Country-level Life Cycle Assessment of Greenhouse Gas Emissions from Liquefied Natural Gas Trade for Electricity Generation

SUPPORTING INFORMATION

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1. Units and Conversion Factors

Table S1: Units and conversion factors used in this study

1 kWh = 3.6 MJ
1 MMTPA = 0.1315 BCF/D
1 metric ton = 1,000,000 g
1 lb = 453.6 g
HHV = 52.225 MJ/kg
LHV = 47.141 MJ/kg
Natural Gas Density = 0.77 kg/m^3

2. Baseline Emissions Data

The baseline data provides a basis from which country-specific datasets can be created. It presumes the unavailability of country level data; in lieu of it, estimates of the greenhouse gas (GHG) emissions arising from Canadian liquefied natural gas (LNG) are made using values typical of North American natural gas networks and power systems. Emissions data upstream of liquefaction is extracted from U.S. studies and Canadian sources[1-14] and supplemented by downstream data from a U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) study of U.S. export of LNG[15]. This results in 14 sets of data, which in totality, forms the baseline dataset presented in Table S2.

Together, the base data set shown in Table S2 provides an estimate of the greenhouse gas (GHG) emissions arising from Canadian liquefied natural gas (LNG). A number of modifications were made to ensure a basic level of consistency:

1. The studies are often presented with very different system boundaries. Data from the different studies were placed into the most comparable segments.
2. Data are presented in units of gCO_2e/kWh (HHV) based on the AR4 100 year Global Warming Potentials and a power plant efficiency of 46.4%, the average fleet efficiency of the U.S. natural gas generating plants.[15]
3. Emissions arising from natural gas liquefaction, tanker berthing and deberthing, LNG regasification, as well as the electricity transmission and distribution loss factor were obtained from a DOE/NETL study[15] of LNG export from the U.S.
4. The emission factor for ocean transport was taken from the DOE/NETL report,[15] and used to estimate emissions arising from ocean transport from Kitimat, BC to prospective export destinations. The DOE/NETL report[15] provides low, medium, and high estimates of the emissions factor; the medium value is used in the baseline data. The value presented in the base dataset represents an average that is weighted by the market potential of each country. This was estimated by first determining the ocean distances in nautical miles from the export port (Kitimat, BC) to a selected LNG regasification terminal in the destination country. Using the ocean distance from the export port, the emission factor from the DOE/NETL report[15] was then adjusted to determine the LNG transport emission factor of each destination. Finally, a weighted average LNG transport emission factor (representative of the expected trade from Kitimat) was calculated based on the size of the electricity generation of each country.
5. Data extracted from the GHGenius database[16] do not include emissions arising from fuel dispensing.
6. Natural gas distribution is omitted from the study boundaries, since natural gas bound for power plants do not proceed through the distribution networks. Burnham *et al*. lump emissions arising natural gas transmission networks together with those arising from distribution networks. Burnham’s value is therefore replaced with the one provided by JISEA (19 gCO2,e/kWh at 51% power plant efficiency), after adjusting to 46.4% power plant efficiency

7. Emissions arising from power plant operations were calculated based on a carbon intensity factor of 50 gCO_2e /MJ[7] of combusted natural gas.

Table S2: Baseline data showing estimates of GHG emissions arising from Canadian liquefied natural gas based on different studies.

Baseline	Construction	Drilling	Fracturing	Completion	Flaring	Lease Energy (production)	Plant emissions (processing)	Vented CO2	Fugitive well	Fugitive plant	Workovers	Liquids unloadings	Compression	Fugitive transmission	Liquefaction	LNG Transport	Tanker Berthing & Deberthing	LNG Regasification	Power Plant Operations	Electricity T&D	T&D Losses (7%) @46.4% eff	Total (gCO2,e/kWh)
Howarth	0.0	0.0	0.0	75.7	0.0	0.0	37.9	43.8	0.0	0.0	0.0	5.2	0.0	20.9	64.7	32.8	1.5	17.7	388.0	3.3	48.4	739.9
Burnham	25.6	48.0	0.0	0.0	29.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.9	64.7	32.8	1.5	17.7	388.0	3.3	44.2	675.8
Jiang	1.1	1.8	3.1	10.1	85.0	0.0	37.7	0.0	0.0	0.0	0.0	0.0	12.3	0.0	64.7	32.8	1.5	17.7	388.0	3.3	46.1	705.3
Venketash	0.0	0.0	0.0	0.0	85.0	0.0	37.7	0.0	0.0	0.0	0.0	0.0	12.3	0.0	64.7	32.8	1.5	17.7	388.0	3.3	45.0	688.0
Stephenson	0.0	3.5	1.3	9.9	33.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.4	0.0	64.7	32.8	1.5	17.7	388.0	3.3	40.0	611.1
Weber	1.3	1.6	2.6	9.5	4.7	25.3	0.0	9.5	21.4	14.2	9.5	0.0	3.2	15.0	64.7	32.8	1.5	17.7	388.0	3.3	43.8	669.7
Fulton	93.9	0.0	0.0	0.0	25.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.2	0.0	64.7	32.8	1.5	17.7	388.0	3.3	46.3	707.2
NETL	0.8	0.0	0.0	10.2	0.0	0.0	25.1	0.0	14.2	2.6	36.2	0.0	3.4	18.2	64.7	32.8	1.5	17.7	388.0	3.3	43.3	662.0
JISEA	17.4	0.0	0.0	24.9	7.5	0.0	23.6	0.0	0.0	0.0	0.0	0.0	23.6	0.0	64.7	32.8	1.5	17.7	388.0	3.3	42.4	647.4
Laurenzi & Jersey	0.0	0.0	0.0	77.1	0.0	0.0	10.8	0.0	0.0	0.0	0.0	0.0	38.0	0.0	64.7	32.8	1.5	17.7	388.0	3.3	44.4	678.2
BC- 10kt threshold HHS	0.0	0.0	0.0	23.2	0.0	0.0	23.6	0.0	0.0	0.0	0.0	0.0	6.6	0.0	64.7	32.8	1.5	17.7	388.0	3.3	39.3	600.7
GHGenius 4.0.3 HHS - BC - 2012	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	11.3	6.2	20.6	64.7	32.8	1.5	17.7	388.0	3.3	38.2	584.5
Skone 2012 Marcellus	0.1	0.0	0.0	8.7	0.0	0.0	4.6	0.0	10.4	2.4	24.2	0.0	20.6	16.7	64.7	32.8	1.5	17.7	388.0	3.3	41.7	637.5
Skone 2012 Barnett	0.7	0.0	0.0	7.4	0.0	0.0	4.6	0.0	10.4	2.3	26.2	0.0	21.6	16.7	64.7	32.8	1.5	17.7	388.0	3.3	41.9	639.8
Hultman et al.	0.0	0.0	0.0	39.9	1.5	0.0	0.0	0.0	18.5	5.4	39.9	0.0	0.0	17.2	64.7	32.8	1.5	17.7	388.0	3.3	44.1	674.5

3. Country Level Data

To demonstrate potential regional variation in GHG emissions arising from BC LNG exports, the baseline data were adjusted with country specific values. In theory, all life cycle segments downstream of liquefaction would be expected to correlate with the import country and to vary across countries. However, country specific information was not obtainable for several downstream processes. For these segments, we relied on the U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) study for data, which were then applied across all countries. These “shared” data are called “Common Values” in Table S3, which presents a breakdown of the lifecycle segments examined into upstream and downstream (common and country specific) categories.

We examined three major factors observed to vary across countries: ocean transport, power plant efficiency, and electricity T&D losses. A set of data specific to each country is created, shown in Table S5, by adjusting baseline data with country specific factors. Unfortunately, the best publicly available country-level data identified were point estimates. More robust sets of country-specific data would better capture regional variation; this scarcity of data is another area of improvement that would facilitate rigorous uncertainty analysis.

Table S3: The LNG life cycle segments analyzed in this study presented in this table are organized by upstream and downstream of liquefaction, and whether the values used are shared across all countries or unique to each country.

