# The Greenhouse Gas Footprint of Liquefied Natural Gas (LNG) Exported from the United States

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## Abstract

LNG exports from the US were banned before 2016, but today the US is the largest LNG exporter globally. Greenhouse gas emissions depend on the type of tanker used to transport the LNG, being far larger for transport by older tankers burning fuel oil, with emissions dominated by venting of methane by “boil off” evaporation. More modern tankers can capture boil-off methane and use it for their power, thereby lowering methane emissions. For these more modern tankers (more than 80% of the LNG tanker fleet), the largest greenhouse gas emissions are from the production, processing, storage, and transport of the natural gas used to make the LNG. Methane emissions are particularly important, but so are carbon dioxide emissions from the energy intensive processes behind shale gas extraction. In all of the scenarios considered, these upstream emissions exceed the emissions of carbon dioxide from the final combustion of LNG when methane is compared to carbon dioxide on a time period of 20 years. Also, emissions of unburned methane (again considered on the 20-year period) exceed emissions of carbon dioxide from the final combustion of LNG. Methane appears less important when viewed over a 100-year time period, but that time period understates the climate influence of methane. 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.

## Introduction

In this paper, I analyze the greenhouse gas footprint of liquefied natural gas (LNG) produced in and exported from the United States. The United States prohibited the export of LNG before 2016, but since the lifting of the ban at that time, exports have risen rapidly (DiSavino 2017). In 2022 the United States became the largest exporter of LNG globally (EIA 2023-a). Exports doubled between 2019 and 2023, and if allowed by the United States government, LNG exports were predicted to double again over the next four years (Joselow and Puko 2023). As of 2022, the LNG exported from the United States represented almost 20% of all global LNG transport (based on US export of 104.3 billion $m^3$ and total global transport of 542 billion $m^3$; Statista 2023-a, 2023-b). In January of 2024, President Biden placed a moratorium on increasing exports of LNG pending further study of the consequences of such exports, including the analysis of greenhouse gas emissions (Carbon Brief 2024). An earlier version of my analysis presented in this paper was used by the White House as evidence for the need for greater study on the greenhouse gas emissions from LNG, particularly methane emissions (Clarke 2024).

Proponents of increased exports of LNG exports from the United States have often claimed a climate benefit, arguing that the alternative to the increased export of LNG both to Europe and Asia would be greater use of coal produced domestically in those regions (Sneath 2023; Joselow and Puko 2023). In fact, even though carbon dioxide emissions are greater from burning coal than from burning natural gas, methane emissions can more than offset this difference (Howarth et al. 2011; Howarth 2014; Howarth and Jacobson 2021; Gordon et al. 2023). As a greenhouse gas, methane is more than 80 times more powerful than carbon dioxide when considered over a 20 year period (IPCC 2021), and so even small methane emissions can have a large climate impact. Clearly, greenhouse gas emissions from LNG must be larger than from the natural gas from which it is made, because of the energy needed to liquefy the gas, transport the LNG, and re-gasify it. The liquefaction process alone is highly energy intensive (Hwang et al. 2014; Pace Global 2015). A full lifecycle assessment is required to determine how much greater the magnitude of these LNG greenhouse gas emissions are.

There are relatively few full lifecycle assessments of greenhouse gas emissions from LNG in the peer-reviewed literature, and as far as I am aware, none since the start of export of LNG from the United States in 2016 (Tamura et al. 2001; Okamura et al. 2007; Abrahams et al. 2015), although the US Department of Energy produced an updated, non-peer-reviewed assessment in 2019 (NETL 2019). Some prior assessments did not consider upstream emissions of methane from the production and use of natural gas, and none of the peer-reviewed studies have considered the emissions of carbon dioxide associated with the production, processing, and transport of the natural gas used to make LNG, although this is included in NETL (2019). Most natural gas production in the United States is shale gas produced by high volume hydraulic fracturing and high-precision directional drilling, two technologies that only began to be used commercially to develop shale gas in this century (Howarth 2019, 2022-a). It is the rapid increase in shale gas production in the United States that has allowed and driven the increase in export of LNG (Joselow and Puko 2023). As shown in Figure 1, production of natural gas in the United States was relatively flat from 1985 to 2005. Since then, production has risen rapidly, driven almost entirely by the production of shale gas. The United States was a net importer of natural gas from 1985 to 2015, with net exports as LNG only since 2016 driven by production in excess of domestic consumption. Shale gas production is quite energetically intensive, and the related emissions of carbon dioxide need to be considered in any full lifecycle assessment of LNG. Further, methane emissions from shale gas can be substantial. Since 2008, methane emissions from shale gas in the United States may have contributed one third of the total (and large) increase in atmospheric methane globally (Howarth 2019, 2022-a).

