Update to the Life-Cycle Analysis of GHG Emissions for US LNG Exports Analysis

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Executive Summary

Introduction

ICF was asked by the American Petroleum Institute (API) to update a May 2014 report published by US DOE/NETL entitled “Life Cycle Greenhouse Gas Perspective on Exporting Liquefied Natural Gas from the United States”. That 2014 NETL report compared life cycle greenhouse gas (GHG) emissions for US liquefied natural gas (LNG) used for power generation against the use of pipelined natural and coal for power generation. The NETL results indicated that electricity generated from US LNG delivered to consumers in Europe and Asia had a 474 to 310 kg/MWh lower GHG LCA compared to electricity generated with domestic coal. On a percentage basis, US LNG was 44% to 28% to lower (Reference case results for AR4 20-year and 100-year GWPs). Various reports published since 2014 and other data suggest that trends have led to more favorable GHG impacts when US LNG is used instead of coal. However, to be credible and useful, the ICF report needed to compile, check, convert to a common basis for systematic comparisons, and properly document that information.

This study is intended to update estimates presented in the 2014 NETL report. Concurrently with ICF’s analysis, NETL released a September 2019 update of the 2014 study of interest. As noted, results of ICF’s analysis are compared with both the original 2014 NETL study and the 2019 update.

Overall Results

This study presents estimates of the life cycle greenhouse gas emissions related to the generation and delivery of electricity to consumers made from US LNG and compares those emissions to that of electricity made from coal and other sources of natural gas.

Specifically, results compare the emission impacts from the generation of electricity in German, Chinese, and Indian markets. Scenarios vary by fuel source origination, including:

- Natural gas produced in the US (Marcellus and Permian), Australia, and Mozambique.
- Natural gas pipelined from Russia.
- Domestically produced or imported coal.

More detail on these scenarios is provided in the following Methodology section.

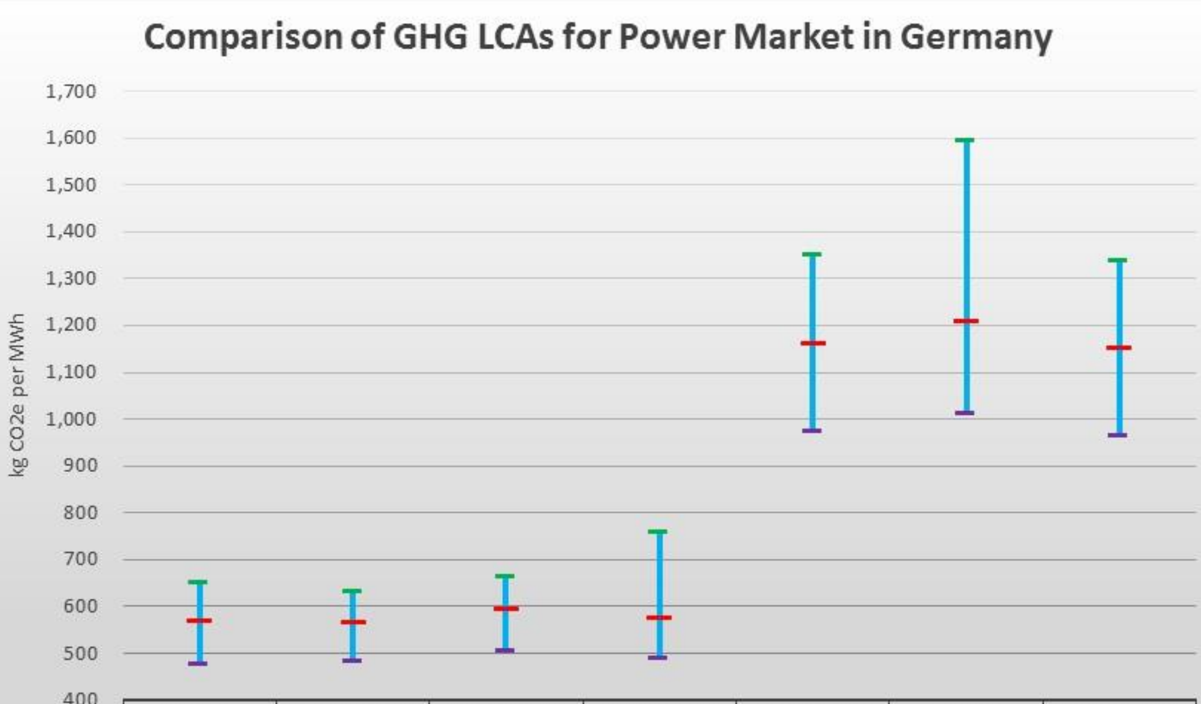
The study also considers the implications of key parameters by performing a sensitivity analysis. Results are generated across each scenario for every sensitivity case. The analysis suggests that results are most sensitive to assumed power plant efficiencies. All other items tested had smaller effects.