Upstream	**Downstream: Common values**	**Downstream: Country Specific**
Construction	Liquefaction	LNG Ocean Transport
Drilling	Tanker Berthing & Deberthing	Power Plant Operations
Fracturing	LNG Regasification	Electricity T&D Losses (Direct)
Completion	Electricity T&D Losses (Indirect)	
Flaring		
Lease Energy (production)		
Plant emissions (processing)		
Vented CO2		
Fugitive well		
Fugitive plant		
Workovers		
Liquids unloadings		
Compression		
Fugitive NG transmission		

The following adjustments were made to the baseline level data to derive country-specific datasets (presented in Table 5):

1. Data are presented in functional units of gCO2,e/kWh HHV based on AR4 100 year GWPs, but values are adjusted to represent country specific average efficiency of NG combustion plants.
2. Direct electricity T&D losses arise from losses across the power T&D networks. To compensate for losses, additional energy must be produced to meet energy demand. The emissions arising from this excess energy is taken to be those attributed to direct electricity T&D losses.
3. The country average natural gas plant efficiency data and T&D losses (except China) were sourced from the World Energy Council (WEC).[17] The natural gas plant efficiency data for China is the average of the range reported in Kahrl *et al*. (2013)[18].

4. The weighted LNG transport emissions factor in the baseline data is replaced with the emissions expected to arise from ocean transport of LNG from Kitmat, BC to each specific country. These estimates are again based off the emissions fact or provided in Skone *et al*. (2014).[15]
5. Although emissions arising from shipping emissions is dependent on a variety variable inputs, Abrahams *et al*.[20] suggest that its associated GHG consequences are relatively minor in the overall life cycle. The study found LNG shipping to comprise of only 3.5-5.5% of pre-combustion emissions, assuming no fugitive emissions occur in the shipping stage. LNG shipping emissions from Skone's (2014) case study of LNG exports from New Orleans to Rotterdam, Netherlands comprises of 11.9% of its estimated pre-combustion emissions. Relative to these ranges, ocean transport contributes on average 15% to the pre-combustion emissions of our baseline data, but ranges from 11% - 24% arising from variation in estimated upstream emissions across the collected datasets.
6. Emissions arising from power plant operations were calculated based on a carbon intensity factor of 50 gCO_2e /MJ[7] of combusted natural gas.
7. All of these data, used in analyses, and the resulting country-specific power plant operations and LNG transport GHG emissions, are presented in Table S4.

Table S4: Base values of country specific values describing natural gas plant efficiency, T&D losses, and emissions expected from ocean transport of LNG from Kitimat, BC, to each respective location.

Country	NG Plant Eff (HHV)	Direct T&D Losses (%)	Power Plant Operations Adjusted for NG Plant Eff	LNG Transport Emissions Factor Adjusted for NG Plant Eff
Belgium	0.51	0.05	351.6	42.9
Germany	0.44	0.04	405.5	51.0
Spain	0.56	0.10	323.7	40.0
UK	0.53	0.08	342.4	42.2
Turkey	0.51	0.15	351.8	48.8
Argentina	0.46	0.15	387.5	42.7
Brazil	0.45	0.15	399.1	46.1
China	0.46	0.06	395.0	25.6
India	0.41	0.20	444.2	50.1
Japan	0.47	0.05	381.1	18.7
South Korea	0.44	0.03	406.3	25.8
Taiwan	0.52	0.04	343.0	24.0

Table S5: Baseline data in Table S2 adjusted with country specific factors to derive sets of country-specific data. Values shown represent total life cycle emissions.

Total Emissions (gCO$_2$,e/kWh), HHV	Belgium	Germany	Spain	UK	Turkey	Argentina	Brazil	China	India	Japan	South Korea	Taiwan
Burnham	612.3	702.1	592.6	617.1	681.8	736.1	762.1	674.9	880.8	635.6	675.1	573.7
Jiang	638.4	732.0	617.9	643.4	710.6	767.7	794.7	704.6	918.5	663.9	704.9	598.9
Venketash	623.1	714.5	603.1	628.0	693.8	749.2	775.6	687.2	896.4	647.3	687.5	584.2
Stephenson	555.0	636.5	537.2	559.4	618.6	666.7	690.4	609.4	797.9	573.3	609.6	518.3
Weber	606.8	695.9	587.4	611.6	675.8	729.5	755.2	668.6	872.9	629.6	668.9	568.4
Fulton	640.1	733.9	619.5	645.1	712.5	769.8	796.8	706.6	921.0	665.7	706.9	600.6
NETL	600.0	688.1	580.8	604.7	668.3	721.3	746.7	660.8	863.0	622.2	661.1	561.8
JISEA	587.1	673.3	568.3	591.7	654.0	705.6	730.6	646.1	844.3	608.2	646.3	549.3
Laurenzi & Jersey	614.4	704.6	594.7	619.3	684.2	738.7	764.7	677.3	883.8	637.9	677.6	575.8
BC- 10kt threshold HHS	545.8	626.0	528.3	550.1	608.5	655.6	678.9	598.9	784.5	563.4	599.1	509.4
GHGenius 4.0.3 HHS - BC - 2012	531.4	609.6	514.4	535.7	592.7	638.2	661.0	582.5	763.8	547.8	582.7	495.5
skone (marcellus)	578.3	663.3	559.8	582.9	644.4	695.0	719.6	636.1	831.6	598.7	636.3	540.9
Skone (barnett)	580.4	665.6	561.8	585.0	646.6	697.5	722.2	638.4	834.6	600.9	638.6	542.8
Hultman et al.	611.2	700.8	591.5	616.0	680.6	734.7	760.6	673.5	879.1	634.3	673.8	572.6
Mean	594.6	681.9	575.5	599.3	662.3	714.7	739.9	654.6	855.2	616.3	654.9	556.6

4. Upstream Emissions Data

We compare the collected data to the set of harmonized data by Heath *et al*. (2014) to better understand the differences in system boundaries.[19] Heath *et al*. examined U.S. shale and unconventional gas; we therefore limit this study to the subset of twelve U.S centric studies for this comparison. The data were minimally modified for consistency, but a full harmonization was not conducted in order to retain the original variation under examination. Specifically, the following adjustments were made:

1. Our data set examined LNG while Heath *et al*. (2014).[19] did not include liquefaction. Segments related to liquefaction of natural gas were therefore excluded and only emissions arising from segments through power plant combustion were considered.
2. Emissions associated with electricity transport and distribution (T&D) and losses from the electricity T&D network were excluded.
3. The power plant efficiency in electricity generation was assumed to be 51% (HHV).
4. A carbon intensity of 50 gCO_2e /MJ[7] was used for the calculation of combustion emissions.

Heath *et al*. (2014)[19] applied Global Warming Potentials (GWP) presented in the IPCC Fifth Assessment Report (AR5), in which the 100-year GWP of methane was updated to 30 from 25. Our data remains representative of the AR4 value of 25. To convert to the AR5 GWP value, access to a complete breakdown of CO_2 and methane emissions is required; most studies reviewed report only aggregated emissions in units of CO_2 equivalence. Figure S1 presents the distribution of our set of life cycle emissions compared with that of data from Heath *et al*. (2014).[19] Data from Howarth *et al*. (2011) is not included in the analysis due to questions about its comparability and validity.