The types of ships used to transport LNG have been changing in recent years, and the global fleet now consists of both steam-powered tankers and tankers powered by internal-combustion engines, including both 2-stroke and 4-stroke engines (Huan et al. 2018; Bakkali and Ziomas 2019; Pavlenko et al. 2020). In general, tankers powered by steam engines and 4-cycle engines are dual fuel and can burn either LNG or fuel oils. Older tankers powered by 2-stroke engines are not capable of burning LNG and use only fuel oils. Modern tankers powered by 2-stroke engines are dual fuel and can burn LNG as well as fuel oils. My analysis considers four different types of tankers: 1) old vessels that burn only heavy fuel oil; 2) steam-powered vessels that can use either fuel oil or methane from the boil off of LNG; 3) modern tankers built over the past 20 years that are powered by 4-cycle engines capable of using fuel oil, diesel oil, or methane from LNG boil off; and 4) very modern tankers powered by 2-cycle engines capable of using either fuel oil or boil off. Boil off is the evaporative loss of methane due to some heat leakage through insulation and into the tanks that hold LNG.

The LNG tanker fleet today is dominated by tankers that can burn LNG, including steam-powered engines (approximately 50% of the fleet) and 4-stroke engines (a little over 30% of the fleet; Bakkali and Ziomas 2019; Pavlenko et al. 2020). Old tankers driven by 2-stroke engines that burn only fuel oil are approximately 10% of the fleet (Bakkali and Ziomas 2019). There are very few of the modern tankers powered by dual-fuel 2-stroke engines: as of 2019, one was in construction and another four were planned (Bakkali and Ziomas 2019; Pavlenko et all. 2020). These dual-fuel 2-stroke tankers are likely to become more common in the future because of their high fuel efficiencies (Huan et al. 2018; Pavlenko et al. 2020). As of 2020, LNG supplied more than 80% of the fuel for all LNG tankers, with fuel oils contributing the rest (IMO 2021). Emissions of both carbon dioxide and methane vary significantly across these different tankers and fuels. For example, older tankers that burn heavy fuel oils are more likely to vent unburned methane from boil off to the atmosphere. More modern tankers can capture and use the LNG, and thus vent less boil-off methane (Bakkali and Ziomas 2019). Tankers powered by 4-stroke and 2-stroke engines are more efficient in their fuel use than are steam-powered tankers, and so have lower carbon dioxide emissions (Bakkali and Ziomas 2019; Pavlenko et al. 2020). However, when they burn LNG as a fuel, some methane slips through unburned and is emitted in the exhaust gases (Pavlenko et al. 2020; Balcombe et al. 2021). These differences in emissions from tankers are a major focus of the analysis I present here. My analysis relies heavily on three recent, comprehensive assessments of the use of LNG as a marine fuel (Pavlenko et al. 2020; Balcombe et al. 2021; Rosselot et al. 2023)

Here, I present a full lifecycle assessment for the LNG system, from the production of shale gas that provides the feedstock through to combustion by the final consumer. My analysis focuses on emissions of carbon dioxide and methane and excludes other greenhouse gases such as nitrous oxide that are very minor contributors to total emissions for natural gas and LNG systems (Howarth 2020; Pavlenko et al. 2020). Included are emissions of carbon dioxide and methane at each step along the supply chain, including those associated with the production, processing, storage, and transport of the shale gas that is the feedstock for LNG (referred to as upstream and midstream emissions), emissions from the energy used to power the liquefaction of shale gas to LNG, emissions from the energy consumed in transporting the LNG by tanker, emissions from the energy used to re-gasify LNG to gas, and emissions from the delivery of gas to and combustion by the final consumer. For upstream and midstream methane emissions, I rely on a very recent and comprehensive analysis that used almost one million measurements in the United States (Sherwin et al. 2024). As with some other prior lifecycle assessments for LNG, I explicitly compare the emissions from LNG to those for coal (Abrahams et al. 2015; NETL 2019).

## Methods

Calculations use net calorific values (also called lower heating values). Note that the use of net calorific values is standard in most countries, but the United States uses gross calorific values. Emissions expressed using net calorific values are 10% greater than when using gross calorific values (Hayhoe et al. 2002; Howarth et al. 2011; Howarth 2020). LNG and heavy fuel oils are assumed to have energy densities of 48.6 MJ/kg and 39 MJ/kg respectively (Engineering Toolbox 2023). I convert methane emissions to carbon dioxide equivalents using a 20-year Global Warming Potential ($GWP_{20}$) of 82.5 and a 100-year $GWP_{100}$ of 29.8 (IPCC 2021).

Upstream plus midstream emissions:

Upstream plus midstream emissions of both carbon dioxide and methane are based on the total quantity of natural gas and other fuels consumed in the LNG endeavor. In addition to the natural gas burned by the final consumer, natural gas and LNG are burned to provide the energy required for the liquefaction, tanker transport, and regasification processes. The upstream and midstream emissions include emissions in the gas development fields as well as from storage and processing plants and from the high-pressure pipelines that bring natural gas to LNG liquefaction facilities. The following two equations give the upstream plus midstream emissions for methane and carbon dioxide respectively in units of g of methane and g of carbon dioxide per kg of LNG burned by the final consumer:

Equation 1 $$CH_4 = [(0.028)*(1.028)*(1{,}000 \text{ g } CH_4/\text{kg}) * \mathbf{LNG.tot}] + [\mathbf{Heavy.fuel.oil} * (3.9 \text{ g } CO_2/\text{kg oil})]$$

Equation 2 $$CO_2 = [(612 \text{ g } CO_2/\text{kg LNG}) * \mathbf{LNG.tot}] + [\mathbf{Heavy.fuel.oil} * (616 \text{ g } CO_2/\text{kg oil})]$$

where **LNG.tot** is the total mass of methane gas consumed or emitted, including not only from the final combustion of the fuel but also upstream and midstream, during liquefaction to produce LNG, during transport of LNG in tankers, and emitted from pipelines transporting gas from the LNG destination port to the final consumer. **Heavy.fuel.oil** is the quantity of fuel oil consumed by ships (for those ships that use fuel oil as their primary source of energy) divided by the total quantity of LNG delivered per voyage, in units of kg oil/kg LNG. The calculations for **LNG.tot** and for **Heavy.fuel.oil** are shown below in equations #3 and #10.

