Lifecycle GHG Emissions of US LNG Exports

Concepts, Methodologies, Data and Results

July 30, 2024

Prepared by: ICF

Prepared for:

Natural Allies for a Clean Energy Future

PAGE Partnership to Address Global Emissions

ES. Executive Summary

ES.1 Introduction to Lifecycle GHG Emissions of US LNG Exports: Concepts, Methodologies, Data and Results

This Study was prepared by ICF for Natural Allies for a Clean Energy Future (NACEF) and the Partnership to Address Global Emissions (PAGE). The purpose of the Study is to provide a detailed explanation of how lifecycle analyses (LCAs) of greenhouse gas (GHG) emissions for US exports of liquefied natural gas (LNG) are estimated and how those estimated emissions compare with the LCA GHG emissions of alternative fuels such as coal and petroleum products. The Study presents a Base Case analysis using transparent, well-documented and consistent data and methods and, where uncertainties exist for important parameters used to make these estimates, the Study also provides sensitivity analyses.

- *The Study shows that US LNG exports have lower lifecycle GHG emissions compared to using coal alone, fuel oil alone or the expected mix of alternative fuels (summed across all countries importing US LNG) that would most likely replace imported US LNG.*
- *Without US LNG exported abroad, that energy would be replaced with 54% coal, 34% fuel oil, 16% domestic natural gas, and 7.8% renewable sources.*
- *Under this Study's Base Case assumptions, shifting from US LNG to coal increases GHG emissions by 47.7% to 85.9%. Shifting US LNG to fuel oil increases emissions by 24.8% to 41.8%.*
- *The majority of other studies reviewed here show similar results to this Study when comparing LNG with coal and fuel oil in power-plant or industrial applications.*
- *The limited number of studies that show US LNG as having more LCA emissions than coal tend to use outlier data, apply questionable emission factors that differ greatly from the US EPA GHG inventory and the GREET factors designated by Congress in the Inflation Reduction Act, highlight improbable scenarios, and fail to account for relative end-user fuel efficiencies which favor natural gas.*

Additionally, the Study compares its results to other studies and identifies how the application of assumptions such as methane leak rates and the global warming potent (GWP[1]) factor can affect the results. The Study primarily deals with lifecycle GHG analysis of LNG and alternative fuels for the historical year of 2022 but also looks at what emissions might look like in the year 2030 if the downward trend in methane emissions from the oil and gas systems as estimated in the Environmental Protection Agency's National GHG Inventory (EPA GHGI) were to continue.

ES.2 Conclusions Related to Differences in Methodologies

- The LNG supply chain includes several steps or segments, each of which has its own energy consumption and GHG emissions profile. The carbon intensity of LNG is the sum of all of these segments adjusted for losses along the supply chain. The example shown below is for LNG made from Marcellus natural gas and exported from the US East Coast to

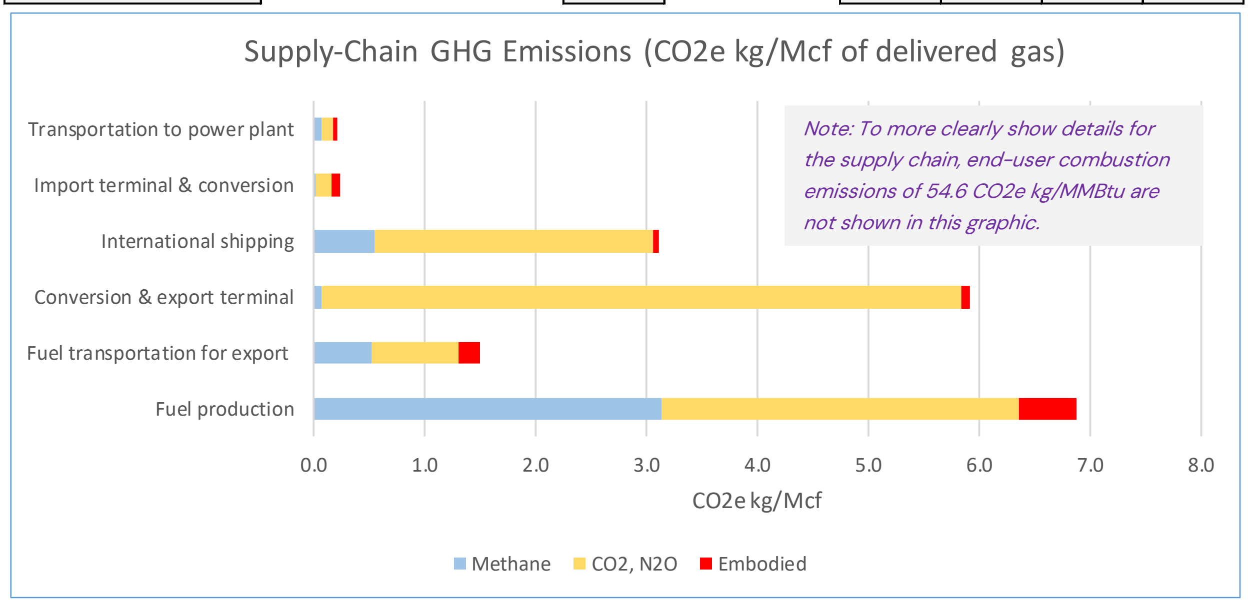
---

[1] The GWP is a factor by which one mass unit (e.g., a kilogram) of a GHG such as methane is multiplied to approximate the global warming potential of carbon dioxide. A methane GWP of 28 means that 1 kg of methane has the same global warming potential as 28 kg of CO_2.