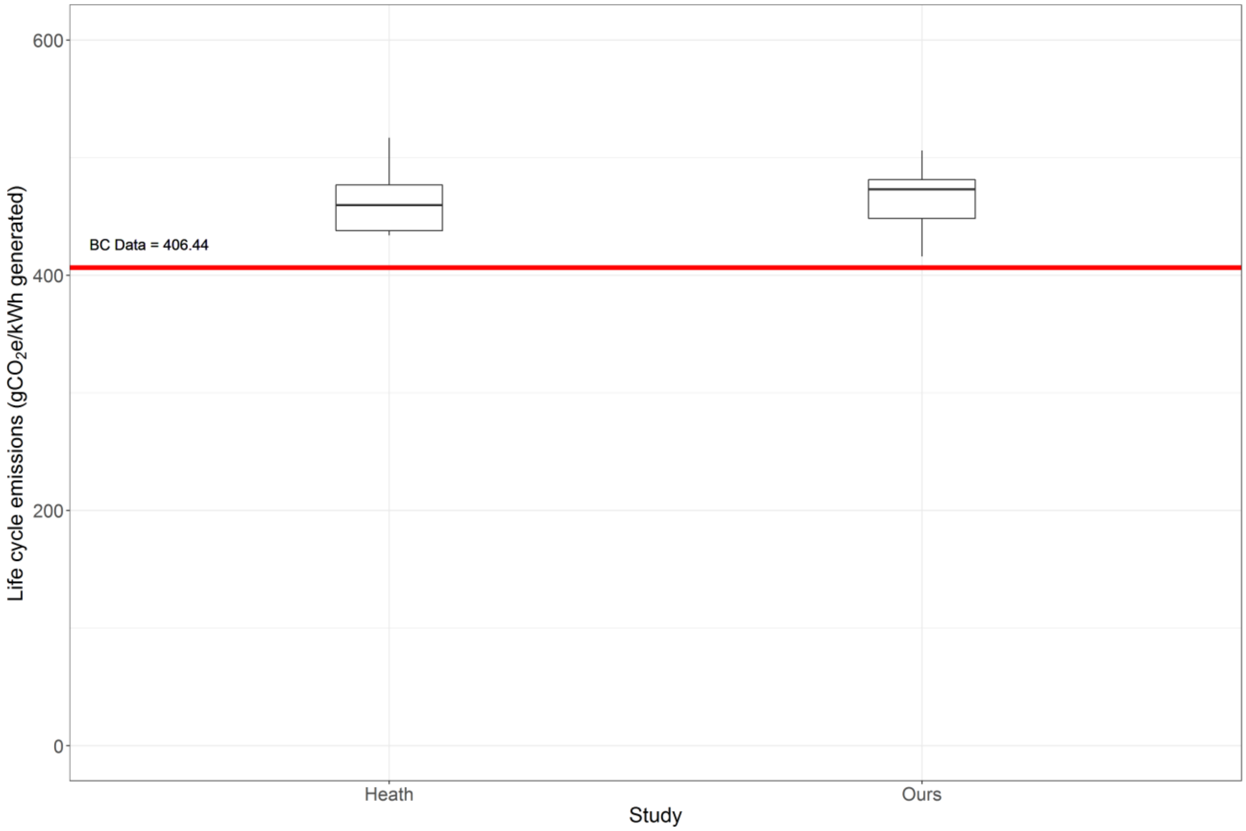


Figure S1: Comparison of distribution of life cycle emissions of data from Heath *et al*. (2014) and data from this study.

Summary statistics (presented in Table S6) describing the distributions of upstream data suggest that the resulting data set from our analysis is comparable the data set presented by Heath *et al*. (2014).[19] In both cases, the mean is larger than the median, suggesting a right-skew. There is significant overlap between the two data sets. The shift upward of Heath's dataset relative to the dataset of this study may be attributed to the usage of the AR5 GWP for methane. No outliers are observed; An outlier is defined here as a data point greater than the Q3 by 1.5 times the IQR, or less than the Q1 by more than 1.5 times the IQR [i.e. > (Q3 + 1.5*IQR) or < (Q1 - 1.5*IQR)]. The whiskers extend to the highest and lowest data values excluding the outliers.

Table S6: Summary of important statistics distribution of life cycle emissions of data from Heath *et al*. (2014)[19] and data from this study.

gCO_2,e/kWh (HHV)	**Min**	**1st Quartile**	**Median**	**Mean**	**3rd Quartile**	**Max**
Our data set	416.0	448.2	473.0	467.8	481.2	506.0
Heath et al.	434.0	438.0	459.5	464.1	476.8	517.0

The best estimate of total life cycle emissions specific to British Columbia (BC) is represented by the red line in Figure S1. While proximate to the minimum value in the U.S data, the BC data point is lower than most values reported in all sets of US data. A major potential contribution to the differences may be inherent in the data sources. While the U.S. studies focused on shale and unconventional gas, the BC data is representative of the entire oil and gas industrial facilities that release at least 10 kilotonnes (kt) of CO_2,e per year. Specifically, the value presented is the summed segmental emissions reported in the Question and Answer section of the 2012 Industrial Facility Greenhouse Gas Emissions Report produced by the BC government.[12] Unfortunately, without further resolution into the segments and data, it is impossible to limit the data set to only shale gas, nor is it possible to pinpoint the exact factors that contribute to the low value. Emissions are simply reported in large aggregations as four broad categories: well drilling and completions, upstream/gathering, processing, and transmission.

A key take-away from the exercise of developing Figure S1 is the lack of standardization across data sets. Disaggregating values into smaller, more specific processes and activities would allow direct comparisons across studies and sets of data. Moreover, the studies often provide little transparency in the underlying assumptions of the reported values. It is difficult to accurately work with aggregated data without sufficient documentation. The comparison of BC data to U.S. data presented in Figure S1, for example, should be interpreted with caution because they comprise of different activities and processes. Additionally, it is unclear what these specific differences are across datasets as the methods used to aggregate the data are inconsistent. The interpretation of the results drawn from poorly detailed data is limited. Transparency in reporting and assumptions in calculations allows for consistent comparisons to be made.

5. Sensitivity Analysis

5.1 AR5 vs. AR4

In 2014, the IPCC updated its estimate of the Global Warming Potential of methane from 25 to 34. The AR5 introduces methane GWP estimates which reflect the effects of climate-carbon feedback. The IPCC notes that this new addition better aligns the methodology applied to obtain the GWP estimates. While the AR4 carbon dioxide Absolute Global Warming Potential calculations include the impacts of climate carbon feedback, those of non-CO2 gases did not. The IPCC AR4 GWP values for methane may therefore be understated. With climate feedback, the IPCC report[21] estimates the AR5 methane 100-year GWP to be 34, relative to that of carbon dioxide. All publications examined in this study predate the release of the Fifth Assessment Report (AR5). We do not attempt to update the gathered dataset to reflect AR5 GWP values, as these studies do not provide the necessary data resolution needed to isolate methane from other greenhouse gas emissions. In lieu, we present a simple assessment of the sensitivity of the change in methane GWP in Figure S2. Skone *et al.*[14] estimates that the total emissions arising from the export of LNG from New Orleans to Rotterdam, Netherlands to be 13.8% methane to 85.5% CO2. Based on this breakdown, the life cycle emissions attributable to methane (approximated to be 13.8% of total gCO2,e/kWh) is adjusted to AR5 values. Doing so adds less than 5% to the original estimations.

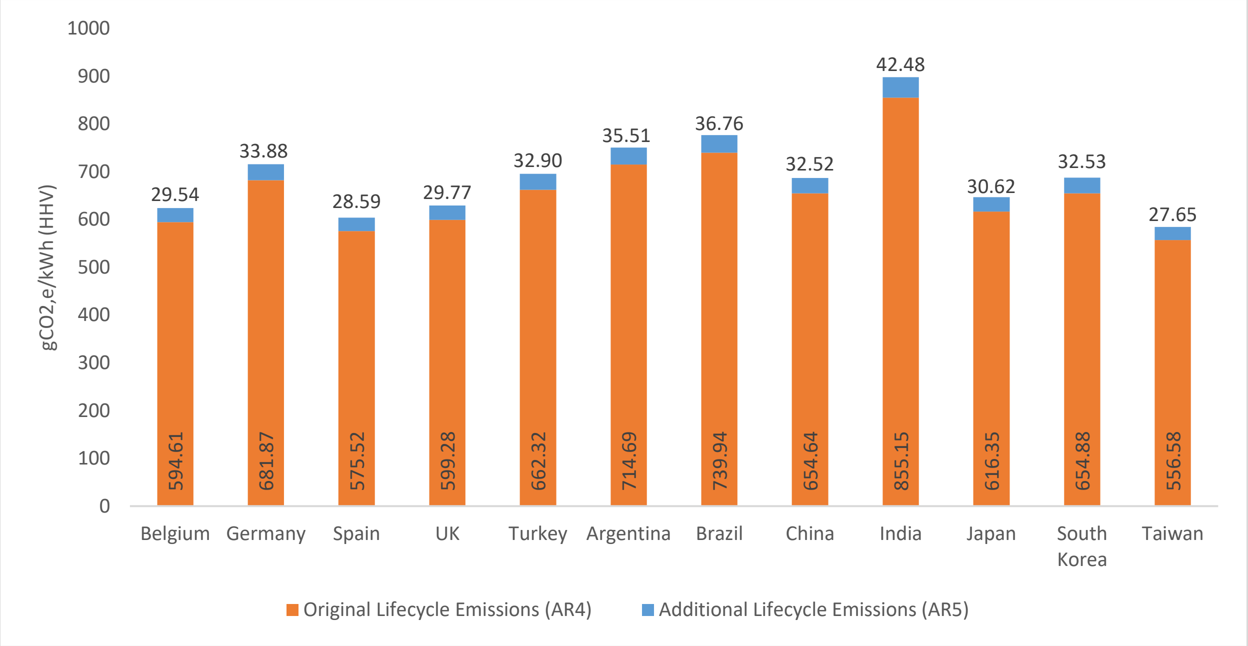


Figure S2: Approximate emissions increases arising from a switch to the AR5 estimate of methane is shown in blue. This calculation assumes methane comprises of approximately 13.8% of total GHG emissions arising from BC LNG exports. The original life cycle emissions based on AR4 values is shown in gray.