The methane emission factor for natural gas of 0.028 (2.8% of gas production) used in equation #1 is based on a very recent and comprehensive analysis for upstream and midstream emissions in the United States that combines a very large data set of observations taken by aircraft flyovers with empirically derived simulations (Sherwin et al. 2024). Here, we use their estimates for the Permian Basin, and weigh the upstream emissions by the portion of energy produced as natural gas compared to oil, as recommended by Sherwin et al. (2024). Details are provided in Supplemental Table A and supporting on-line only text. The vast majority of LNG exports from the United States are from Texas and Louisiana (EIA 2023-a). The Permian Basin and similar oil-associated gas fields are providing most of the gas used for these LNG exports, a trend that is predicted to continue because of proximity (EIA 2022-a, 2022-b, 2023-b). Methane emissions from producing fuel oil are estimated as 0.10 g $CH_4$/MJ (NETL 2008; Howarth et al. 2011). With an energy density of 39 MJ/kg for fuel oil, this is equivalent to 3.9 g $CH_4$/kg oil. The emission factors for indirect carbon dioxide emissions in equation #2 are 612 g $CO_2$/kg LNG for natural gas and 616 g $CO_2$/kg oil for fuel oil (DEC 2021, table A.1, converted to net calorific and metric units, and expressed per mass of fuel using the energy densities provided above). These indirect carbon dioxide emissions are from the energy used to explore and drill gas and oil wells, hydraulicly fracture the wells, and process, store, and transport the fuels.

The total mass of methane burned to carbon dioxide or emitted as methane over the entire life cycle for LNG is calculated in equation #3:

Equation 3 **LNG.tot** = (1 kg/kg LNG) + **LNG.liq** + **LNG.ship** + **Vent.boil.off** + (0.0032 kg/kg LNG)

where 1 kg/kg LNG is the quantity of LNG burned by the final consumer. **LNG.liq** is the total mass of methane gas consumed or emitted during the liquefaction process, **LNG.ship** is the mass of gas consumed by a tanker as fuel (for those tankers that burn LNG) divided by the mass of LNG delivered, in units of g $CH_4$/kg LNG delivered to the destination port. **Vent.boil.off** is the mass of methane vented to the atmosphere by tankers from the evaporative loss of methane from the LNG tanks (for those tankers that cannot burn LNG) divided by the mass of LNG delivered to the destination port, in units of g $CH_4$/kg LNG. The value of 0.0032 kg/kg LNG is the methane emitted during pipeline transportation from the LNG terminal to the electric plant where the gas is finally consumed. As is discussed below, my analysis is for the case where LNG is used to produce electricity in the destination country, and the value of 0.0032 kg/kg LNG is for high-pressure delivery pipes from the LNG terminal to an electric plant (Alvarez et al. 2018). Emissions in the destination country would be substantially higher for the case of delivery of gas to homes and commercial buildings for heating (Howarth 2022-b).

The calculations for **LNG.ship** is shown below in equation #8. The calculation for **Vent.boil.off** is described below equation #9. **LNG.liq** is calculated by summing the mass of methane burned to produce the $CO_2$ emissions for liquefaction shown in equation #4 below (converted from mass of $CO_2$ to mass of $CH_4$ by diving by 44 g/mol and multiplying by 16 g/mol) and the mass of methane emitted during liquefaction shown in equation #5 below (converted to units of kg/kg LNG).

## Emissions at liquefaction plants:

A substantial amount of energy is required to liquefy methane into LNG, and this energy is provided by burning natural gas. That is, natural gas is both the feed source and energy source used to produce LNG (Hwang et al. 2014). Equations #4 and #5 show the emissions of methane and carbon dioxide from the liquefaction process, in units of g $CH_4$/kg LNG burned by the final consumer and g $CO_2$/kg LNG burned by the final consumer. Note that emissions of both methane and carbon dioxide from the liquefaction process are larger when expressed per kg of final consumption than per kg of LNG liquefied.

Equation 4 $$CH_4 = (3.5\ \text{g}\ CH_4/\text{kg LNG}) * (1\ \text{kg/kg LNG} + \mathbf{LNG.ship} + \mathbf{Ven.boil.off} + 0.0032\ \text{kg/kg LNG})$$

Equation 5 $$CO_2 = (270+57+18\ \text{g}\ CO_2/\text{kg LNG}) * (1\ \text{kg/kg LNG} + \mathbf{LNG.ship} + \mathbf{Vent.boil.off} + 0.0032\ \text{kg/kg LNG})$$

These two equations are simply multiplying emission factors applicable to the liquefaction process by the total amount of LNG that is transported away from the liquefaction plant in tankers, including LNG burned by the final consumer, LNG burned or emitted by tankers, and methane emissions from pipelines in the destination country that carry gas to the final consumer. As noted for equation #3 above, the value of 1 kg/kg LNG represents the LNG burned by the final consumer, and the value of 0.0032 kg/kg LNG is the methane emitted during pipeline transportation from the LNG terminal to the electric plant where the gas is finally consumed (Alvarez et al. 2018).