France under the Study's Base Case assumptions. The left-hand portion of the chart represents emissions measured at each supply chain segment in units of kilograms of carbon dioxide equivalent per thousand cubic feet of natural gas. The right-hand side of the chart shows emissions scaled up to represent emissions delivered to a consumer. The scale up factor accounts for consumption of natural gas and releases of natural gas along the supply chain. Because of these losses, more than one unit of supply in the early portions of the supply chain is needed to ultimately deliver one unit to the consumer. The result for this example is an LCA of 72.48 CO_2e kg/Mcf or 69.87 CO_2e kg/MMBtu. The emissions for the regasified LNG delivered to consumers (excluding the final step of combustion by the consumer) are also shown graphically in units of CO_2e kg/Mcf at the bottom of the chart.

Exhibit 1: Example LNG LCA Analysis under Base Case Assumptions

Summary of LNG LCA Analysis: ICF Base Case Assumptions with Embodied									
Marcellus, East Coast to France	Measured at Each Supply-Chain Segment (CO2e kg/Mcf of gas exiting segment)				Scaling Factor between Segment and Customer	Delivered to Customer (CO2e kg/Mcf of delivered gas)			
	Methane	CO2, N2O	Embodied	Total		Methane	CO2, N2O	Embodied	Total
Fuel production	2.76	2.84	0.45	6.05	113.7%	3.14	3.22	0.52	6.88
Fuel transportation for export	0.46	0.69	0.17	1.32	113.9%	0.53	0.78	0.20	1.50
Conversion & export terminal	0.07	5.60	0.08	5.74	103.2%	0.07	5.78	0.08	5.92
International shipping	0.55	2.50	0.05	3.10	100.5%	0.55	2.51	0.05	3.11
Import terminal & conversion	0.03	0.14	0.08	0.24	100.2%	0.03	0.14	0.08	0.24
Transportation to power plant	0.07	0.11	0.03	0.21	100.0%	0.07	0.11	0.03	0.21
NG Combustion	0.14	54.46	0.00	54.60	100.0%	0.14	54.46	0.00	54.60
Sum at Customer				71.27		4.53	67.00	0.95	72.48

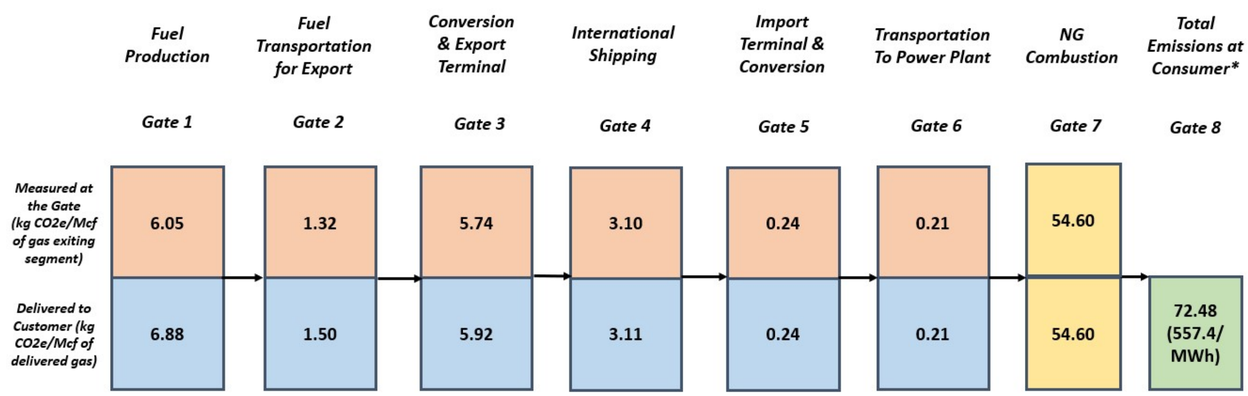


- There are several ways in which analysts have estimated the GHG emissions for LNG both in terms of emissions from the LNG supply chain itself and in terms of the alternative fuels to which LNG may be compared. It is important to understand the scope, methodology and data used by these analysts when comparing different estimates and determining their accuracy, usefulness and relevance.
- The energy consumption along the LNG supply and the resulting carbon dioxide emissions are much better understood and more easily estimated than emissions from

methane releases. Therefore, the differences in estimates of the carbon intensity of LNG among studies are often due to differences in the estimates of methane release rates (typically represented as the percent of gas production or throughput that is released to the atmosphere in each supply chain segment) and the translation of methane release rates into a carbon dioxide equivalent mass units (most often done using a global warming potential (GWP) factor and an estimate of what portion of the released natural gas is made up of methane.)

- Another important difference among studies is where along the LNG supply chain (the so-called supply chain "gates") the carbon intensity is being calculated and how comparisons are done between LNG and alternative fuels. The ultimate and arguably most relevant point of measure is the "end-user energy services" gate, which takes into account the carbon intensity of the entire supply chain that brings the re-gasified LNG (or alternative fuel) to the end-user and the efficiency of converting that fuel into a useful energy service. The useful energy service might be a megawatt hour of electricity (MWh) from a power plant or a thousand pounds of steam from an industrial boiler.
- Exhibit 2 recasts the data previously shown in Exhibit 1 into the "gates" concept wherein LNG exports pass through eight gates, starting from production and going to consumption by end users. The top part of each rectangle (shown in beige) under each gate represents emissions as measured at each supply chain segment. The bottom portion of each rectangle (shown in blue) are those same emissions scaled up for losses (natural gas releases and fuel consumption) that will occur in later segments. As the gas moves from left to right in the diagram, more GHG emissions accumulate. The last gate is the sum of the scaled-up values for gates #1 to #7. Gate #8 is also shown on the basis of one megawatt-hour of electricity using a heat rate of 7,690 Btu/kWh (the 2022 weighted average for countries importing US LNG).