5.2 Country Specific Factors

A sensitivity analysis was conducted for each of the three factors expected to vary across countries: power plant efficiency, ocean transport, and electricity T&D losses. After defining a low and high extreme for each factor, we isolate the singular effects of the factors on overall lifecycle emissions by changing one variable at a time and holding all else constant. The average value for each set of country-level data is calculated and presented in Figures S3, S4, and S5. The sensitivity of each factor is presented in a separate figure and the corresponding change in percentage of total emissions is shown in Table S7. In each, the country level datasets are shown together to capture the regional variation across the estimated life cycle emissions. The lower bound of the shaded bars represent the low emissions case of each country. The higher bound of the shaded bars represent the high emissions case of each country.

1. The sensitivity of ocean transport is bounded by the high and low emissions factors (57.23 and 47.07 kgCO2e/MWH, respectively) provided in the DOE/NETL report. Emissions arising from ocean transport are based on calculated by the shortest distance from Kitimat to the respective export locations, and adjusted by average natural gas generation efficiency of each country.
2. Power plant efficiency is bounded by the highest and lowest average natural gas generation efficiencies across the average NG fleet efficiencies of the 12 surveyed countries. India provides the higher bounding value at 41% HHV, while Spain provides the lower bounding value at 56% HHV. Both values are provided by WEC.
3. The sensitivity analysis of direct electricity losses is bounded by the highest and lowest electricity loss percentage across the surveyed countries. India experiences the highest network losses at 20%, while South Korea experiences the lowest losses at 3%.

Amongst the factors explored, LNG emissions are most sensitive to power plant efficiency and least sensitive to ocean transport. Reductions in GHG stand to see significant gains by improving combustion efficiencies and by minimizing electricity network losses.

Table S7: Percent change in life cycle emissions from high and low case sensitivity factors

Country	Transport		Electricity T&D Losses		Plant Efficiency	
	Low case	High case	Low case	High case	Low case	High case
Belgium	-0.7%	0.7%	-1.5%	14.8%	-8.6%	26.3%
Germany	-0.7%	0.7%	-0.7%	15.7%	-20.7%	9.5%
Spain	-0.7%	0.7%	-6.2%	9.2%	-0.7%	37.2%
UK	-0.7%	0.7%	-4.8%	10.9%	-6.1%	29.7%
Turkey	-0.7%	0.7%	-10.6%	4.1%	-8.6%	26.3%
Argentina	-0.6%	0.6%	-10.4%	4.4%	-17.0%	14.6%
Brazil	-0.6%	0.6%	-10.5%	4.2%	-19.4%	11.3%
China	-0.4%	0.4%	-3.1%	12.9%	-18.6%	12.4%
India	-0.6%	0.6%	-14.0%	0.2%	-27.6%	0.0%
Japan	-0.3%	0.3%	-1.7%	14.6%	-15.6%	16.6%
South Korea	-0.4%	0.4%	-0.4%	16.0%	-20.9%	9.3%
Taiwan	-0.4%	0.4%	-0.6%	15.8%	-6.3%	29.5%

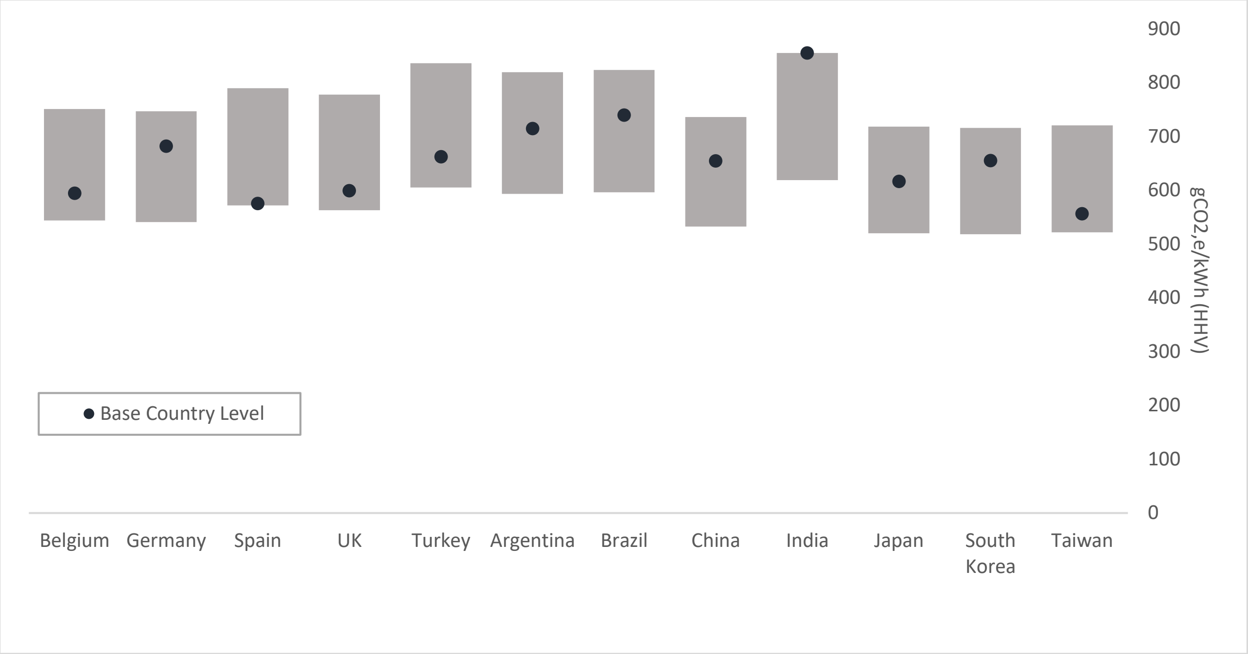


Figure S3: Sensitivity of lifecycle emissions to power plant efficiency. Baseline values for each country are indicated by the black dots. The top and bottom of the gray columns represent the total emissions resulting from application of the high and low factors, respectively.

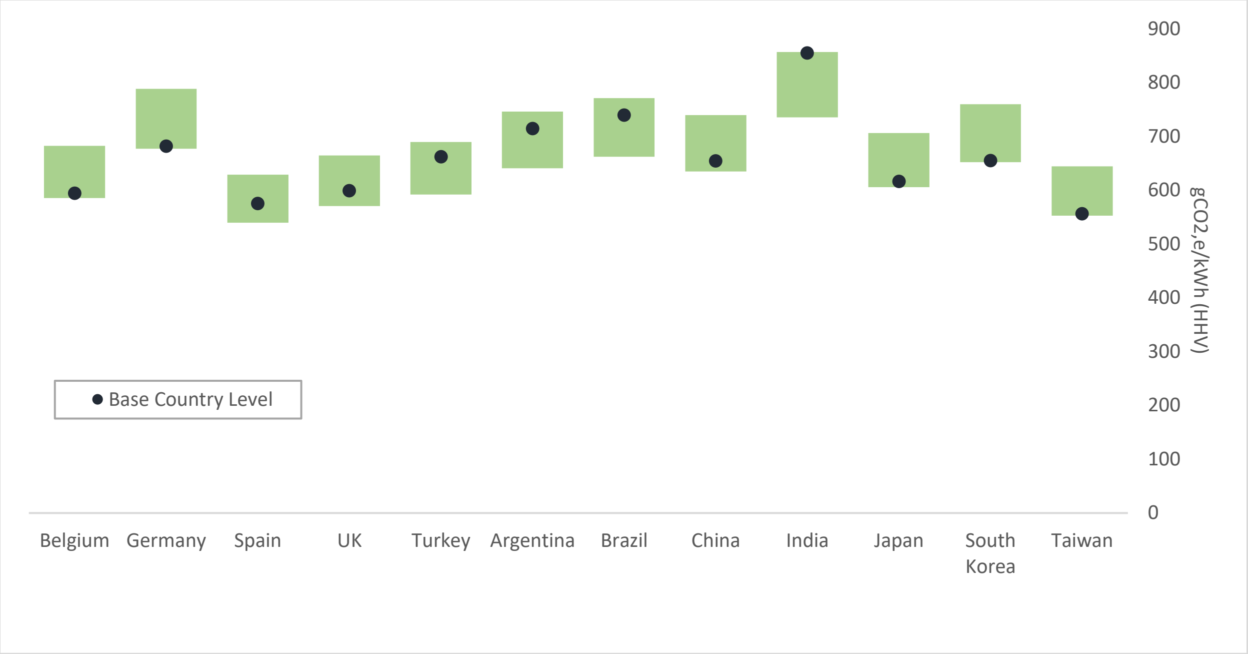


Figure S4: Sensitivity of lifecycle emissions to electricity losses through the T&D network. Baseline values for each country are indicated by the black dots. The top and bottom of the green columns represent the total emissions resulting from application of the high and low factors, respectively.