For equation #4, 0.88 g $CH_4$/kg LNG is the total rate of release of unburned methane during liquefaction and for regasification based on recent measurements made by Innocenti et al. (2023). This is much lower than generally estimated for such emissions. For example, the mean from the review by Balcombe et al. (2021) was 3.5 g $CH_4$/kg LNG. However, the documentation behind most prior estimates is poor compared to the data presented by Innocenti et al. (2023). Nonetheless, these measurements may represent a best case since they required the cooperation from owners of the LNG facilities (Frank 2023). Thus my analysis is likely quite conservative in choosing this low rate of methane emission. For equation #5, the values 270 g $CO_2$/kg LNG, 57 g $CO_2$/kg LNG, and 18 g $CO_2$/kg LNG are respectively the quantities of carbon dioxide emitted from burning gas to power liquefication, from the $CO_2$ that was in the natural gas before processing, and from carbon dioxide produced from flaring. Carbon dioxide emissions from the combustion of the gas powering the plants have been measured at many facilities in Australia, Alaska, Brunei, Malaysia, Indonesia, Oman, and Qatar, with emissions varying from 230 to 410 g CO2/kg of LNG liquefied (Tamura et al. 2001; Okamura et al. 2007). Here, I use the mean estimate of 270 g CO2/kg LNG liquefied, which is equivalent to 9.8% of the natural gas that is being liquefied This is comparable to the value used by Balcombe et al. (2021) in their lifecycle assessment and is at the very low end of emission estimates provided by Pace Global (2015) for guidance for new plants built in the United States: 260 to 370 g CO2 per kg of LNG liquefied. My estimate is therefore conservative. In addition, carbon dioxide present in raw natural gas is emitted to the atmosphere as the methane in natural gas is liquefied. These emissions are estimated as 23 to 90 g CO2/kg of LNG liquefied (Tamura et al. 2001; Okamura et al. 2007). Here I use a mean estimate of 57 g CO2/kg. In addition, some natural gas is flared at liquefaction plants to maintain gas pressures for safety, with a range of measured carbon dioxide emissions from zero up to 50 g CO2/kg of LNG, and a mean estimate of 18 g CO2/kg (Tamura et al. 2001; Okamura et al. 2007).

Volume of LNG tanker cargo and length of tanker voyages:

Emissions of both carbon dioxide and methane from LNG tankers depends on the size of the tanker and the length of cruises. Most LNG tankers have total capacities between 125,000 to 150,000 $m^3$ (Bai and Jin 2016). In this analysis, I use a value of 135,000 $m^3$, or 67,500 tons LNG (Raza and Schoyne 2014). Generally, not all of the gross LNG cargo is unloaded at the point of destination. Some is retained for the return voyage, both to serve as fuel and to keep the LNG tanks supercooled. Here, I assume that 90% of the cargo is unloaded (Raza and Schoyne 2014). Therefore, the average delivered cargo is 60,800 tons LNG.

For the length of the voyage, I use the global average distance for LNG tankers (16,200 km each way) as well as the shortest regular commercial route from the US (9,070 km each way, Sabine Pass, TX to the UK; ) and the longest regular commercial route from the US (29,461 km each way, Sabine Pass, TX to Shanghai; Oxford Institute for Energy Studies 2018). The vast majority of LNG exports from the US are from the Sabine Pass area, so these distances well characterize US exports (Joselow and Puko 2023). Considering the average speed of 19 knots (35.2 km per hour; Oxford Institute for Energy Studies), these cruise distances correspond to times of 19 days, 10.7 days, and 35 days each way, respectively. Note that the travel distances for LNG tankers have been increasing over time (Timera Energy 2019). In 2023, a drought limited the capacity of the Panama Canal, leading to LNG tankers from Texas to Asia taking longer routes through the Suez Canal or south of Good Hope in Africa (Williams 2023).

## Emissions during transport by LNG tankers:

The carbon dioxide emissions during LNG transport are largely from the combustion of the fuel that powers the tankers and related equipment onboard the vessels, such as generators. Methane emissions are from the release from boil off and from the incomplete combustion of fuel by some tankers, with release of unburned methane in the exhaust gases. As noted in the introduction, my analysis considers four different types of tankers: 1) old vessels that burn only heavy fuel oil; 2) steam-powered vessels that can use either fuel oil or methane from the boil off of LNG; 3) modern tankers built over the past 20 years that are powered by 4-cycle engines capable of using fuel oil, diesel oil, or methane from LNG boil off; and 4) very modern tankers powered by 2-cycle engines capable of using either fuel oil or boil off.