Exhibit 2: Gate Concepts from Production to End-user Consumption



**Note – Gate #1 to 7 are incremental values per Mcf of natural gas. The total emissions shown at Gate #8 are cumulative (value in parenthesis is given in units per 1 MWh electricity generated). Values for this chart are derived from Exhibit 1 and apply to Marcellus Shale gas exported from the US East Coast to France.*

- To compare emissions between imported LNG and other fuels, the most significant end-use gate to consider is electricity generation. Because the energy conversion efficiency of gas-fired power plants is higher than those of coal or oil-fired plants, the carbon intensity comparisons with coal and fuel oils is more favorable toward LNG at the end-user energy services gate of power generators (measured in kilograms of carbon dioxide equivalent per megawatt of electricity or CO_2e kg/MWh) as compared to the "delivered to end user" gate (measured in CO_2e kg/MMBtu).

- Exhibit 3 uses the weighted average LCA GHG values for US LNG, coal and fuel oil and the weighted average heat rates for power plants in countries importing US LNG in 2022 to show LCA GHG values for those fuels delivered to large consumers and those fuels converted to electricity. The exhibit shows that coal converted to electricity has 85.9% higher GHG emissions than US LNG whereas the difference measured for delivered and combusted fuel is 47.7%. The same pattern exists for fuel oil, which has 41.8% more GHG emission compared to US LNG when both are converted to electricity using weighted average heat rates.

Exhibit 3: Analysis for Delivered Fuels versus Conversion to Electricity

GWP = 28 *CH_4 Calib = 1*	LCA for Delivered Fuel: Base Case		Fuel Converted to Electricity: Base Case		
	CO_2e kg/MMBtu	Percent Difference from US LNG	Average Heat Rate (Btu/kWh)	CO_2e kg/MWh	Percent Difference from US LNG
US LNG	71.6	0.0%	7,690	550.3	0.0%
Coal	105.7	47.7%	9,680	1,023.2	85.9%
Fuel Oil	89.3	24.8%	8,736	780.5	41.8%

Note: This table is for the Study's Base Case. See Exhibit 42 to Exhibit 44 for similar tables for all cases.

- Another difference among studies is whether the so called "embodied GHG emissions" are being quantified and included. Embodied GHG emissions (as used here) are those associated with the manufacturing and construction of facilities, equipment and infrastructure used to produce, process and transport the LNG and alternative fuels to end-users. For example, the emissions associated with drilling and completing a gas well, including the emissions associated with producing and delivering all materials and equipment to the well site. For a gas pipeline, embodied emissions would be the GHGs associated with manufacture, production and delivery of all materials and equipment used to construct the pipeline and ancillary facilities and the emissions related to construction process itself. It is common for studies to ignore embodied emission since they are difficult to estimate and there are no universally accepted standards for estimating them when both existing and new infrastructure may be employed in the supply chain. For this analysis, ICF has calculated embodied emissions as if new infrastructure assets (e.g., pipelines, gas carriers) are built and their embodied emission are spread over the production/throughput volumes expected over the asset's expected useful life (typically 20 to 30 years). In the example LCA shown in Exhibit 1, embodied emissions for delivered LNG came to 0.95 CO_2e kg/Mcf or 1.3% of the total of 72.46 CO_2e kg/Mcf.

ES.3 Set Up of Cases Presented in this Study

- The analytic cases produced for this report include a Base Case that has a "methane release calibration" based on the EPA GHGI 2022 release rates by segment of the natural gas and oil supply chains. In recognition of the uncertainty in these estimates, Sensitivity Cases were created to determine the effect of increasing assumed methane releases by

44.6% (per Argonne National Laboratory (ANL) GREET[2] assumptions), by 88% (per International Energy Agency (IEA) estimates), and by 200% (per estimates derived from remote sensing surveys).

- The Base Case GWP value for methane is 28, which is based on the IPCC Fifth Assessment Report (AR-5) 100-year Biogenic Methane factor and is used now by EPA for the EPA GHGI and for the Greenhouse Gas Reporting Program survey of large GHG emitters. Sensitivity Cases were created to use the corresponding AR-5 20-year value of 84.[3]
- The Study's Base Case includes "embodied GHGs" associated with the manufacturing and construction of facilities, equipment and infrastructure used to produce, process and transport the LNG and alternative fuels to end-users. A Sensitivity Case excludes them to provide a more direct comparison to studies that do not include embodied emissions.
- The world GHG emission impact of US LNG exports in 2022 was calculated in the Study by estimating the supply chain GHG to produce LNG and ship it from each US exporting facility to each country that received LNG from that facility in 2022.
- Using IEA data on energy consumption by country and sector, this Study estimated how much natural gas (and US LNG) and other fuels were used in each sector of each importing country. For each energy source, this Study estimated GHG emissions for both the "delivered to end use gate" and "end-use energy services gate" concepts.