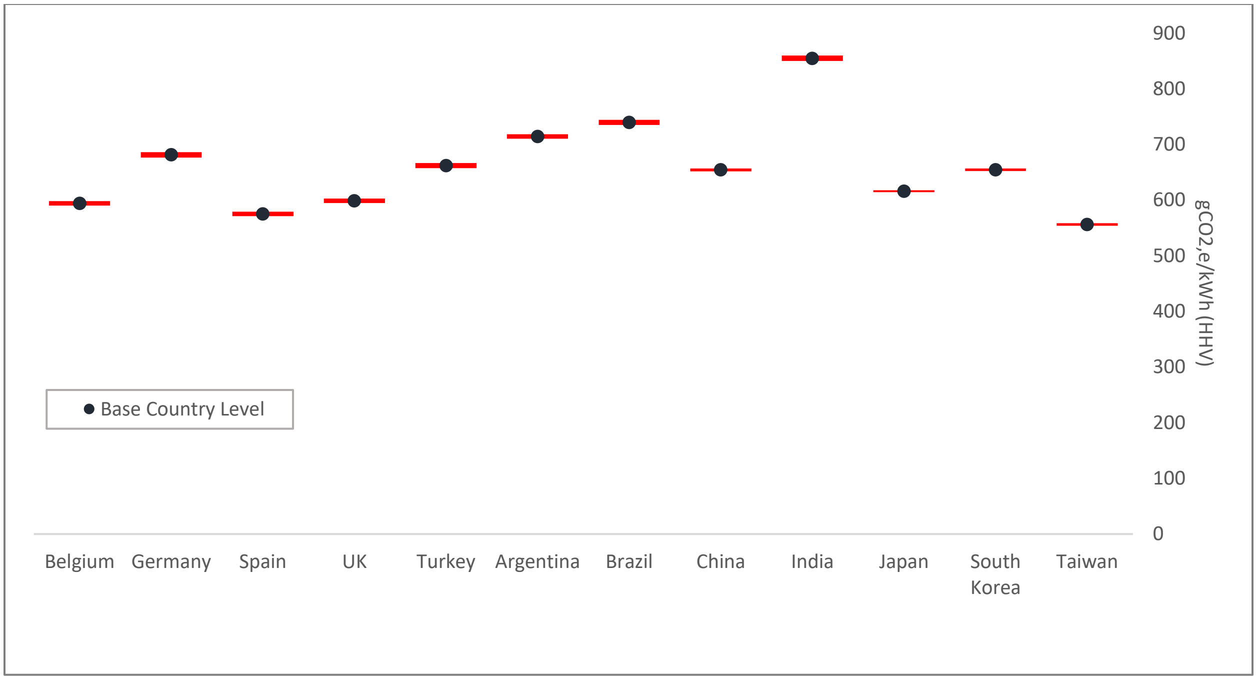
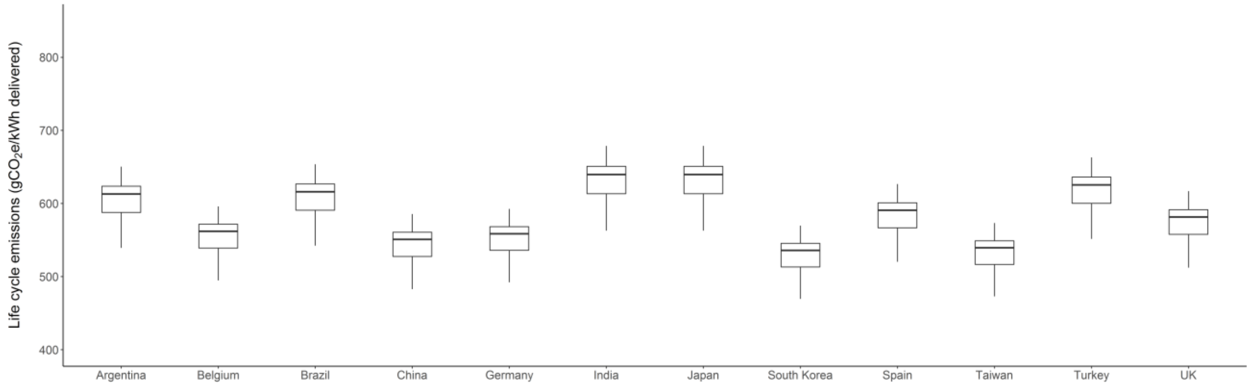


Figure S5: Sensitivity of lifecycle emissions to ocean transport. Baseline values for each country indicated by the black dots. The top and bottom of the red columns represent the total emissions resulting from application of the high and low factors, respectively.

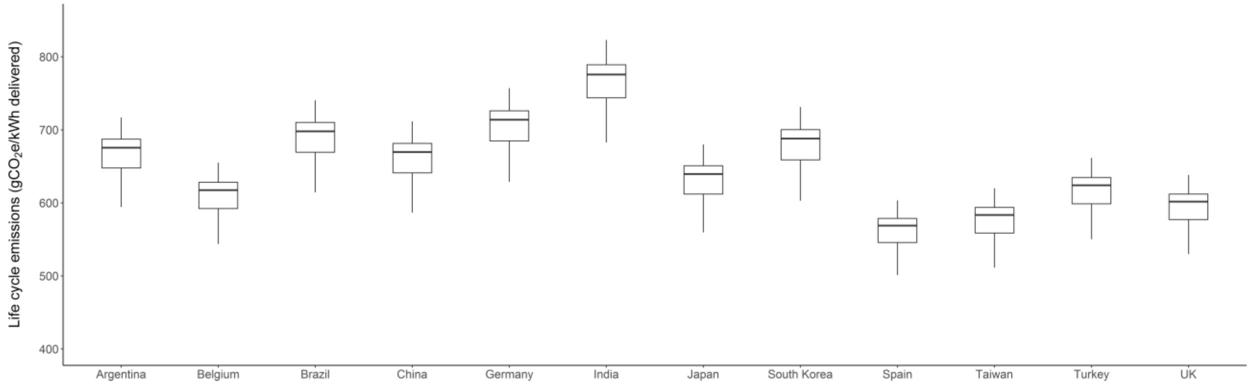
5.3 Future Technology Advances and Infrastructure Upgrades

Countries continue to upgrade or replace existing infrastructure with newer technologies to reduce line loses and improve power plant efficiencies. It is therefore interesting to consider the sensitivity of the country level emissions to these infrastructure upgrades. Three scenarios are identified to function as sensitivities to Figure 2, and explore the impacts of state of the art technology and infrastructure on the spread of emissions across the different countries. Figure S6a presents the first sensitivity, in which power plant efficiencies are considered to be the state of art (55% HHV) across all countries, while varying T&D losses and ocean transport assumptions by country. Figure S6b demonstrates the second sensitivity to infrastructure upgrades, in which T&D losses are assumed to be 7%, meant to reflect typical T&D losses across OECD countries[22]. Power plant efficiencies and ocean transport assumptions vary by country. Figure S6c presents the country level data in which T&D losses and power plant efficiencies are assumed to be state of art (55% HHV and 7%, respectively). In this last subplot, ocean transport assumptions continue to vary by country.