In this paper, I assume that any tanker that can use LNG for its fuel will meet virtually all of its fuel needs from this source. Although most tankers can burn fuel oil and/or diesel oil, consumption of these fuels tends to be very low compared to LNG (Raza and Schoyen 2014; Bakkali and Ziomas 2019; Balcombe et al. 2022), except in those rare times when LNG prices are high relative to fuel oils (Jaganathan and Khasawneh 2021). And while it might be expected that tankers would burn fuel oil if the rate of unforced boil off were not sufficient, many tankers instead are likely to force more boil off for their fuel, if necessary, in part to meet stringent sulfur emission standards for ships that went into effect in 2020 (Bakkalil and Ziomas 2019).

Emissions of methane and carbon dioxide are calculated using equations #6 and #7, with units of g $CH_4$/kg LNG burned by the final consumer and g $CO_2$/kg burned by the final consumer.

Equation 6 $CH_4$ = [ **LNG.ship** ∗ Slip ∗ 1,000] + **Vent.boil.off**

Equation 7 $CO_2$ = [**LNG.ship** ∗ (44 g $CO_2$/mol)/(16 g $CH_4$/mol) ∗ 1,000 g $CH_4$/kg $CH_4$]

+ [**Heavy.fuel.oil** ∗ (80 g $CO_2$/MJ oil) ∗ (39 MJ/kg oil)]

where **Slip** is the fraction of the burned LNG fuel that is emitted unburned as methane in the exhaust stream. Equation #7 converts the mass of LNG methane consumed by ships for fuel to the mass of carbon dioxide emitted using the masses of methane and carbon dioxide per mole. The value of 80 g $CO_2$/MJ is the carbon dioxide emission factor per unit of energy for heavy fuel oil (Pavlenko et al. 2020) and 39 MJ/kg is the energy density for fuel oil.

For vessels powered by 4-stroke engines, I assume **Slip** is 0.031 (3.1%) of the LNG burned by the tanker, based on data in Balcombe et al. (2021). This emission rate is slightly lower than assumed by Pavlenko et al. (2020). For tankers powered by 2-stroke engines burning LNG, I assume a 0.038 methane slip rate based on data in Balcombe et al. (2022) for a newly commissioned tanker. Note that this is higher than 0.023 reported in Balcombe et al. (2021) or values reported in Pavlenko et al. (2020), due to emissions of unburned methane from electric generators, which are necessary for tankers powered by 2-stroke engines. Methane emissions in the exhaust of steam-powered tankers are negligible, as are emissions from burning fuel oils in 2-stroke engines (Pavlenko et al. 2020), and are ignored in this analysis.

Equation #8 provides the estimation for the amount of LNG consumed by tankers, for those tankers that burn LNG, normalized to the delivery of LNG.

Equation 8 **LNG.ship** = **Days** ∗ (**LNG.fuel** / 60,800,000 kg LNG)

where **Days** is the number of days for a round-trip cruise to an from the liquefication facility, **LNG.fuel** is the rate of LNG consumption per day, and 60,800,000 kg LNG is the average delivered cargo, as discussed above. Fuel consumption rates are assumed to be 175 tons LNG per day for steam-powered tankers, 130 tons LNG per day for ships powered by 4-cycle engines, and 108 tons LNG per day for ships powered by modern 2-cycle engines (Raza and Schoyen 2014; Bakkali and Ziomas 2019).

Boil off of methane during the voyage is calculated in equation #9.

Equation 9 **Boil.off** = (0.00135 kg CH4/kg LNG per day) ∗ **Days** ∗ (1,000 g CH4/kg CH4)

where **Boil.off** is the unforced rate of evaporation from the tanker's LNG tanks during the voyage. The value 0.00135 kg CH4/kg LNG per day is the average rate of boil off of methane, equivalent to 0.135% per day of the LNG cargo, normalized to the volume of the cargo. This is the mean value for LNG tankers, with rates as low as 0.1% per day at ambient temperatures of 5° C and as high as 0.17% per day at temperatures of 25° C (Hassan et al. 2009; Huan et al. 2018; BrightHub Engineering 2022; Rosselot et al. 2023). Note that boil off occurs not only during the laden voyage transporting the LNG: some LNG is retained as ballast for the return voyage back to the LNG loading terminal, typically 5% of the gross cargo (Hassan et al. 2009). This is necessary to keep the tanks at low temperature, and the mass of methane boiled off per day during the return ballast voyage is essentially the same as during the laden voyage (Hassan et al. 2009).

Note that **Vent.boil.off** is equivalent to **Boil.off** as calculated in equation #8 for those tankers that do not burn LNG and are not equipped with equipment to capture and reliquefy methane to LNG. Most older tankers that are not capable of burning LNG are unlikely to have equipment for reliquefaction and are therefore likely to emit the boil off to the atmosphere (Hassan et al. 2009; Bright Hub Engineering 2022). For those tankers that are capable of burning LNG, I assume that all boil off methane is used for fuel, or if boil off exceeds the fuel needs of a tanker, the excess boil off methane is captured and reliquefied with no methane emitted to the atmosphere

The quantity of fuel oil burned by ships, for those ships that do not burn LNG, is calculated by equation #10.