ES.4 Results from the Cases

- Employing a counterfactual assumption that no US LNG was produced or traded in 2022, the Study estimated how much alternative fuels and electricity would have substituted for the unavailable US LNG. For all but one of the Cases (Sensitivity #10), this substitution was conducted assuming that the disruption to US LNG supplies would have taken place over several years and that medium-term demand elasticities would allow substitution to many kinds of alternative fuels including renewable energy. The Study then calculated the GHG associated with those substitute energy sources.
  - Coal is estimated to supply 2,186 trillion Btu (TBtu), or 53.9% of the 4,058 TBtu of unavailable energy in US LNG.
  - Substitution by fuel oil and other petroleum products is estimated as 1,381 TBtu, or 34% of the unavailable energy in US LNG.
  - Substitution by domestically produced natural gas (in importing countries that have natural gas production) is estimated to contribute 16.3%, or 662 TBtu, of the unavailable energy in US LNG.
  - Primary renewable energy and waste fuel is estimated to have contributed 317 TBtu, or 7.8% of the energy in the unavailable US LNG.
  - Total primary energy summed across all fuels goes up by 489 TBtu. This occurs primarily because the heat rates of non-gas power plants are greater than those of

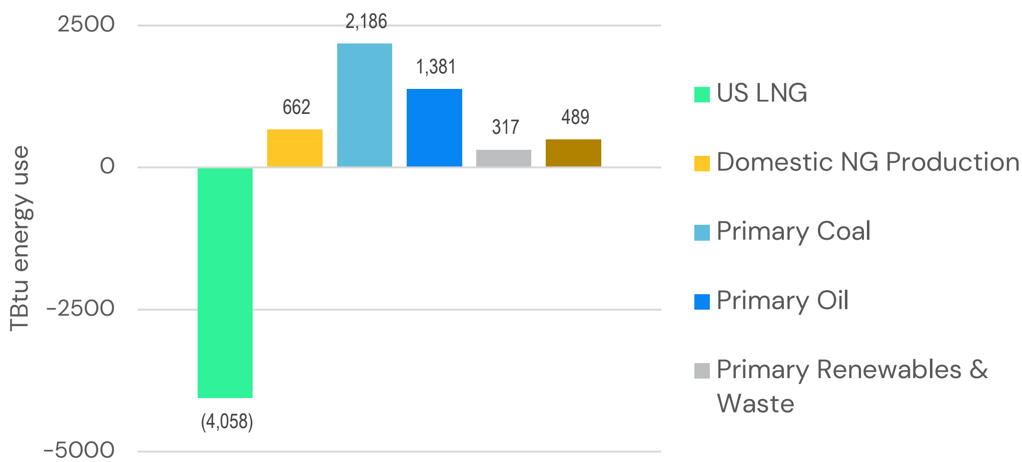
---

[2] Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model (GREET) model was developed under sponsorship of DOE to examine the lifecycle impacts of efficiency technologies and energy systems. GREET now has more than 40,000 registered users worldwide. See GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model | Argonne National Laboratory (anl.gov)

[3] Since methane oxidizes in the atmosphere and turns into CO_2, its global warming impact is greater in the years immediately after it is released as compared to decades later. Therefore, if averaged over 100 years, the methane GWP is estimated as 28 times CO_2 while if averaged over the first 20 years (when the methane is mostly still methane) the impact is estimated as 84 times CO_2.

gas-fired power plants. The second reason is that the direct use of natural gas in many applications requires less primary energy than substitute electric technologies if electricity generation has high heat rates and associated transmission and distribution losses.

Exhibit 4: Estimated Shift in Global Primary Fuel Use, 2022 Base Case



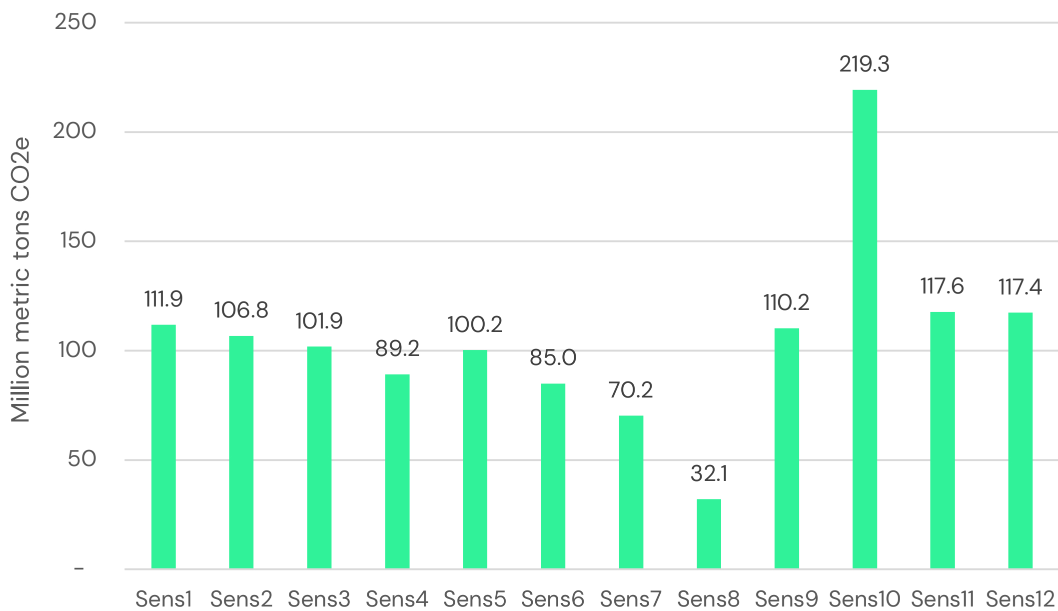
- In total, 12 Cases were analyzed including the Base Case (Case #1) and 11 Sensitivity Cases for which assumptions were varied as summarized in Exhibit 5. The first four Cases (#1 to #4) are based on a methane GWP of 28 and the following four cases (#5 to #9) use a methane GWP of 84. Within each set of four cases, the "CH_4 Release Calibration" for oil and natural gas supply chains are assumed to range from the values estimated in the EPA GHGI as a combined rate of 1.33% (for production, gathering & boosting, gas processing, gas transmission plus gas distribution) up to three times those values, or a combined release rate of 3.99%. These are shown in the table as ratios to the EPA GHGI of 1.0, 1.446, 1.88 and 3.0, respectively. Also shown in the table in the last column are the modelling results of the Cases in terms of how much each million Btu of US LNG exports reduces world GHG emissions. All Cases show that US LNG exports reduce world GHG emissions. This statistic (which can also be expressed in terms of how much world GHG emissions would go up in the absence of US LNG exports) is discussed more fully below.