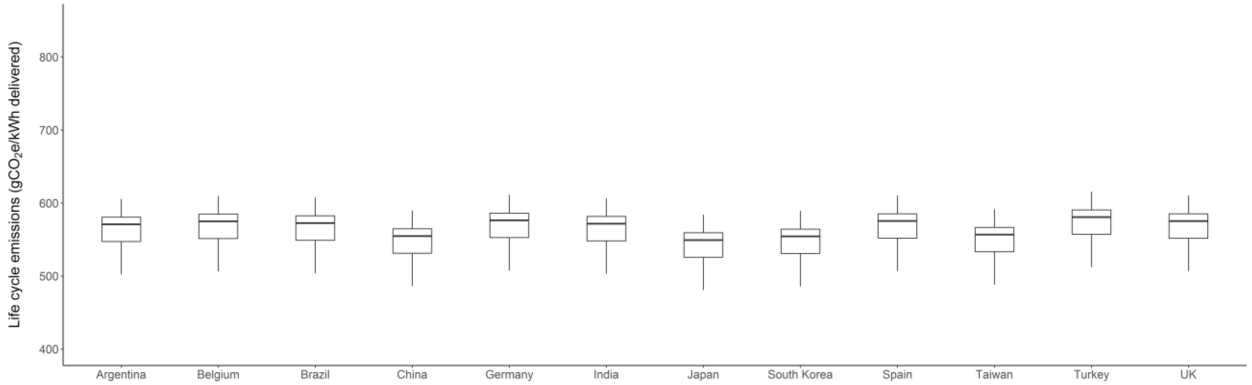
It can be observed that the intensity of emissions across the countries are most sensitive to power plant efficiency; switching to high efficiency generators significantly decreases emissions across the board. Likewise, power plant efficiency also contributes most significantly to the spread in total emission ranges across the countries. When both power plant efficiency and line losses are held constant, variation across the countries is minimal.



(a) All power plant efficiencies = State of Art (55%, HHV)



(b) All T&D losses = 7%



(c) All power plant efficiencies = 55% (HHV) and all T&D losses = 7%

Figure S6: Plant efficiencies in (a) are considered to be the state of art (55% HHV) across all countries, while varying T&D losses and ocean transport assumptions by country. In (b), T&D losses are fixed to 7% to reflect the average T&D losses across OECD countries. Power plant efficiencies and ocean transport assumptions continue to vary by country. Subplot (c) assumes T&D losses and power plant efficiencies are both State of Art (55% HHV and 7%, respectively), but ocean transport assumptions continue to vary by country. The vertical axis is intentionally not set to begin at zero to better visualize the differences between the subplots.

5.3 International Data Sources

Consistent sources of country specific data is largely unavailable. This study relies on 2014 WEC reported power plant efficiency and T&D losses (the two more-impactful country specific factors influencing lifecycle emissions). This resource was chosen for its high regard as a respected global institution. A singular source for the data from also has the benefit of ensuring a basic level of consistency amongst the countries. Table S8 presents a comparison of 2014 WEC reported T&D losses to that reported by IEA. Country level power plant efficiencies were not available. The sensitivity of the calculated life cycle emissions to the T&D values reported by these two sources was examined, and found to be minimal. Table S9 presents the difference in emissions when the two sets of data are applied.

Table S8: A comparison of 2014 WEC reported and IEA reported country-level T&D losses

T&D Losses	**WEC (2014)**	**IEA (2014)**
Belgium	5%	5%
Germany	4%	4%
Spain	10%	10%
UK	8%	8%
Turkey	15%	15%
Argentina	15%	14%
Brazil	15%	16%
China*	6%	5%
India	20%	19%
Japan (2012)	5%	4%
South Korea	3%	3%
Taiwan	4%	NA

Table S9: Difference in total lifecycle emissions with application of 2014 WEC reported T&D losses compared against total lifecycle emissions with application of IEA reported T&D losses

	Belgium	Germany	Spain	UK	Turkey	Argentina	Brazil	China	India	Japan	South Korea
Burnham	5.0	1.0	-1.4	1.0	-2.1	-8.3	4.3	-4.9	-2.2	-2.2	-0.5
Jiang	5.2	1.0	-1.4	1.1	-2.2	-8.6	4.5	-5.1	-2.3	-2.3	-0.5
Venketash	5.1	1.0	-1.4	1.0	-2.1	-8.4	4.4	-5.0	-2.2	-2.2	-0.5
Stephenson	4.5	0.9	-1.2	0.9	-1.9	-7.5	3.9	-4.4	-2.0	-2.0	-0.5
Weber	5.0	1.0	-1.4	1.0	-2.1	-8.2	4.3	-4.9	-2.2	-2.2	-0.5
Fulton	5.2	1.0	-1.4	1.1	-2.2	-8.7	4.5	-5.1	-2.3	-2.3	-0.5
NETL	4.9	1.0	-1.3	1.0	-2.1	-8.1	4.2	-4.8	-2.1	-2.2	-0.5
JISEA	4.8	1.0	-1.3	1.0	-2.0	-7.9	4.1	-4.7	-2.1	-2.1	-0.5
Laurenzi & Jersey	5.0	1.0	-1.4	1.0	-2.1	-8.3	4.3	-4.9	-2.2	-2.2	-0.5
Wakelin_BC	4.5	0.9	-1.2	0.9	-1.9	-7.4	3.8	-4.3	-1.9	-2.0	-0.4
GHGenius 4.0.3 HHS - BC - 2012	4.4	0.9	-1.2	0.9	-1.8	-7.2	3.7	-4.2	-1.9	-1.9	-0.4
Skone (marcellus)	4.7	0.9	-1.3	1.0	-2.0	-7.8	4.1	-4.6	-2.1	-2.1	-0.5
Skone (barnett)	4.8	0.9	-1.3	1.0	-2.0	-7.9	4.1	-4.6	-2.1	-2.1	-0.5
Hultman et al.	5.0	1.0	-1.4	1.0	-2.1	-8.3	4.3	-4.9	-2.2	-2.2	-0.5

5.4 Additional Factors

The following factors were found to be in need of further investigation.

1. Abrahams *et al*.[20] have previously demonstrated that life cycle analysis results of LNG may be very sensitive to fugitive emissions. However, fugitive emissions are difficult to isolate from the data examined in this work. The emissions attributed to fugitive methane are frequently aggregated with other segments in reported LCA data. Heath *et al*.'s harmonization found methane leakage to range quite broadly from 0.6% to 6.2% (in mass of methane per mass of natural gas produced), for unconventional gas and 0.53% to 4.7% in conventional gas. The study also found the term "methane leakage" to be inconsistently defined among studies; the metric may refer to intentional methane emissions (what is often known as fugitive emissions), unintentional methane emissions (often referred to as vented emissions), or a mixture of both. Some studies include other categories of methane emissions, including those from coproduct storage tanks or combustion. Due to the aggregated nature of the data, a sensitivity across countries was conducted using data collected from Weber et. al, (to clarify, the data presented in Figure S7 have been adjusted with country specific factors). This particular study was chosen for its provision of highly granular fugitive emissions breakdown from upstream data. Weber et. al. conducted a Monte Carlo uncertainty analysis was conducted using the ranges reported for each category collected from six shale gas life cycle studies. The 95% percentile range was reported for each subcategories related to fugitive emissions (fugitive at well, fugitive at plant, fugitive transmission). In total, fugitive emissions from the Monte Carlo analysis make-ups 28% to 49% of total upstream emissions, with a mid-value of 44%. The bottom of the bars in Figure S7 represents the total country-specific emissions when lower value of the 95 percentile range is applied, while the upper bars represent the total emissions when the upper value is applied. The country-level emissions were calculated using the mid-point value is represented by the point series. These results support the findings of previous studies, which suggest that life cycle emissions tend to be sensitive to fugitive emissions. Our primary conclusions that results are sensitive to country-level differences in energy infrastructure have been reinforced by this assessment. The focus of this study was to examine the differences in emissions across countries. As a result, we agree with the existing literature that more research is

needed to refine existing methane emissions estimates (e.g. Brandt *et al*. 2014). We go further to note the importance of improving measurement and reporting globally (across countries) to support improvements in country-level analyses.