Exhibit 1 below shows a summary of overall results for each electricity market considered. Results are shown for each source of fuel for power generation, with the Upper and Lower estimates represented by relevant sensitivity results. The LNG and NG cases exhibit lower emissions in every scenario in comparison to coal. The highest emission impact LNG/NG scenario does not surpass the lowest impact coal scenario in any market.

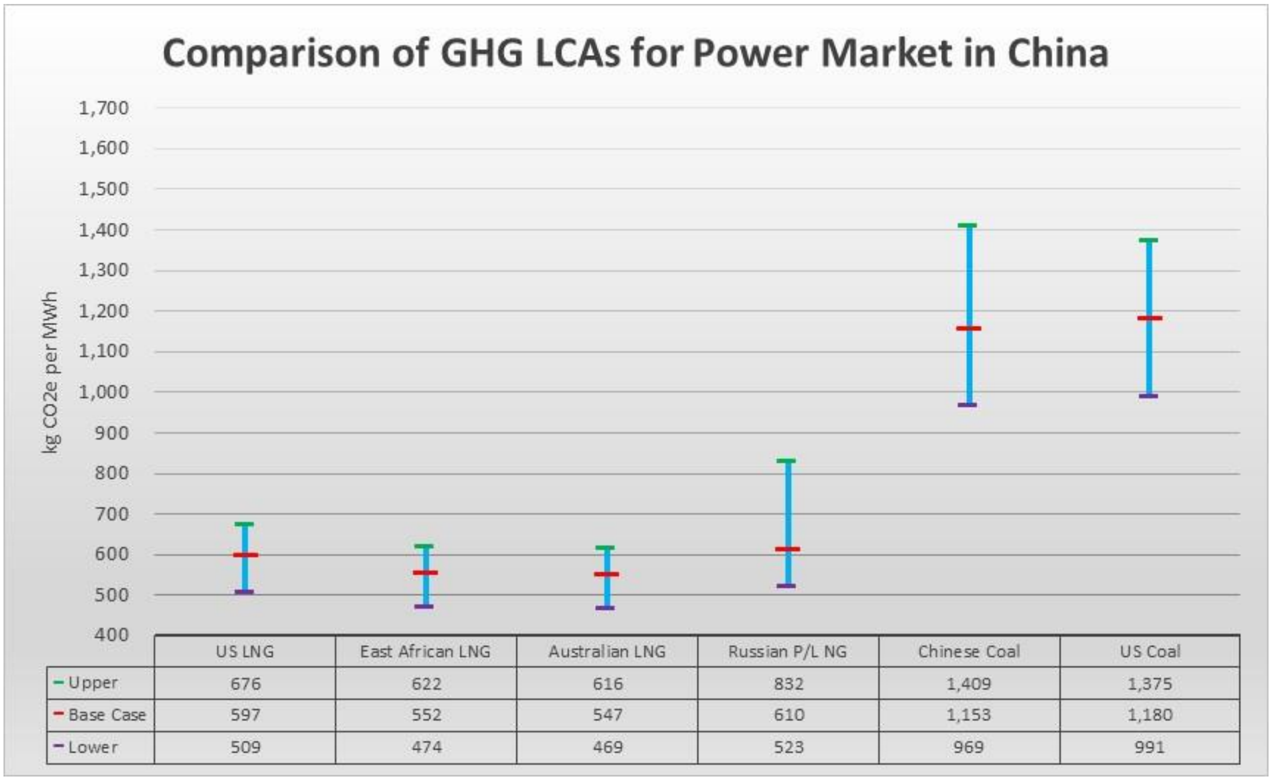
Emission impacts of imported LNG are comparable across each source country considered for each market. For Germany and China, LNG exports from the US and other countries have GHG emissions that fall within a compared range as NG exported by pipeline from Russia, with the exception of the “High Methane Leaks” and “High GWP” sensitivity scenarios. These scenarios cause a substantial increase in estimated GHG emissions from Russian pipeline gas.

All coal scenarios produce larger emissions than all considered LNG/NG scenarios. Impacts from power generation using domestic coal do not vary substantially from imported coal from the US. These results indicate that emissions are mainly generated during the power generation stage while transportation and shipping distance have less impact. Domestic Indian coal and coal imported from the US also exhibit similar Base Case GHG estimates. However, US eastern coals have greater methane release than domestic India coal and show more sensitivity to the “High Methane Leak” and “High GWP” scenarios.