Exhibit 5: Assumptions Used Across Study Cases and Resulting Reductions in World GHG Emissions

Sensitivity#	Embodied Added?	CH4 Release Calibration	CH4 GWP Basis AR5	Substitutability by Renewables	Study Result: Net Emission Rate Reduction in World GHG (CO_2e kg/MMBtu of US LNG)
1 - Base Case	w/Embodied	1.000	AR-5, 100-year	1	27.5
2	w/Embodied	1.446	AR-5, 100-year	1	26.3
3	w/Embodied	1.880	AR-5, 100-year	1	25.1
4	w/Embodied	3.000	AR-5, 100-year	1	21.9
5	w/Embodied	1.000	AR-5, 20-year	1	24.8
6	w/Embodied	1.446	AR-5, 20-year	1	21.1
7	w/Embodied	1.880	AR-5, 20-year	1	17.4
8	w/Embodied	3.000	AR-5, 20-year	1	8.0
9	w/o Embodied	1.000	AR-5, 100-year	1	27.1
10	w/Embodied	1.000	AR-5, 100-year	0	54.0
11	w/Embodied	0.496	AR-5, 100-year	1	29.0
12	w/Embodied	0.496	AR-5, 20-year	1	29.1

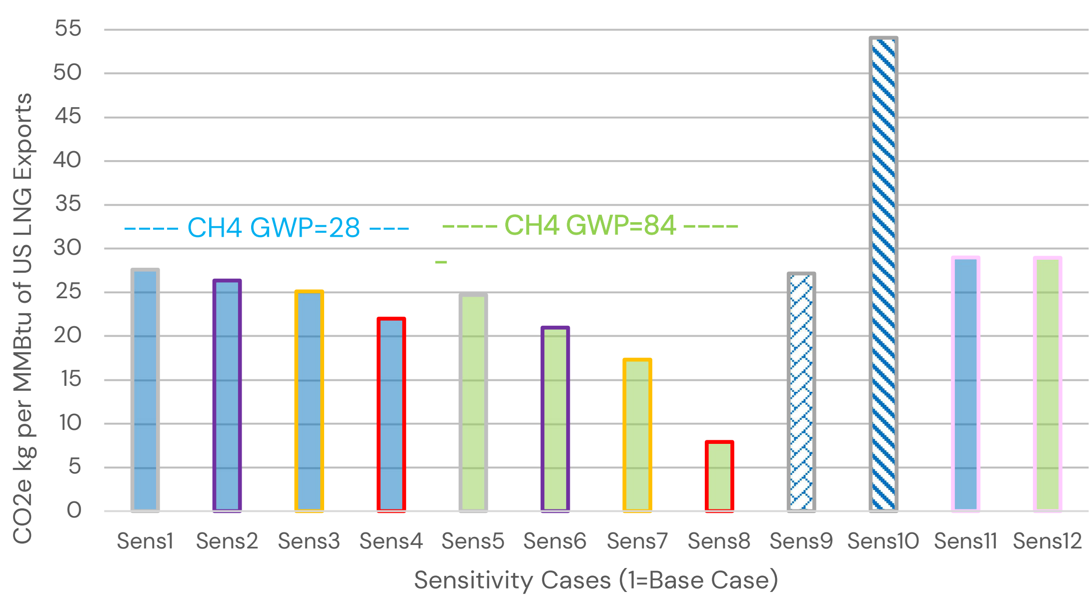
- Sensitivity Case #9 is the same as the Base Case, except that Embodied Emissions are removed from LNG and all competing fuels. Likewise, Sensitivity #10 is the same as the Base Case except that it assumes that there is little opportunity to switch to renewable or waste energy either because the counterfactual disruption to US LNG supply were to occur abruptly or the expansion of renewables and waste fuels were assumed to be already taking place at the maximum possible rate. For this Sensitivity #10, switching to renewables and waste fuels does not occur and the difference is made up by more use of coal, petroleum products and domestic natural gas.
- The last two Sensitivity Cases use the "Progress 2030" assumption that methane emissions along the natural gas supply chain will decline in the next few years. These reductions are expected to result from several factors including EPA and Pipeline and Hazardous Materials Safety Administration (PHMSA) regulations, the effects of the Inflation Reduction Act's (IRA) Waste Emission Charge, the demands from gas purchasers for low-emission gas sources, equipment turnover and voluntary industry actions. For these sensitivities, a reduction in the methane release rate of approximately 60% is assumed to occur by 2030. There are two Sensitivities that apply "Progress 2030" levels of methane releases: Sensitivity Case #11 uses a methane GWP of 28 and Sensitivity Case #12 uses a methane GWP of 84.
- As shown in Exhibit 6, the net impact of US LNG in the Base Case was to decrease 2022 world GHGs by 111.9 million metric tons compared to the estimated mix of alternative fuels. Among the 11 Sensitivity Cases, the net GHG reductions from US LNG ranged from 32.1 to 219.3 million metric tons per year. The lowest impact of 32.1 million tons per year occurs with Sensitivity #8 which combines a methane GWP of 84 with the highest modeled methane release calibration of three times the EPA GHGI values. The largest impact of 219.3 million tons per year occurs with Sensitivity #10 wherein no switching to renewables or waste fuels occurs and, as a result, there is more dependence on coal and fuel oils. All the cases examined here show that the US LNG exports result in a net reduction in the world's GHG emissions compared to the use of the estimated mix of alternative fuels.

