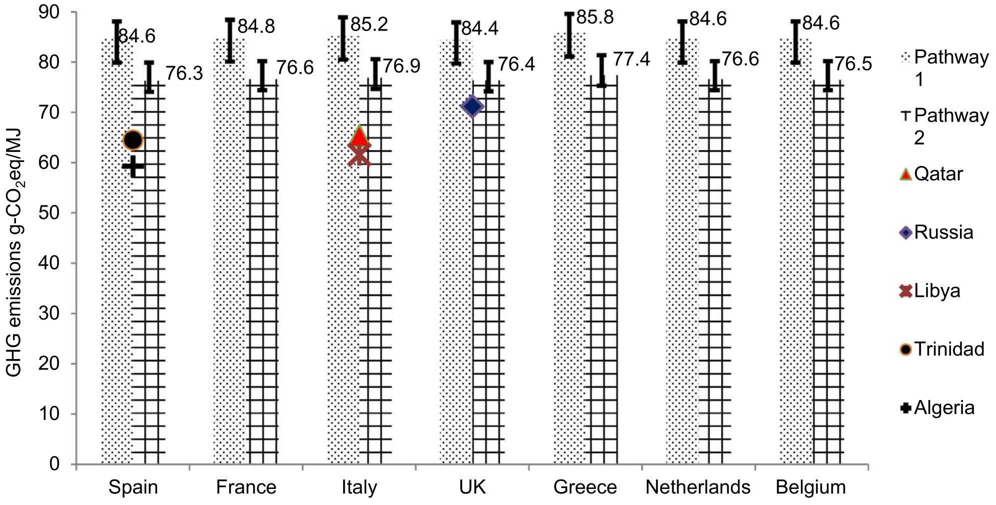

**Fig. 7.** LC WTW GHG emissions of two supply chain pathways of Canadian LNG from the Montney reserve.

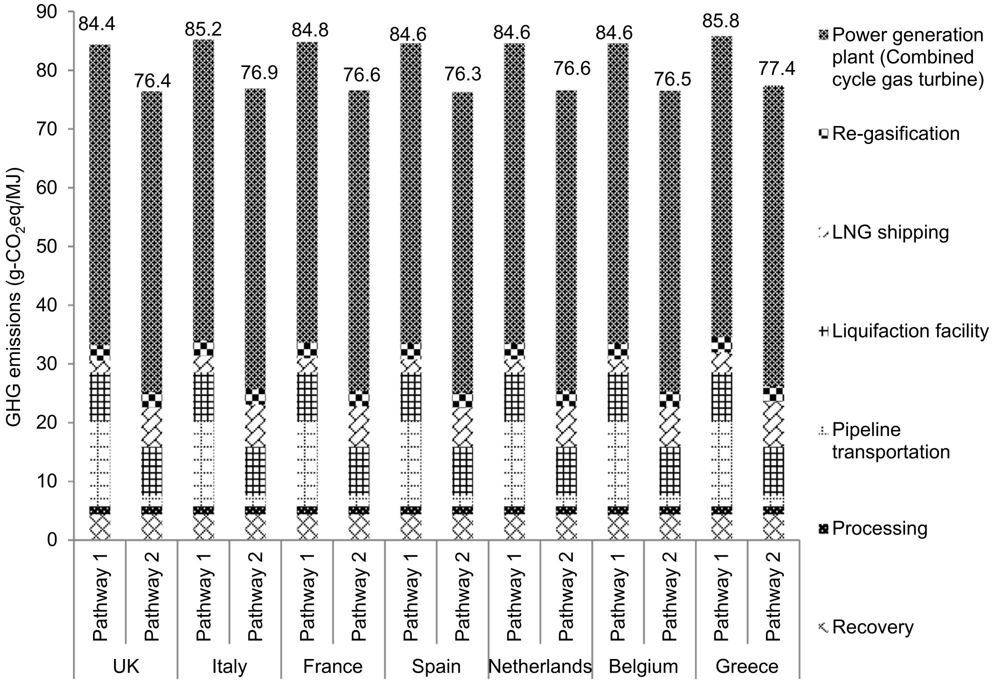

**Fig. 8.** Breakdown of LC WTW GHG emissions of two supply chain pathways of Canadian LNG from the Montney reserve.

28.51–38.45 g-$CO_2$ eq/MJ if pathway 1 route (via the east coast) is followed and 22.94–30.15 g-$CO_2$eq/MJ for pathway 2 (via the west coast). This wide range of uncertainties exists because of the sparsely available data, particularly for Canada, for emissions from operations like drilling and completion, gas composition, and flow back water treatment, as well as the amount of gas vented during the processing phase and the lifetime productivity of the reserves, due to the infancy of Canadian shale gas extraction. GHG emissions can be reduced if the vented and flared gas is captured with shale gas recovery and processing technology.