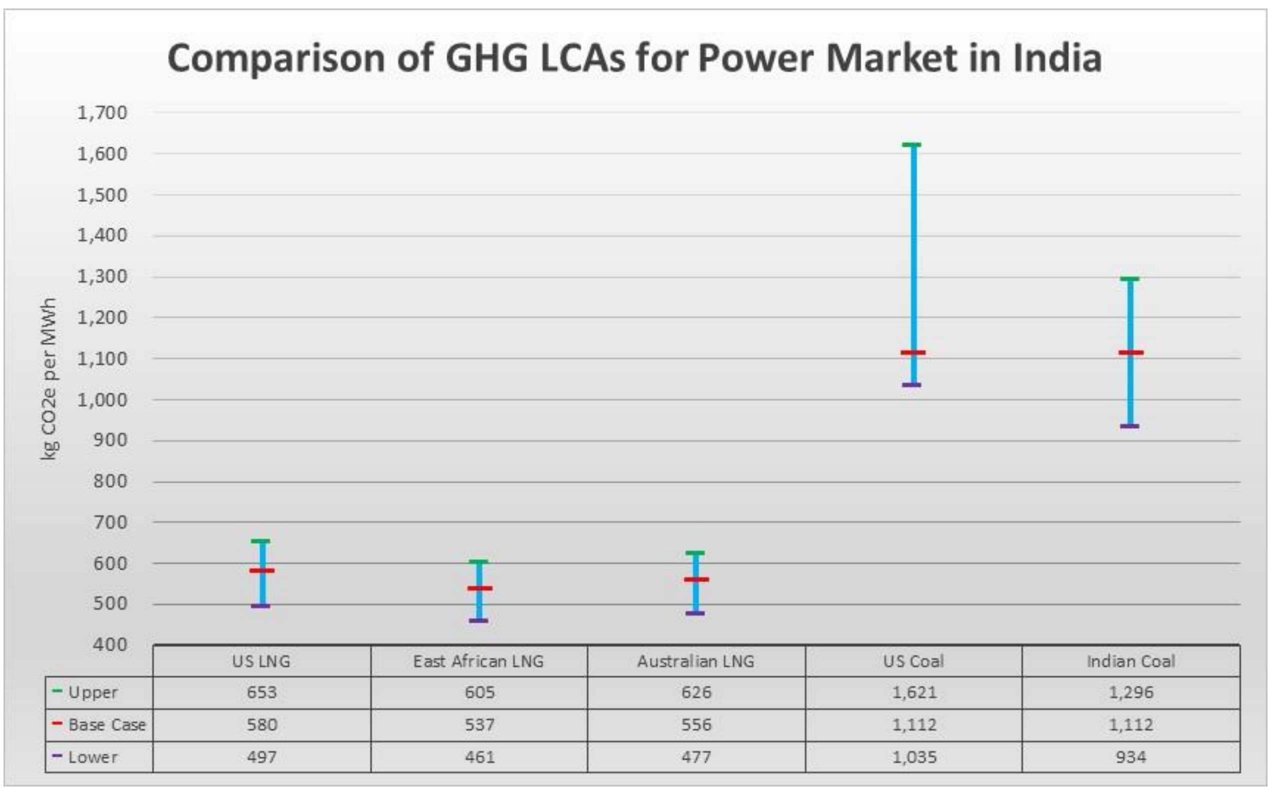
Exhibit 1: Summary of Emission Impacts for Relevant Electricity Generation Markets



	US LNG	East African LNG	Australian LNG	Russian P/L NG	German Coal	US Coal	Colombian Coal
Upper	653	634	666	759	1,352	1,596	1,338
Base Case	568	563	592	573	1,160	1,206	1,148
Lower	479	483	507	491	975	1,014	965



	US LNG	East African LNG	Australian LNG	Russian P/L NG	Chinese Coal	US Coal
Upper	676	622	616	832	1,409	1,375
Base Case	597	552	547	610	1,153	1,180
Lower	509	474	469	523	969	991



	US LNG	East African LNG	Australian LNG	US Coal	Indian Coal
Upper	653	605	626	1,621	1,296
Base Case	580	537	556	1,112	1,112
Lower	497	461	477	1,035	934

Background on NG and LNG role in World Energy Mix

World LNG markets continue to evolve, with a greater total number of LNG consuming countries (many using floating storage and re-gasification), a large share of growth coming from Asia (e.g., China and India), and the establishment of the US as a major and growing supplier of LNG with competing sources expected from established suppliers (Qatar and Australia). Natural gas supplied 138 quads of energy or about 22% of the World's energy demand in 2018.[1] According to EIA, natural gas consumption is expected to grow by 1.2% per year between 2018 and 2040. Due to anticipated capacity growth (see Exhibit 3), World LNG trade is also expected to increase in future years.[2]

Exhibit 2: World Energy, NG Consumption Comparison

	2019 EIA IEO & AEO Reference Case			
	2018	**2030**	**2040**	**% Growth per year**
World Energy Consumption (quads)	620	705	795	1.3%
World Natural Gas Consumption (quads)	138	154	175	1.2%
Volume of US LNG Exports (quads)	1.0	4.9	4.9	17.1%

Exhibit 3 shows current and planned liquefaction plant capacity for the United States and the rest of the World.[3] As shown, US liquefaction capacity is expected to increase substantially with over 60 MTPA planned by 2025. This anticipated increase is 68% more than all other capacity expansions currently planned throughout the rest of the World.