Exhibit 6: Increase in GHG Emissions Caused by Removing US LNG Exports (2022)



- Exhibit 7 shows the net GHG impacts of US LNG in units of kilograms of GHG reduction per million Btu of US LNG exports. Because the natural gas supply chain has more methane releases as compared to the alternative fuels, the increase in emissions caused by having to substitute for US LNG declines when one assumes higher methane release rates and larger methane GWPs. In the Base Case, the net positive impact of US LNG is 27.5 CO_2e kg/MMBtu of US exported LNG and this falls to as low as 8.0 in the Sensitivity Case #8.

Exhibit 7: Net Impacts in GHG Measured per Unit of US LNG Exports (2022)

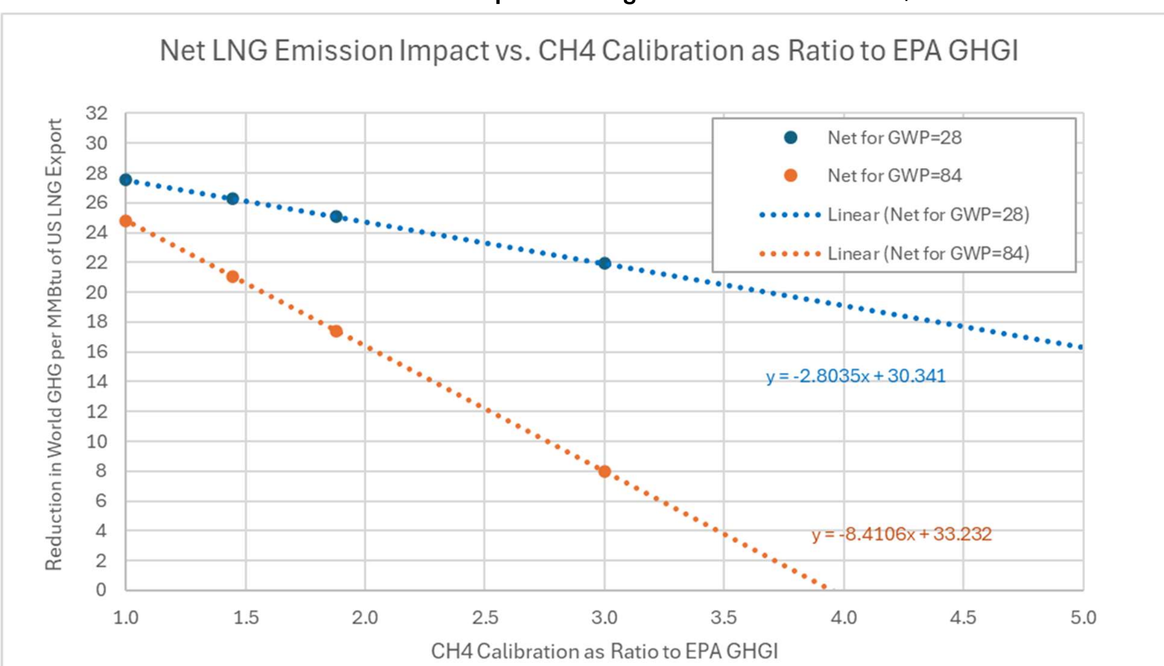


Note: The colored border of each column represents the methane release calibration used. Grey indicates a calibration value of 1, purple uses 1.446, orange uses 1.88, red uses 3.0, and pink uses 0.496.

ES.5 Estimate of “Breakeven” Methane Release Rates

- Exhibit 8 depicts another way to show the effects of the assumed methane GWP of 28 or 84 and methane release calibration values ranging from 1 to almost 4. The blue dots represent the Sensitivity Cases #1 to #4, which are based on a methane GWP of 28. The blue dashed line is a regression line through those points. The orange dots and orange dashed line correspond to Sensitivity Cases #5 to #9, which use a methane GWP of 84. The x-axis of the chart is the methane release calibration value expressed as a ratio to the 2022 EPA GHGI for oil and gas systems. For each of the GWP assumptions, the four related Sensitivity Cases fall in a straight line.
- For the methane GWP of 28, the straight line crosses the x-axis at a value of 10.82 times the EPA GHGI methane release value. In other words, with a methane GWP of 28, methane releases could be up to 10.82 times higher than what is stated in the EPA GHGI and US LNG still would reduce worldwide GHG emissions compared to the mix of alternative fuels that would most likely substitute for the US LNG. This point is sometimes referred to as the “breakeven point” since that is where the GHGs from US LNG would equal those of alternative fuels.
- The regression line for the cases with a methane GWP of 84 is steeper and crosses the x-axis at 3.95 times the EPA GHGI methane release values. This means that methane releases could be up to nearly four times higher than EPA estimates and the export of US LNG would still reduce the worlds GHG emissions when the global warming potential of one mass unit of methane is assumed to be 84 times that of carbon dioxide. In other words, for a GWP of 84 the breakeven point for US LNG is 3.95 times the EPA GHGI methane release values for oil and gas systems.