Equation 10 **Heavy.fuel.oil** = (167,000 kg oil/day) ∗ **Days** / (60,800,000 kg LNG)

where 167,000 kg oil per day is the rate at which a tanker burns heavy fuel oil and 60,000,800 kg/LNG is the quantity of LNG delivered per cruise. The value of 167,000 kg oil per day is estimated by scaling from LNG-powered 2-cycle tankers, assuming 80 g CO2/MJ for heavy fuel oil and 55 g CO2/MJ for LNG (Pavlenko et al. 2020), and using the value from Bakkali and Ziomas (2019) that these tankers burn the equivalent of 115 tons LNG/day.

Final distribution and combustion:

In addition to the methane emissions from upstream and midstream sources before the gas is liquefied to become LNG, considered above, emissions occur after regasification and delivery to the final customer. These emissions are less if the gas is used to generate electricity than if it is delivered to homes and buildings. For the analysis presented in this paper, I only consider the case of electricity generation. For this, methane emissions from transmission pipelines and storage in the destination country are estimated as 0.32% of the final gas consumption (Alvarez et al. 2018), or 0.0032 kg of methane per kg of LNG consumed. As noted above, emissions would be higher for gas used to heat homes and commercial buildings (Howarth 2022-b).

When the gas is burned by the final consumer, I use carbon dioxide emissions of 2,750 g CO2/kg of LNG delivered. This is based on the stoichiometry of carbon dioxide (44 g/mole) and methane (16 g/mole). It is equivalent to 55 g CO2/MJ for natural gas (Hayhoe et al. 2002) and is also the value assumed by the IMO 2021) for burning LNG in tankers.

Comparison to natural gas, diesel oil, and coal used domestically and heat pump:

The emissions of methane and carbon dioxide for natural gas that is used domestically (that is, not converted to LNG) are calculated in equations #11 and #12.

Equation 11 $CH_4 = (0.0312) * (1.0312) * (55 \text{ g } CO_2/\text{MJ}) * (\text{mol} / 44 \text{ g } CO_2) * (16 \text{ g } CH_4/\text{mol})$

Equation 12 $CO_2 = (55 \text{ g } CO_2/\text{MJ}) + (12.6 \text{ g } CO_2/\text{MJ})$

where 0.0312 is the fraction of natural gas that is emitted unburned as methane. This includes 0.028 (2.8%) for upstream and midstream emissions (Sherwood et al. 2024) and 0.0032 (0.32%) for downstream emissions (Supplemental Table A), assuming the gas is used for generation of electric power and not for heating of homes and commercial buildings. These are the same values used for the LNG emission calculations. The value of 55 g $CO_2$/MJ is for the emissions when the gas is burned (EIA 2016, converted to net calorific values), and 12.6 g $CO_2$/MJ are the indirect emissions from the energy used to develop, process, and transport the gas (DEC 2021, Table A-1, converted to net calorific and metric units).

The emissions of methane and carbon dioxide for coal that is used domestically (not transported long distances by ship) are calculated in equations #13 and #14.

Equation 13 $CH_4 = 0.21$ g $CH_4$/MJ

Equation 14 $CO_2 = (99$ g $CO_2$/MJ$) + (3.4$ g $CO_2$/MJ$)$

where 0.21 g $CH_4$/MJ is the emissions factor for methane from the production of coal in the US based on IPCC data (Howarth 2020, converted to net calorific values), 99 g $CO_2$/MJ are the direct emissions when the coal is burned (EIA 2016, converted to net calorific values), and 3.4 g $CO_2$/MJ are the indirect emissions from the energy used to develop and transport the coal (DEC 2021, Table A-1, converted to net calorific and metric units). Note that the emission factors used here are significantly larger for methane and somewhat less for indirect carbon dioxide emissions than used by NETL (2019). Note further that the emission factor for methane is very similar to the mean estimate for deep coal mines in China (0.23 g $CH_4$/MJ; Wang et al. 2019) and for average mining operations in Poland (0.19 g $CH_4$/MJ; Patynska 2014).

The emissions of methane and carbon dioxide for diesel oil that is produced domestically are calculated in equations #15 and #16.

Equation 15 $CH_4 = 0.40$ g $CH_4$/MJ

Equation 16 $CO_2 = (75$ g $CO_2$/MJ$) + (15.8$ g $CO_2$/MJ$)$

where 0.40 g $CH_4$/MJ is the emissions factor for methane from the production of diesel oil, 75 g $CO_2$/MJ are the direct emissions when the oil is burned (EIA 2016, converted to net calorific values), and 15.8 g $CO_2$/MJ are the indirect emissions from the energy used to develop and transport diesel oil (DEC 2021, Table A-1, converted to net calorific and metric units). The methane emission factor is from data presented in supplemental materials for Sherwin et al. (2024) and is based on oil production from the Permian Basin, apportioning upstream methane emissions to the percent of energy produced that is oil compared to natural gas (58%).

Much natural gas is used to heat homes and commercial buildings, not just for electricity. Heat pumps provide an alternative for this heating. To evaluate the greenhouse gas footprint of a heat pump, we use the average emissions from the electric grid in Europe in 2022, reported as 251 g $CO_2$-eq/kwh, or 70 g $CO_2$-eq/MJ (European Environment Agency 2023). The average ground-source heat pump has a

Coefficient of Performance (COP) of 4.8 (Heat Pumps 2024). The emissions for using a heat pump is estimated by dividing the average grid emissions by the COP.