Exhibit 3: Current and Planned Liquefaction Capacity

Region	**2019 Liquefaction Plant Capacity (MTPA)**	**Sanctioned or Under Construction Capacity (MTPA)**
United States	24.8	63.4
Rest of World	375.6	37.9
Total	400.4	101.3

Methodology and Data

This study uses data from a multitude of sources including the US EPA Greenhouse Gas Emissions Inventory, NETL Unit Process Input and Output flows, AP-42 emission factors, UNFCCC country-specific greenhouse gas inventory submissions, and an assortment of construction and energy use requirement sources. Similar to the NETL study, ICF created various scenarios which vary the fuel source, origin country, and electricity generation market. Emissions estimates are calculated using a "bottom up" approach and are presented in terms of emissions contributed by each segment of the supply chain. Calculated emissions include fugitive losses and vented sources during operation, as well as combustion products. Construction material requirements and transportation emissions are also included in all LCA results.

The analysis includes 14 different LNG/NG cases and 7 different coal cases for a total of 21 scenarios. LNG and coal scenarios are shown in Exhibit 4 and Exhibit 5 respectively. For each

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[1] U.S. Energy Information Administration, 2019 International Energy Outlook (IEO)
[2] Forecasted World LNG trade volumes are not available in the 2019 IEO due to changes in the underlying modeling system. However, the 2017 IEO states that trade is expected to nearly triple from 12 Tcf to 31 Tcf between 2015 and 2040, or 6.3% per year.
[3] International Gas Union, 2019 World LNG Report

scenario, emission estimates are calculated for various stages along the Supply Chain. These definitions vary by power generation fuel type (NG/coal):

- ***Fuel Production*** **–** For NG scenarios, this includes the extraction of raw natural gas, gathering & compression and gas processing. For coal scenarios, this represents the mining and extraction of raw coal, as well as post mining activities such as beneficiation.
- ***Fuel transportation for export*** – For NG scenarios, this represents pipeline transportation of natural gas to the liquefaction facility. For coal scenarios, this represents rail, truck, or domestic barge transportation movements to export terminals.
- ***Conversion and export terminal*** – For NG scenarios, this includes the processing of pipeline NG for liquefaction (i.e., CO2 removal) and marine loading. For coal scenarios, this involves marine loading emissions at export terminals.
- ***International shipping*** **–** For both NG and coal scenarios, this represents international carrier transportation emissions to the target market.
- ***Import terminal and conversion*** – For both scenarios, this includes marine unloading emissions. For NG scenarios, this also includes emissions from regasification facilities.
- ***Transportation to the power plant*** **–** For NG scenarios, this represents the pipeline transportation from the import terminal to the power plant in the destination country. For coal scenarios, this includes rail, truck, or domestic barge transportation movements to the power plant.
- ***Power plant*** – For both NG and coal scenarios, this includes emissions from the conversion of the fuel type (NG/coal) to usable electricity (generation).
- ***Electricity Transmission and Distribution*** – For both NG and coal scenarios, this represents emissions from the carrying of electricity from the power plant through transmission and local distribution systems to consumers.

Exhibit 4: LNG LCA Scenarios Considered in ICF Analysis

Case No.	Source Country	Location	Type of Natural Gas	Transport Mode to Point of Export	Liquefaction Plant, Export Port	Destination Port	Use of Canal for Shipping	Transport Mode to Power Plant (from import terminal/ point)	Point of Consumption in Power Plant
1	US	Marcellus	Gas Shale	Pipeline	Cove Point MD USA	Europe - Rotterdam (Gate)	None	Pipeline	Germany, Northrhine-Westphalia (Cologne)
2	US	Marcellus	Gas Shale	Pipeline	Cove Point MD USA	India, Gujarat (Kandla)	Suez	Pipeline	India, Gujarat, near Kandla
3	US	Marcellus	Gas Shale	Pipeline	New Orleans LA, USA	Europe - Rotterdam (Gate)	None	Pipeline	Germany, Northrhine-Westphalia (Cologne)
4	US	Marcellus	Gas Shale	Pipeline	New Orleans LA, USA	China, Shanghai	Panama	Pipeline	China, Shanghai
5	US	Permian	Tight Oil	Pipeline	New Orleans LA, USA	Europe - Rotterdam (Gate)	None	Pipeline	Germany, Northrhine-Westphalia (Cologne)
6	US	Permian	Tight Oil	Pipeline	New Orleans LA, USA	China, Shanghai	Panama	Pipeline	China, Shanghai
7	Australia	NW Shelf	Conventional Offshore	Pipeline	Darwin, Australia	China, Shanghai	None	Pipeline	China, Shanghai
8	Australia	NW Shelf	Conventional Offshore	Pipeline	Darwin, Australia	India, Gujarat (Kandla)	None	Pipeline	India, Gujarat, near Kandla
9	Australia	NW Shelf	Conventional Offshore	Pipeline	Darwin, Australia	Europe - Rotterdam (Gate)	None	Pipeline	Germany, Northrhine-Westphalia (Cologne)
10	Mozambique	Rovuma Basin	Conventional Offshore	Pipeline	Palma, Mozambique	China, Shanghai	None	Pipeline	China, Shanghai
11	Mozambique	Rovuma Basin	Conventional Offshore	Pipeline	Palma, Mozambique	India, Gujarat (Kandla)	None	Pipeline	India, Gujarat, near Kandla
12	Mozambique	Rovuma Basin	Conventional Offshore	Pipeline	Palma, Mozambique	Europe - Rotterdam (Gate)	None	Pipeline	Germany, Northrhine-Westphalia (Cologne)
13	Russia	Yamal	Conventional Offshore	Pipeline	Border near Urumqi China	None	None	Pipeline	China, Shanghai
14	Russia	Yamal	Conventional Onshore	Pipeline	Vyborg Russia	None	None	Pipeline	Germany, Northrhine-Westphalia (Cologne)