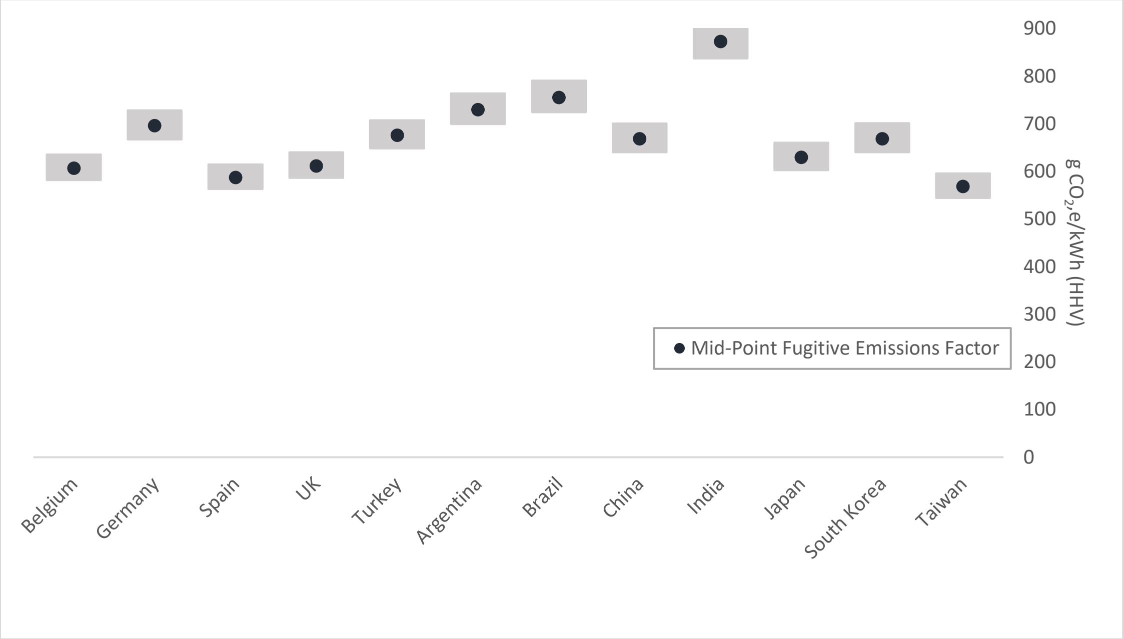


Figure S7: The bottom of the bars represents the total country-specific emissions, when the lower value of the 95-percentile range of Weber's Monte Carlo Analysis is applied. The upper bars represent the total country level emissions when the upper range is applied. Country-level emissions calculated using the mid-point value of the range is shown by the black points.

2. Data concerning the Chinese power sector are not easily obtained. Although the WEC provides point estimates of the average power plant efficiency for many prominent countries globally, it was unable to provide an estimate for China due to a lack of available data. Nonetheless, due to the expected significance in energy demand of the Chinese market, we found it meaningful to include China in our investigation. The best estimate of plant efficiency found amongst the existing literature was a point estimate reported by Karhl *et al.*,[18] though the original source of the value was not specified. Insight into the Chinese power generation efficiency remains an area deserving of improvement.

6. Emissions Displacement Scenarios

Table S8 shows the size of potential Canadian LNG export (as determined by Coleman *et al.*[23]) as a percentage of the electricity generation of the countries shown. It is obvious from Table S10 that the size of the Canadian potential LNG export estimated at 18.4 MMTPA will be too large for countries such as Belgium and Argentina. At 46.4% plant efficiency, Canada's expected LNG output is expected to be able to generate 1.24×10^5 GWh/yr of electricity.

Table S10: Percentage of each export country's total electricity that could theoretically be displaced by Canada's projected 18.4 MMTPA of LNG exports.

Potential Import Country	% of Country's Electricity Generation (2010)
China	3
India	14
Japan 2010	11
Japan 2012	11
South Korea	25
Spain	41
United Kingdom	33
Belgium	132
Argentina	112
Brazil	24
Taiwan	51
France	22
Turkey	59
Germany	20

Table S11 shows the breakdown of electricity generation by source in percent for each selected country. Figure 4 in the paper was plotted using data from this table.

Table S11: Electricity generation by source (%) for selected countries.

	Nuclear	Hydro	Geothermal	Coal	Oil	Natural Gas	Other Renewables
China	1.8	18.3	0.0	76.5	0.3	1.6	1.5
India	2.2	12.5	0.0	67.9	2.7	12.2	2.4
Japan 2010	25.9	7.4	0.2	27.4	8.8	27.4	2.8
Japan 2012	1.5	7.7	0.2	26.2	16.0	48.0	0.5
South Korea	29.9	0.7	0.0	44.1	3.8	20.8	0.6
Taiwan	17.1	1.7	0.0	50.5	3.9	24.9	1.9

With regards to the displacement of renewable electricity in the importing countries considered, Table S12 shows that apart from China, India and Brazil, where Canada's estimated total output electricity generation capacity from LNG is less than the amount of electricity generated from renewables, the total renewable electricity generation of all the other countries is actually much less than the estimated export capacity of Canada (1.24×10^5 GWh/yr) from LNG. Displacement of renewable electricity is thus considered not just with respect to the current renewable capacity, but to future additions of renewable capacity, consistent with long run marginal electricity.

Table S12: Renewable electricity generation in potential import countries and their relative magnitudes compared to Canada’s estimated LNG export capacity.

Potential Import Country	Renewable Electricity Generation (GWh/yr)	% of Country’s Renewable Electricity Generation Relative to Canada's Estimated LNG Export Capacity (2010)
China	7.71E+05	16
India	1.35E+05	92
Japan 2010	1.16E+05	107
Japan 2012	9.13E+04	136
South Korea	6.72E+03	1842
Spain	9.84E+04	126
United Kingdom	2.72E+04	455
Belgium	8.04E+03	1540
Argentina	3.39E+04	366
Brazil	4.33E+05	29
Taiwan	8.82E+03	1403
France	7.99E+04	155
Turkey	5.58E+04	222
Germany	1.13E+05	110

Figure S6 shows the magnitude of the life cycle greenhouse gas emissions (carbon intensity) of electricity generation from different sources, compared to the estimated life cycle emissions that would be generated using BC LNG for electricity generation in import markets. The source of the data is given by Coleman *et al*.[23] They did not consider country-specific efficiencies and they state that “the values of emissions from electricity generated from other sources are from a special report on renewable energy sources and climate change mitigation, and they correspond to the 50th percentile for each technology, from a meta-study of more than 50 papers. The value shown in the figure for “Other Renewables” is an average of life cycle greenhouse gas emissions from electricity generated from ocean, wind, biomass, solar CSP and solar PV. The average value shown is the mean of all estimated greenhouse gas emissions from all other sources of electricity on the chart.”

It is obvious from Figure S8 that, ordinarily, the displacement of renewables by BC LNG will result in a net increase of GHG emission in import countries, however, this scenario can be more practically envisaged in a situation where the price of natural gas, as the long-term marginal source becomes so cheap compared to the cost of additional renewable capacity, that policy makers weigh the expected GHG emissions reduction in adding renewable capacity, to the economic benefits of adding state-of-the-art natural gas plants.