Natural gas is imported to Europe in gaseous form by pipeline and LNG form by LNG tankers from exporting countries like Russia, Algeria, Norway, and Qatar. The GHG emissions reported in the literature are lower than those in the Canadian LNG supply chain. Therefore, finding alternative sources of natural gas in Eastern Canada could offer lower GHG-intensive substitutes to the Canadian LNG supply chain to Europe, reducing the large portion of supply chain transportation GHG emissions. However, currently there are insufficient data available to explore the market potential for Eastern Canada. The Government of Quebec have given priority to exploring the natural gas resource potential in that province, and in future, natural gas supply from this region is expected.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jngse.2018.01.048.

## References

Baron, R., Bernstein, P., Montgomery, W.D., Tuladhar, S., 2015. Macroeconomic impacts of LNG exports from the United States. Econ. Energy Environ. Pol. 4, 37–58.

Chi-Chyong, K., Kazmin, R., 2016. The Economics of Global LNG Trade: the Case of Atlantic and Pacific Inter-basin Arbitrage in 2010–2014.

Council of European Energy Regulators, 2016. CEER Analysis on the Role of LNG to Improve Security of Supply. Available at: www.ceer.eu/.../2016/C15-LNG-25-03_LNG-SoS%20Analysis_3-Feb-2016.pdf, Accessed date: 13 February 2017.

European Commission, 2015. Quarterly Report on European Gas Markets: Market Observatory for Energy. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/quarterly_report_on_european_gas_markets_q1_2015.pdf, Accessed date: 21 February 2017.

Howarth, R.W., Santoro, R., Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change 106, 679.

Hultman, N., Rebois, D., Scholten, M., Ramig, C., 2011. The greenhouse impact of unconventional gas for electricity generation. Environ. Res. Lett. 6, 044008.

Hureau, G., Jordan, L., 2015. Waiting for the Next Train? an Assessment of the Emerging Canadian LNG Industry. Available at: http://www.cedigaz.org/documents/2015/Canada%20LNG%20%20Final.pdf, Accessed date: 21 January 2017.

Intergovernmental Panel on Climate Change, 2013. Climate Change 2013: the Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 8: Anthropogenic and Natural Radiative Forcing. Available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf, Accessed date: 16 August 2016.

Interstate Natural Gas Association of America, 2005. Greenhouse Gas Emission Estimation Guidelines for Natural Gas Transmission and Storage, vol. 1.

ISO, 2006. Environmental Management – Life Cycle Assessment - Principles and Framework. ISO 14040. Genève, Switzerland.

Italian Institute for International Political Studies, 2015. LNG in Asia and Europe: Converging Prices, Diverging Basins. Available at: http://www.ispionline.it/en/energy-watch/lng-asia-and-europe-converging-prices-diverging-basins-13770, Accessed date: 7 February 2017.

Javanmardi, J., Nasrifar, K., Najibi, S., Moshfeghian, M., 2006. Feasibility of transporting LNG from South-Pars gas field to potential markets. Appl. Therm. Eng. 26, 1812–1819.

Jiang, M., Griffin, W.M., Hendrickson, C., Jaramillo, P., VanBriesen, J., Venkatesh, A., 2011. Life cycle greenhouse gas emissions of Marcellus shale gas. Environ. Res. Lett. 6, 034014.

Jones, D., Dufour, M., Gaventa, J., 2015. Europe's Declining Gas Demand Trends and Facts on European Gas Consumption. Available at: https://www.e3g.org/docs/E3G_Trends_EU_Gas_Demand_June2015_Final_110615.pdf, Accessed date: 24 February 2017.

King, Spalding, 2016. LNG in Europe 2016/2017: an Overview of LNG Import Terminals in Europe. Available at: http://www.energylawexchange.com/kslaw/wp-content/uploads/2017/01/1-LNG-In-Europe_dec-2016-redu.pdf, Accessed date: 13 February 2017.