Exhibit 5: Coal LCA Scenarios Considered in ICF Analysis

Case No.	State/ Province	Location	Type of Coal	Type of Mine	Transport Mode to Point of Export	Export Port	Destination Port	Use of Canal for Shipping	Transport Mode to Power Plant (from domestic mine or import terminal)	Point of Consumption in Power Plant
15	Germany	~40 km west of Cologne	Lignite	Underground	None	None	None	None	Truck	Germany, Northrhine-Westphalia (Cologne)
16	Shanxi Province, China	near Jinzhong	Bituminous	Underground	None	None	None	None	Rail	China, Shanghai
17	India	Madhya Pradesh	Bituminous	Underground	None	None	None	None	Rail	India, Gujarat, near Kandla
18	West Virginia	Appalachian Basin	Bituminous	Underground	Rail	Hampton Roads, VA USA	Europe - Rotterdam (Gate)	None	Barge	Germany, Northrhine-Westphalia (Cologne)
19	West Virginia	Appalachian Basin	Bituminous	Underground	Rail	Hampton Roads, VA USA	India, Gujarat (Kandla)	Suez	Rail	India, Gujarat, near Kandla
20	Montana	Powder River Basin	Subbituminous	Surface	Rail	Seattle WA, USA	China, Shanghai	None	Rail	China, Shanghai
21	Colombia	Cerrejon Coal Mine	Bituminous	Surface	Rail	Puerto Bolivar, Colombia	Europe - Rotterdam (Gate)	None	Barge	Germany, Northrhine-Westphalia (Cologne)

Exhibit 6: Sensitivity Analysis Parameters

Sensitivity Case	Sensitivity Name	GWP	Coal power plant efficiency	Gas power plant efficiency	Liquefaction plants fuel use	LNG Carrier fuel use	LNG Regas fuel use	Boil-off gas use (as max % of available daily BO)	Fugitive CH4 from Coal Mines	FVF CH4 from Russian Gas System
1	Base Case GWP=25	AR4: 100 Year (25)	33.0%	46.4%	9.0%	Default	Default	100.0%	Default	Default
2	AR5 100yr w/oxi, GWP=36	AR5: 100 Year Fossil w/Oxidation (36)	33.0%	46.4%	9.0%	Default	Default	100.0%	Default	Default
3	AR5 20yr w/oxi, GWP=87	AR5: 20 Year w/Oxidation (87)	33.0%	46.4%	9.0%	Default	Default	100.0%	Default	Default
4	High Methane Leaks	AR4: 100 Year (25)	33.0%	46.4%	9.0%	Default	Default	100.0%	High	High
5	High CH4 Leaks + Highest GWP	AR5: 20 Year w/Oxidation (87)	33.0%	46.4%	9.0%	Default	Default	100.0%	High	High
6	High Power Plant Effec.	AR4: 100 Year (25)	39.3%	54.2%	9.0%	Default	Default	100.0%	Default	Default
7	Low Power Plant Effec. (NETL's)	AR4: 100 Year (25)	28.3%	41.2%	9.0%	Default	Default	100.0%	Default	Default
8	High LNG Supply Chain Effic.	AR4: 100 Year (25)	33.0%	46.4%	8.0%	Low	Low	100.0%	Default	Default
9	All-Diesel LNG Carrier	AR4: 100 Year (25)	33.0%	46.4%	9.0%	Default	Default	0.0%	Default	Default