## Results and Discussion

### Boil off:

The rate of LNG used to power tankers is compared with unforced boil off in Table 1, for those tankers that are capable of burning LNG. The unforced boil off predicted from the assumed percentage of gross cargo per day, 0.1% at an ambient temperature of 5° C and 0.17% at a temperature of 25° C (Hassan et al. 2009), is always less than the fuel required for tankers powered by steam engines and 4-stroke engines. This is also true for tankers powered by modern 2-stroke engines at the lower temperature. My analysis therefore assumes that these tankers force additional boil off to meet their fuel needs (Bakkali and Ziomas 2019), and the total LNG fuel consumption is included in the overall lifecycle assessment for each type of tanker. For tankers powered by modern 2-stroke engines at the higher temperature, the unforced boil off of 115 tons LNG per day exceed the fuel requirement of 108 tons LNG per day, although not by much (Table 1). All tankers powered by 2-stroke engines that are capable of burning LNG are relatively new and are likely to be equipped with equipment to re-liquefy boil off in excess of their fuel needs. Consequently, I assume that no boil off from these tankers is vented to the atmosphere and all is captured. However, old tankers driven by engines that cannot use LNG for fuel are extremely unlikely to have the re-liquefaction equipment, so their boil-off methane is assumed to be vented to the atmosphere (Hassan et al. 2009). This venting is required for safety reasons.

### Comparison of emissions of $CO_2$ from final combustion to methane and indirect $CO_2$ emissions:

Table 2 presents emissions of carbon dioxide, methane, and total combined emissions expressed as $CO_2$-equivalents for each of the four scenarios considered, using different types of tankers and the global average time for voyages. Emissions are separated into the upstream plus midstream emissions, those from liquefaction of gas into LNG, emissions from the tankers, emissions associated with the final transmission to consumers, and emissions as the gas is burned by the final consumer to produce electricity. These emissions are also summarized in Figure 2, with emissions broken down into the carbon dioxide emitted as the fuel is burned by the final consumer, other carbon dioxide emissions, and emissions of unburned methane. For both Figure 2 and the combined emissions presented in Table 2, methane emissions are compared to carbon dioxide using $GWP_{20}$ (IPCC 2021). The emissions for the scenario using tankers powered by heavy fuel oil rather than LNG are substantially larger than for the other three scenarios. This is largely due to the venting to the atmosphere of unburned methane from boil off. This venting contributes 36% of the total greenhouse gas emissions for the scenario based on these steam-powered tankers using heavy fuel oil (Table 2).

Carbon dioxide emissions from final combustion are important but not a dominant part of total greenhouse gas emissions across all four scenarios. These final-combustion emissions make up 24% of total greenhouse gas emissions for the case where LNG is transported by tankers using heavy fuel oil. For the other three scenarios where tankers burn LNG rather than heavy fuel oil, the emissions from final combustion make up 36% of total greenhouse gas emissions (Figure 2, Table 2). Even larger than the emissions from combustion of the LNG by the final customer, though, are upstream and midstream emissions of methane and carbon dioxide from producing, processing, storing, and transporting natural gas (Table 2). This is true across all scenarios, with these upstream and midstream emissions composing 32% of total emissions for the scenario where tankers burn heavy fuel oil and approximately 50% of total emissions in the other three scenarios. Indirect carbon dioxide emissions are an important part of these upstream and midstream emissions, reflecting the use of fossil fuels to power the shale gas extraction and processing systems, but methane emissions from upstream and midstream sources are the dominant factor across all scenarios (Table 2).

The liquefaction process is an important source of emissions of carbon dioxide, reflecting the large amount of energy needed to super cool methane to liquid form (Table 2). In this analysis, methane emissions at the liquefaction plants appear to be fairly small, but as noted in the "methods" section, actual methane emissions could be substantially larger. The data used to inform my analysis required the cooperation of plant owners, and so likely reflect a best-case scenario. Using remote techniques such as airplane flyovers or satellites to gain better information of emissions from LNG plants should be a priority (Frank 2023). Total liquefaction emissions are the third largest source of emissions, after the upstream and midstream emissions and emissions of carbon dioxide from the combustion of gas by the final customer, for all three scenarios where LNG is transported by tankers that burn LNG, although these are dwarfed by boil off methane emissions from tankers for the scenario where the tankers are powered by heavy fuel oil.

Tanker emissions dominate for this scenario of LNG being transported by tankers that burn heavy fuel oil, and emissions from tankers in the other scenarios are only slightly less than those from the liquefaction process (Table 2). Of interest, among the tankers that burn LNG, carbon dioxide emissions are greatest for those powered by steam engines, with lower emissions from vessels powered by 4-stroke and modern 2-stroke engines (Table 2), reflecting greater efficiencies (Table 1). However, methane emissions, which are negligible in the tankers powered by steam engines, are significant in tankers with 4-stroke and 2-stroke engines that burn LNG, with these emissions (expressed as carbon-dioxide equivalents) being comparable to the carbon dioxide emissions from the exhaust of these vessels (Table 2). Consequently, total emissions are actually less for the steam-powered vessesl than for the more fuel-efficient tanker. These methane emissions from the modern 4-stroke and 2-stroke tankers result from slippage of methane, that is methane emitted unburned in the exhaust stream (Pavlenko et al. 2020; Balcombe et al. 2021, 2022). As noted above, my analysis assumes no methane emissions from boil off in these tankers. When scaled to the distance LNG is transported, my estimates for emissions of both methane and carbon dioxide for those tankers burning LNG are quite comparable to those presented in the recent analysis by Rosselot et al. (2023), falling very near the mean of their estimates.