Exhibit 8: Net LNG Emissions Impacts Using Various EPA GHGI CH_4 Calibrations



- It is noteworthy that US LNG exports can be shown to have benefits of reduced worldwide GHG emissions even when both a high methane GWP is applied and methane calibration values of three or more times the EPA GHGI are used. This occurs in large part because these same methane-related assumptions also affect the LCA GHG values of petroleum products, domestically produced natural gas in the importing countries, and to a lesser extent domestic and imported coal. The LCA of coal is affected because coal mine fugitive emissions are subject to any increases in the methane GWP and the emissions attributable to the uses of petroleum products and electricity for coal mining, processing, and transportation are affected when the methane GWP or the methane calibration for oil and gas operations are changed. These effects are shown in Exhibit 9 which depicts the average LCA values for US LNG delivered to large customers, domestic natural gas delivered to large customers, delivered coal, and delivered petroleum products (chiefly residual and distillate fuel oils).

Exhibit 9: LCA Factors for All Fossil Fuels are Affected by GWP and Methane Release Assumptions

	Calculated CO_2e kg/MMBtu (Higher Heating Value) all Countries 2022				
Sensitivity#	Imported US LNG (CO_2e kg/MMBtu)	Domestic NG Prod. (CO_2e kg/MMBtu)	Coal (CO_2e kg/MMBtu)	Oil (CO_2e kg/MMBtu)	Renewables & Waste (CO_2e kg/MMBtu)
1 Base Case	71.6	64.5	105.7	89.3	15.6
2	73.4	66.2	105.7	90.2	15.6
3	75.2	67.8	105.8	91.0	15.6
4	79.8	72.1	105.8	93.2	15.6
5	80.1	72.3	112.2	92.4	15.6
6	85.6	77.4	112.3	95.0	15.6
7	91.0	82.3	112.4	97.5	15.6
8	104.8	95.2	112.6	103.9	15.6
9	70.4	63.3	104.9	88.2	7.7
10	71.6	64.5	105.6	89.4	15.3
11	69.5	62.5	105.7	88.4	15.6
12	73.8	66.5	112.1	89.5	15.6

ES.6 Potential Impact of Expected Growth in US LNG Exports

- The Study estimates for all of the Cases presented here reflect 2022 actual exports of US LNG. Looking to the future, DOE's Energy Information Administration in its 2023 Annual Energy Outlook Reference Case expects US LNG exports to grow from 3,959 bcf in 2022 to 6,880 bcf by 2030. That is an expected increase of 74% in annual export volumes over eight years.

☐ *DOE's Energy Information Administration expects US LNG exports to increase by 74% by 2030.*

- Thus, if all other assumptions are held constant, the benefits of US LNG exports could be 74% greater in the year 2030 due to there being a larger demand for US LNG. For example, if the net Base Case impact were to remain at 27.5 CO_2e kg/MMBtu of US LNG exports, the reduction in the world's GHG that could be attributed to US LNG exports in 2030 would reach 194 million tons of CO_2e per year. Applying the full range of impacts estimated in the Sensitivity Analyses (8.0 to 54.0 CO_2e kg/MMBtu of US LNG exports), the reduction in the world's GHG emissions that could be attributed to US LNG exports in 2030 would be projected to be between 56 and 381 million tons of CO_2e per year.

ES.7 Comparisons to Other Studies

- This Study contains a literature review of life cycle assessments to compare the results and assumptions of other studies to those of this Study. This review included prominent studies, models, and databases that contain emission calculations related to the production and supply of natural gas, LNG and other fuels. This literature review also provided an illustration of the impact that the assumptions, methodology, and scope considered in each study have on the determined results. Details of this review are contained in Chapter 6 of this Study.
- One study which has received public attention (including from the White House when it announced its "Temporary Pause on Pending Approvals of Liquefied Natural Gas Exports" on January 26, 2024[4]) is a 2023 LCA analysis published by Robert Howarth of Cornell University.[5] The study quantifies LCA emissions generated from the supply chain used to export domestically produced natural gas as LNG. The study states that:

  > *The greenhouse gas footprint of LNG is always substantially larger than for natural gas consumed domestically (regardless of time scale), because of the large amount of energy needed to liquefy and transport the LNG. Greenhouse gas emissions from LNG are also larger than those from domestically produced coal, ranging from 28% to 2-fold greater for the average cruise distance of an LNG tanker, evaluated on the 20-year time scale. Even when evaluated on the 100-year time scale, emissions from LNG range from being equivalent to coal to being 64% greater.*

  These conclusions by Howarth are not supported by this Study and are contradicted by other similar analyses including those conducted by DOE's NETL and the National Petroleum Council. Several methodological choices and assumptions implemented by Howarth result in emissions for LNG that are higher than those of this Study.
- Exhibit 10 provides a comparison of emissions between the Howarth study and in a similar scenario (e.g., for a one-way shipping distance of 10,066 nautical miles and using national average methane release rates) under this Study's Base Case assumptions. The Howarth results - converted to a methane GWP of 28 and expressed in units of CO_2e kg/MMBtu higher heating value – are 99.84 CO_2e kg/MMBtu while the corresponding value using this Study's Base Case assumption are 75.23 CO_2e kg/MMBtu – a difference of 33%. The major points of difference and the apparent reasons for these differences are:
  - Methane releases from upstream and midstream segments (production, gathering and boosting, gas processing, plus gas transmission and storage) are 13.50 CO_2e kg/MMBtu higher in the Howarth assessment - representing 54.8% of the total difference. This result comes from using a higher methane release calibration value that is roughly