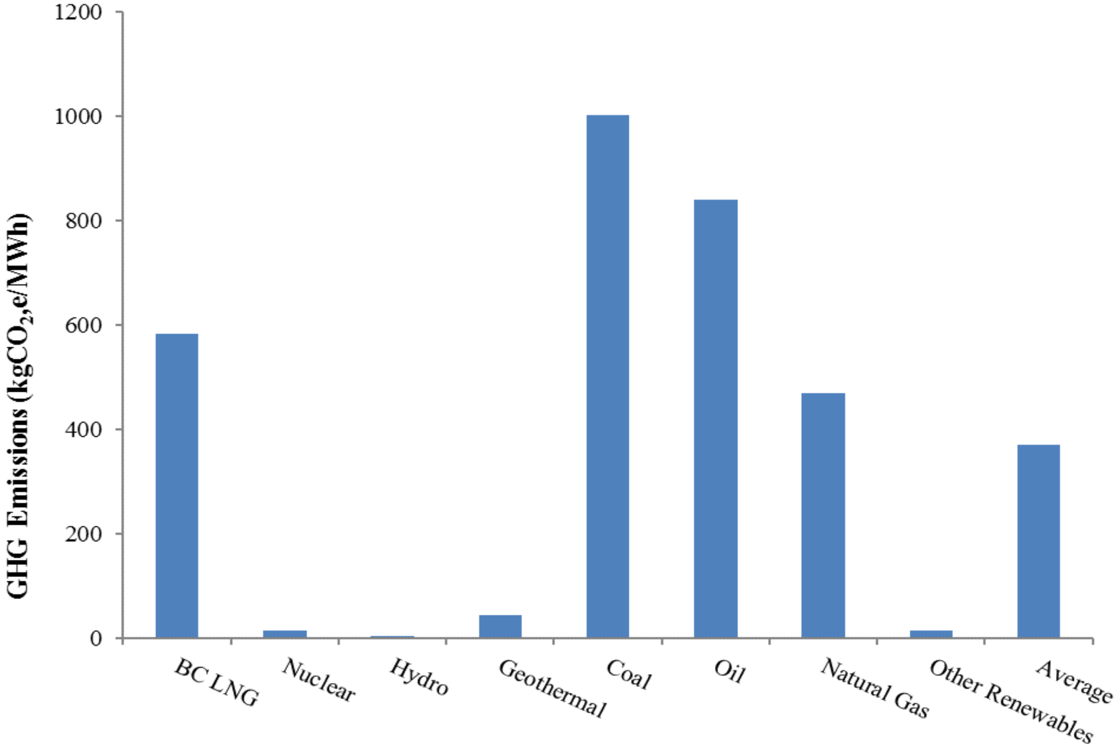


Figure S8: Life cycle greenhouse gas emissions from different sources of electricity generation.[20] (Used with permission from Canadian Institute of Resources Law)

Table S13 below shows the amount of electricity generated from each source in the year 2010 for all potential importing country considered.

Table S13: Electricity generation by source in import countries.

COUNTRY	Electricity Generation by source (2010) (TWh)						
	Nuclear	Hydro	Geothermal	Coal	Oil	Natural Gas	Other Renewables
China	70.205	713.790	0.000	2987.881	12.101	63.018	56.967
India	19.457	113.280	0.000	613.825	24.855	110.722	21.968
Japan 2010	288.230	82.220	2.630	304.500	97.450	304.510	31.220
Japan 2012	15.900	83.700	2.600	286.680	175.060	525.170	5.000
South Korea	148.600	3.680	0.000	219.280	18.940	103.180	3.040
Spain	61.990	42.280	0.000	26.320	16.560	96.620	56.120
United Kingdom	62.140	3.600	0.000	108.800	4.860	175.000	23.580
Belgium	47.940	0.310	0.000	5.950	0.410	31.420	7.730
Argentina	7.171	33.826	0.000	0.000	1.337	68.304	0.025
Brazil	13.797	399.256	0.000	10.672	15.121	34.332	33.672
Taiwan	41.629	4.194	0.000	123.289	9.462	60.800	4.628
Turkey	0.000	51.790	0.670	55.040	2.180	98.150	3.360
Germany	140.560	20.430	0.030	273.550	8.360	86.830	92.310

To get the total emissions by electricity generation source for country (gCO_2,e), the life cycle greenhouse gas emissions of electricity generation from different sources (gCO2,e/kWh), shown in Figure S8 was multiplied by the corresponding amount of electricity generated by source for each country (kWh), given in Table S13 above. The results, emissions by electricity generation source are given in Table S14.

Table S14: Emissions by electricity generation by source in import countries.

COUNTRY	**Emissions by Electricity Generation Source**						
	gCO$_2$,e						
	Nuclear	**Hydro**	**Geothermal**	**Coal**	**Oil**	**Natural Gas**	**Other Renewables**
China	1.12E+12	2.86E+12	0.00E+00	2.99E+15	1.02E+13	2.96E+13	1.23E+12
India	3.11E+11	4.53E+11	0.00E+00	6.14E+14	2.09E+13	5.19E+13	4.75E+11
Japan 2010	4.61E+12	3.29E+11	1.18E+11	3.05E+14	8.19E+13	1.43E+14	6.74E+11
Japan 2012	2.54E+11	3.35E+11	1.17E+11	2.87E+14	1.47E+14	2.46E+14	1.08E+11
South Korea	2.38E+12	1.47E+10	0.00E+00	2.19E+14	1.59E+13	4.84E+13	6.57E+10
Spain	9.92E+11	1.69E+11	0.00E+00	2.63E+13	1.39E+13	4.53E+13	1.21E+12
United Kingdom	9.94E+11	1.44E+10	0.00E+00	1.09E+14	4.08E+12	8.21E+13	5.09E+11
Belgium	7.67E+11	1.24E+09	0.00E+00	5.96E+12	3.44E+11	1.47E+13	1.67E+11
Argentina	1.15E+11	1.35E+11	0.00E+00	0.00E+00	1.12E+12	3.20E+13	5.49E+08
Brazil	2.21E+11	1.60E+12	0.00E+00	1.07E+13	1.27E+13	1.61E+13	7.27E+11
Taiwan	6.66E+11	1.68E+10	0.00E+00	1.23E+14	7.95E+12	2.85E+13	1.00E+11
Turkey	0.00E+00	2.07E+11	3.02E+10	5.51E+13	1.83E+12	4.60E+13	7.26E+10
Germany	2.25E+12	8.17E+10	1.35E+09	2.74E+14	7.02E+12	4.07E+13	1.99E+12

The aggregate emissions intensity by electricity generation source was then obtained by multiplying the fraction of electricity generated from each source by the corresponding carbon intensity of each electricity generation source (Figure S8). The addition of all emission intensities for the different electricity generation sources for each country gave the total emissions from electricity generation for that country. This is shown in Table S15 below.

Table S15: Contribution to country total emission intensity by electricity generation source in import countries.

COUNTRY	Aggregate Emissions Intensity by Electricity Generation Source gCO$_2$,e/kWh							
	Nuclear	Hydro	Geothermal	Coal	Oil	Natural Gas	Other Renewables	Total
China	0.29	0.73	0.00	766.11	2.60	7.57	0.32	777.62
India	0.34	0.50	0.00	679.61	23.09	57.44	0.52	761.51
Japan 2010	4.15	0.30	0.11	274.41	73.70	128.57	0.61	481.84
Japan 2012	0.23	0.31	0.11	262.28	134.40	225.12	0.10	622.55
South Korea	4.79	0.03	0.00	441.90	32.03	97.42	0.13	576.30
Spain	3.31	0.56	0.00	87.85	46.39	151.10	4.04	293.26
United Kingdom	2.63	0.04	0.00	288.13	10.80	217.14	1.35	520.09
Belgium	8.18	0.01	0.00	63.52	3.67	157.17	1.78	234.34
Argentina	1.04	1.22	0.00	0.00	10.15	289.48	0.00	301.89
Brazil	0.44	3.15	0.00	21.08	25.06	31.77	1.43	82.93
Taiwan	2.73	0.07	0.00	505.78	32.57	116.87	0.41	658.43
Turkey	0.00	0.98	0.14	260.88	8.67	217.97	0.34	488.98
Germany	3.62	0.13	0.00	440.18	11.29	65.46	3.21	523.89

The assumptions stated in section 2 (baseline emissions data) were used to get first order estimates of what the emissions would be if BC LNG were exported to each of the import countries considered, the only difference being the use of 46% power plant efficiency (representative of average U.S. efficiency).[15] The results are given Table S16.

Table S16: Life cycle GHG emissions from electricity generation using BC LNG in potential importing countries.

Import Country	Life Cycle GHG Emissions from Imported BC LNG (gCO_2,e/kWh)
China	576
India	595
Japan 2010	570
Japan 2012	570
South Korea	576
Spain	599
UK	599
Belgium	599
Argentina	594
Brazil	596
Taiwan	578
Turkey	605
Germany	600

Knowing the emissions intensity and total emissions for each potential importing country, and the same values if BC LNG were used in each country, the BC LNG values were then used to displace different groups of electricity generation sources (representing the different scenarios already discussed in the paper). The total emissions before displacement were then subtracted from the total emissions after displacement to obtain the change in emissions after displacement for each country. The expected change in GHG emissions in both gCO2e/kWh and Mton/yr in selected countries, resulting from the displacement of whole mix, dispatchable and marginal electricity is presented in the main paper as Table 2.

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