Kocak, K.A., Micco, P.D., 2016. The Quest for Natural Gas Pipelines. Available at: http://www.europarl.europa.eu/RegData/etudes/STUD/2016/586626/EPRS_STU(2016)586626_EN.pdf, Accessed date: 24 February 2017.

Kumar, S., Kwon, H.-T., Choi, K.-H., Cho, J.H., Lim, W., Moon, I., 2011. Current status and future projections of LNG demand and supplies: a global prospective. Energy Pol. 39, 4097–4104.

Macquarie Private Wealth, 2012. Macquarie Private Wealth: Canadian LNG: the Race to the Coast. Available at: http://www.investorvillage.com/uploads/8056/files/Cdn_LNG_100912.pdf, Accessed date: 21 February 2017.

Medlock, K.B., 2012. Modeling the implications of expanded US shale gas production. Energy Strat. Rev. 1, 33–41.

National Energy Board, 2016. Canada's Energy Future 2016: Energy Supply and Demand Projections to 2040. Available at: https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2016/index-eng.html#s6, Accessed date: 13 February 2017.

Netusil, M., Ditl, P., 2011. Comparison of three methods for natural gas dehydration. J. Nat. Gas Chem. 20, 471–476.

Peters, L., Hussain, A., Follmann, M., Melin, T., Hägg, M.-B., 2011. CO 2 removal from natural gas by employing amine absorption and membrane technology—a technical and economical analysis. Chem. Eng. J. 172, 952–960.

Petrovich, B., 2013. European Gas Hubs: How Strong Is Price Correlation? Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2013/10/NG-79.pdf, Accessed date: 28 November 2017.

Polishchuk, B., 2016. Ukrainian Energy Politics. Available at: https://enerpojournal.com/2016/11/14/ukrainian-energy-politics/, Accessed date: 7 February 2017.

Raj, R., Ghandehariun, S., Kumar, A., Geng, J., Linwei, M., 2016a. A techno-economic study of shipping LNG to the Asia-Pacific from Western Canada by LNG Carrier. J. Nat. Gas Sci. Eng. 34, 979–992.

Raj, R., Ghandehariun, S., Kumar, A., Linwei, M., 2016b. A well-to-wire life cycle assessment of Canadian shale gas for electricity generation in China. Energy 111, 642–652.

Raj, R., Suman, R., Ghandehariun, S., Kumar, A., Tiwari, M.K., 2016c. A techno-economic assessment of the liquefied natural gas (LNG) production facilities in Western Canada sustainable energy. Technol. Assess. 18, 140–152.

S & P Global Platts, 2016. Portworld Distance Calculator. Available at: http://www.portworld.com/map, Accessed date: 12 February 2016.

Sinha, R., Nik, W.M.N.W., 2012. Investigation of propulsion system for large LNG ships. In: IOP Conference Series: Materials Science and Engineering, vol. 1 IOP Publishing, 012004.

Skone, T.J., Cooney, G., Jamieson, M., Littlefield, J., Marriott, J., 2014. Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States. National Energy Technology Laboratory Available at: https://energy.gov/sites/prod/files/2014/05/f16/Life%20Cycle%20GHG%20Perspective%20Report.pdf, Accessed date: 28 February 2017.

Söderbergh, B., Jakobsson, K., Aleklett, K., 2009. European energy security: The future of Norwegian natural gas production. Energy Policy 37, 5037–5055.

Stephenson, T., Valle, J.E., Riera-Palou, X., 2011. Modeling the relative GHG emissions of conventional and shale gas production. Environ. Sci. Technol. 45, 10757–10764.

Taglia, A., Rossi, N., 2009. European Gas Imports: GHG Emissions from the Supply Chain. Available at: http://www.aaee.at/2009-IAEE/uploads/fullpaper_iaee09/P_238_Taglia_Antonio_31-Aug-2009,%2017:24.pdf, Accessed date: 22 February 2017.

TransCanada, 2014. Coastal GasLink Pipeline Project: Greenhouse Gas Emissions Technical Data Report. Available at: http://a100.gov.bc.ca/appsdata/epic/documents/p392/d37367/1394553608449_d56d24ee466441db246e16e23e42e730633649487df1686d6220780282b5a309.pdf, Accessed date: 23 February 2017.

TransCanada PipeLines Limited, 2017. TransCanada: mainline tariff. Available at: http://www.tccustomerexpress.com/docs/ml_regulatory_tariff/Approved-Tolls-Effective-January-1-2017-Amended-November-1.pdf, Accessed date: 28 November 2017.