[4] FACT SHEET: Biden-Harris Administration Announces Temporary Pause on Pending Approvals of Liquefied Natural Gas Exports | The White House
[5] The Greenhouse Gas Footprint of Liquefied Natural Gas (LNG) Exported from the United States; Howarth, 2023; Cornell University

equivalent to three times the EPA GHGI value - an assumption that is similar to the methane calibration value used in this Study's Sensitivities #4 and #8. While such an assumption can be considered to be within the outer ranges of uncertainty for methane releases from oil and gas systems, it may not be appropriate as a "best estimate" to be used for policy decisions. For example, the ANL GREET Model – which has been designated by Congress in the IRA and by the IRS[6] as the basis for determining 45V hydrogen tax credits - uses a methane calibration value of 1.446, or less than half of the Howarth assumption.

- Carbon dioxide emissions from upstream and downstream segments are 9.68 CO_2e kg/MMBtu higher in the Howarth estimates and represent 39.3% of the total difference. Howarth's referenced source for this value is a New York State report (see Chapter 6) that applies to gas delivered to that state. Since New York has no LNG export terminals, that reference is not particularly relevant. Moreover, the value itself is unusually high. Compared again to the ANL GREET model, the Howarth calculations for upstream and downstream carbon dioxide emissions are about twice the GREET values.

Exhibit 10: Comparison of Howarth LNG Analysis and Base Case Assumptions

Howarth World Average Distance Case Results				
Howarth, 2-stroke engine tankers powered by LNG, 10,066 nm one-way	**CO2 (kg/MMBtu HHV)**	**CH4 (kg/MMBtu HHV)**	**CH4 (CO2e kg/MMBtu HHV, GWP=28)**	**All CO2e (kg/MMBtu HHV, GWP=28)**
Upstream & midstream emissions	14.15	0.68	18.98	33.13
Liquefaction	7.05	0.02	0.50	7.54
Emissions from tanker	3.55	0.05	1.39	4.94
Final transmission & distribution	0.00	0.06	1.71	1.71
Combustion by final consumer	52.51	0.00	0.00	52.51
Total	**77.26**	**0.81**	**22.58**	**99.84**

Results of this Study, Base Case Assumptions				
10,066 nm one-way, open rack re-gasifier	**CO2 (kg/MMBtu)**	**CH4 (kg/MMBtu)**	**CH4 (CO2e kg/MMBtu, GWP=28)**	**All CO2e (kg/MMBtu, GWP=28)**
Upstream & midstream emissions	4.47	0.20	5.48	9.95
Liquefaction	5.71	0.00	0.07	5.77
Emissions from tanker	6.00	0.02	0.54	6.54
Final transmission & distribution	0.24	0.00	0.10	0.33
Combustion by final consumer	52.50	0.00	0.14	52.64
Total	**68.91**	**0.23**	**6.32**	**75.23**

[6] Treasury Sets Out Proposed Rules for Transformative Clean Hydrogen Incentives | Clean Energy | The White House

- The high end of Howarth's comparison range (i.e., LNG is 28% to 2-fold greater than coal for the average cruise distance LNG) comes from comparing coal to LNG shipped by a steam-powered LNG carrier that uses bunker fuel for power and releases boil-off gas to the atmosphere. Such a configuration would have never made economic sense since the boil-off gas can be readily used as fuel in the carrier's boiler. As importantly, steam-powered carriers are the oldest and least fuel-efficient ships in the world's LNG carrier fleet and are used for only 2% of the ton-miles of US export shipments. (See Exhibit 28: Summary of U.S. LNG Shipping Operations 2022) Therefore, the shipping scenario that yields the "2-fold greater" result is improbable and, in any case, nearly irrelevant for the US from which steam carriers are seldom used.
- As stated above, the end-use application of the fuel should be considered when LCA emissions are being compared between LNG and alternative fuels. One notable methodological error by Howarth is that he compares the GHG LCAs of LNG and coal on the basis of combustion of delivered fuel without considering fuel efficiency differences. As was shown earlier in Exhibit 3, accounting for fuel efficiencies has a noticeable impact on emission results in the case of power generation (the most important end-use comparison between LNG and coal), where natural gas-fired power plants are more efficient than coal power plants.
- In summary, the Howarth results should be considered with caution because:
  - The methane release values employed by Howarth for the LNG supply chain are at the high end of the uncertainty range and may not be appropriate as a "best estimate" to be used for policy decisions.
  - Howarth's estimates for carbon dioxide emissions from upstream and downstream segments are contradicted by the "bottom up" estimates presented in this report and values estimated in the ANL GREET model.
  - The steam carrier shipping scenario that produces the high end of Howarth's comparison with coal is improbable and, in any case, nearly irrelevant for the US where steam carriers are seldom used.
  - The most appropriate way to compare using US LNG versus other fuels is to take into account relative fuel efficiencies. In the power sector, this means that approximately 1.26 Btu's of coal or 1.14 Btu's of fuel oil must be burned to replace each Btu of LNG. By not taking this into account, Howarth miscalculates the relative GHG impacts of coal and fuel oil compared to LNG.