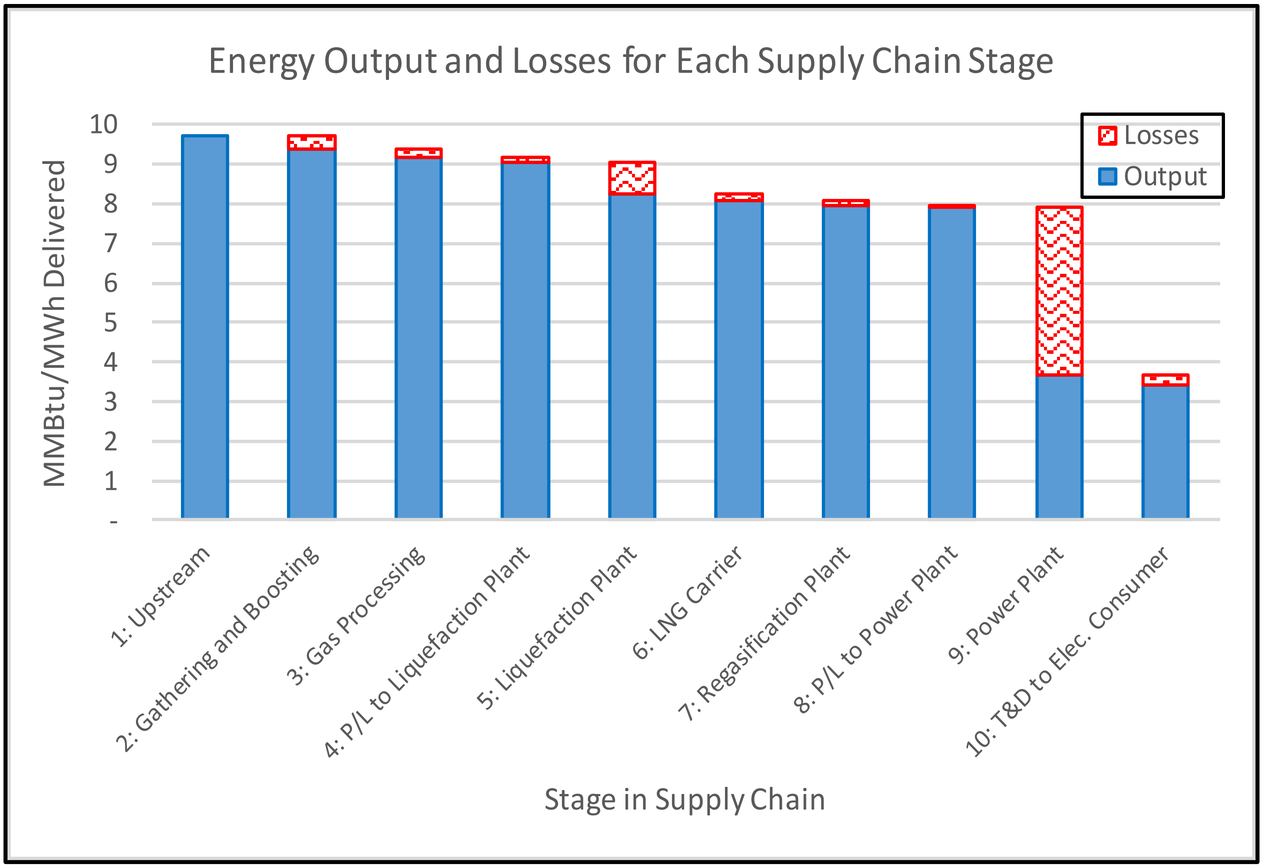
ICF determined GHG emissions within each supply chain stage using relevant emission factors and supporting calculations. Emissions from construction material and transportation requirements were determined using common LCA factors based on various products, as seen in Exhibit 7. Each stage results in a reported total kilogram (kg) and kilograms of carbon dioxide equivalent (CO2e) of emissions per unit of output for that stage. The emissions for each supply chain step are then combined to calculate a final LCA result for each scenario. For natural gas the unit of measure is usually thousand cubic feet of gas (Mcf). For coal, the unit of measure is metric ton (MT) of coal. The unit of measure for electricity is megawatt-hour (MWh). For natural gas, coal and electricity, outputs at each stage are also measured in units of million Btu (MMBtu).

Exhibit 7: LCA Factors for Various Construction Materials

Cradle to Gate LCA for Producing Different Products		Typical Transport Distance (miles)	
Product	**kg CO2e/MT of Product**	**Truck**	**Rail**
Frac Sand	6.0	72	670
Grav el	6.0	47	0
OCTG	2,180.0	394	853
Clean Water	0.25	50	0
Diesel Fuel	750.0	50	50
O/G Well Cement	554.0	50	100
Steel Line Pipe	2,180.0	394	853
Machinery	3,000.0	394	853
Asphalt	730.0	50	50
Structural Steel	2,100.0	394	853
Concrete	171.0	50	100
Aluminum	12,000.0	394	853
Stainless Steel	2,300.0	394	853
Iron Parts	2,000.0	394	853
Lime	758.0	50	100
Miscellaneous	125.0	250	500

For electricity made from LNG, as energy moves between successive stages in the supply chain, a portion of that energy is lost as fugitive emissions or energy consumption in that stage. Therefore, to report each stage's contribution to emissions on the basis of delivered MWh of electricity, it is necessary to multiply the kg/unit GHG emissions for each stage by the number of units needed to ultimately supply one MWh of electricity to the consumer to account for losses along the supply chain. For illustration, the raw output volumes and losses of natural gas per MWh of electricity delivered to consumers are shown in Exhibit 8.

Exhibit 8: Amount of Natural Gas Supplied to Generate 1 MWh of Electricity



Using the above methodology, ICF generated “Base Case” results for all 21 scenarios. The “Base Case” scenario of results utilizes IPCC AR-4 100-year emission factors (CH4 GWP=25). These results are shown by supply chain stage and scenario in Exhibit 9 and Exhibit 10. To further illustrate influence, ICF performed 8 sensitivity analyses which vary certain key parameters. A new set of results are generated for each scenario and new key parameter assumption. The following parameters were altered for sensitivity comparisons:

- Assuming different GWPs for methane.
- Accounting for uncertainties by applying higher estimates for methane release from coal mines and Russia natural gas system.
- Applying different power plant efficiencies (high and low for coal and gas).
- Assuming greater liquefaction plant, gas carrier, and regasification plant energy consumption efficiencies.
- Substituting of all diesel fuel for LNG carriers (instead of mostly burning boil-off gas).

Assumptions for each sensitivity case are shown in Exhibit 6.

Exhibit 9: Base Case Results for LNG Scenarios (AR4, 100-year GWP)

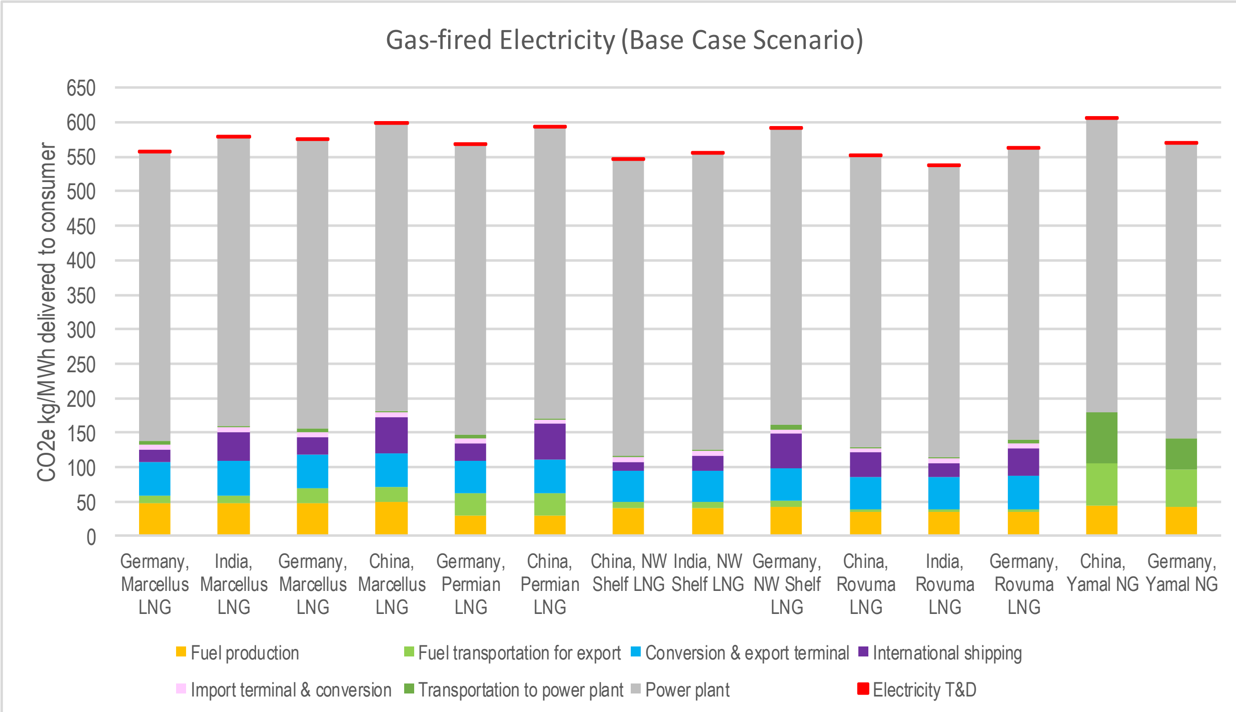
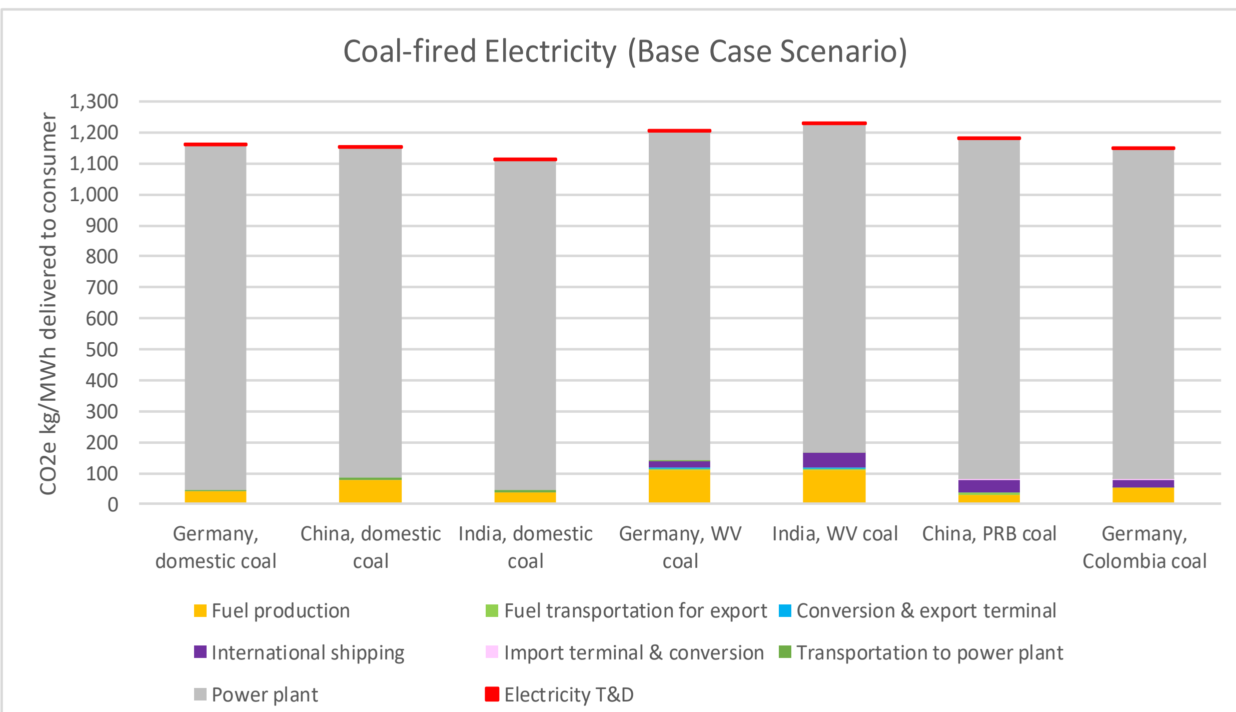


Exhibit 10: Base Case Results for Coal Scenarios (AR4, 100-year GWP)



Comparison to NETL Results

Resulting ICF estimates for the LCA of LNG are roughly 6% lower than the 2014 NETL estimates. The biggest difference between NETL results is the upstream stage of the supply chain wherein more recent (and lower) rates of methane leaks have been applied by ICF. LCA results for coal are about 5% higher than the NETL cases. The major source of difference is due to methane released in the coal mining process. NETL did not analyze differences among countries and types of mines. Instead they applied US data for surface mines, which are among the lowest methane emitters in the world. The 6% reduction for LNG combined with the 5% increase for coal mean that the differences between LNG and coal are greater than shown by NETL in the 2014 study. Exhibit 11, Exhibit 12, and Exhibit 13 compare ICF's analysis with NETL study results.

ICF also compared results with other recent Power Generation LCA studies. Due to wide ranging assumptions and methodologies, results were difficult to compare in a meaningful way for the purposes of this study.

Exhibit 11: Comparison between ICF and NETL Results in European LNG Markets

US LNG Case Comparisons (CO2e kg/MWh)

	NETL 2014	NETL 2019	ICF 2019
Value Chain Stage	**NOL to Rotterdam**	**NOL to Rotterdam**	**NOL to Rotterdam**
Natural Gas Extraction + Processing	61.1	88.0	47.7
Domestic PL Transport	27.8	61.0	21.6
Liquefaction	63.6	38.0	48.7
Tanker Transport + Berthing & Deberthing	26.2	28.0	25.0
LNG Regasification	17.7	4.0	7.1
Power Plant Operations	414.7	416.0	418.3
Electricity T&D	3.3	2.0	1.7
Total	**614.3**	**636.0**	**570.1**

Methane GWP: NETL 2014=25, NETL 2019=36, ICF=25.

Exhibit 12: Comparison between ICF and NETL Results in Chinese Coal Markets

Chinese Coal Case Comparisons (CO2e kg/MWh)			
	NETL 2014	NETL 2019	ICF 2019
Supply Chain Stage	Chinese Regional Coal	Chinese Regional Coal	Chinese Coal
Coal mining	7.8	9.0	79.4
Transportation	14.4	11.0	8.2
Coal-fired Power Plant	1,063.0	1,063.0	1,063.9
T&D to Electricity Consumer	3.4	2.0	1.7
Total	**1,088.6**	**1,085.0**	**1,153.1**

Methane GWP: NETL 2014=25, NETL 2019=36, ICF=25.

Exhibit 13: Comparison between ICF and NETL Results in European Coal Markets

European Coal Case Comparisons (CO2e kg/MWh)			
	NETL 2014	NETL 2019	ICF 2019
Supply Chain Stage	European Regional Coal	European Regional Coal	German Lignite
Coal mining	7.8	9.0	42.8
Transportation	14.4	11.0	3.9
Coal-fired Power Plant	1,063.0	1,063.0	1,111.6
T&D to Electricity Consumer	3.4	2.0	1.7
Total	**1,088.6**	**1,085.0**	**1,160.0**

Methane GWP: NETL 2014=25, NETL 2019=36, ICF=25.

Conclusions

This study illustrates that fewer emissions are produced from US LNG exports than other sources of power generation in foreign markets. Emissions from LNG exports are consistent across various sources of NG, and similar to pipeline exports although generally less on average. Power plant efficiency has the largest impact on emissions throughout the supply chain. Power generation from coal produces the highest emissions, which are primarily generated during power plant operation.