Methane emissions from the final transmission of gas to the consumer are relatively small, only 264 g $CO_2$-equivlants/kg LNG delivered, for all of the different tanker scenarios (Table 2). This is because my analysis focuses on the use of LNG to produce electricity, and the transmission pipelines that deliver gas to such facilities generally have moderately low emissions (Alvarez et al. 2018). However, LNG is also used to feed gas into urban pipeline distribution systems for use to heat homes and commercial buildings. Methane emissions for these downstream distribution systems can be quite high, with the best studies in the United States finding that 1.7% to 3.5% of the gas delivered to customers leaks to the atmosphere unburned (see summary in Howarth 2022-b and references therein). This corresponds to a range of 1,400 to 2,890 g $CO_2$-equivalents per kg LNG delivered, increasing the total greenhouse gas footprint of LNG by up to 35% above the values shown in Table 2. Emissions from distribution systems are not as well characterized in either Europe or Asia as in the United States (Howarth 2022-b), although one study suggests emissions in Paris, France are in the middle range of those observed in the United States (Defratyka et al. 2021).

### Importance of cruise length:

My analysis includes scenarios with the shortest and longest cruise distances from the United States, in addition to the world-average distance shown in Figure 2 and Table 2. See Supplemental Tables B and C for emission estimates from these shortest and longest voyages. The shortest distance represents a voyage from the Gulf of Mexico loading port to the United Kingdom, while the longest distance is for a voyage from the Gulf of Mexico to Shanghai, China, not going through the Panama Canal. Not surprisingly, total emissions go down for the shorter voyage and increase for the longest voyage for all four scenarios considered. This is particularly true for the scenario where LNG is transported in tankers that burn heavy fuel oil, and is due primarily to differences in methane emissions from boil off, which is a function of time at sea (Supplemental Table B, Supplemental Table C). For all four scenarios, emissions from fuel consumption increase or decrease as travel distances and time at sea increase or decrease. The upstream and downstream emissions and emissions from liquefaction also increase or decrease as the travel distances change, when expressed per mass of LNG delivered to the final consumer. This reflects an increase or decrease in the total amount of LNG burned or boiled off by tankers during their voyages. Qualitatively, the patterns described above based on world average tanker travel distances (Table 2) hold across the cases for shorter and longer voyages. In all cases, total greenhouse gas emissions exceed the carbon dioxide emissions when the LNG is burned by the final consumer, by 2.6-fold for the shortest cruises and most efficient tankers (Supplemental Table B) to 5.7-fold for the longest cruises and oldest tankers (Supplemental Table C).

### Comparison to coal, diesel oil, and natural gas used domestically, and to electric-driven heat pumps:

Figure 3 compares the greenhouse gas footprint of LNG in different tanker-delivery scenarios to those of coal used domestically near the site of production, natural gas that is not liquefied but rather used domestically, and diesel oil, based on $GWP_{20}$ for comparing methane to carbon dioxide. Table 3 also shows this comparison with LNG tankers for the average tanker-cruise length, focusing on the tankers that have the largest and smallest total greenhouse gas emissions, that is those tankers that are powered by heavy fuel oil and tankers with 2-stroke engines powered by LNG. The carbon dioxide emissions just from combustion are substantially greater for coal, 99 g $CO_2$/MJ vs 55 g $CO_2$/MJ for LNG. Total carbon dioxide emissions from coal, including emissions from developing and transporting the fuel, are also greater than for LNG, but the difference is less, 102.4 g $CO_2$/MJ for coal vs 81.6 to 85.5 g $CO_2$/MJ for LNG (Table 3). This is because of higher emissions of carbon dioxide for developing and transporting the LNG compared to coal. Methane emissions for LNG are substantially larger than for coal, 71.7 to 157 g $CO_2$-equivalents/MJ for LNG compared to only 17.3 g $CO_2$-equivalents/MJ for coal (Table 3). As discussed above in the "methods" sections, this result for methane emissions for coal is quite robust across regions, including China and Poland (Wang et al. 2019; Patynska 2014). Consequently, total greenhouse gas emissions are larger for LNG than for coal, by 28% to 2-fold for the cases of average tanker cruise lengths (Table 3).

Natural gas used domestically in the United States (that is not liquefied to LNG) for electricity production has a greenhouse gas footprint that is very similar to that of coal (Figure 3) when methane emissions are included using $GWP_{20}$, as we have previously demonstrated (Howarth and Jacobson 2021). Neither natural gas or coal used domestically in the United States has a large major climate advantage over the other (Gordon et al. 2023). The greenhouse gas footprint for diesel oil from the Permian Basin also is similar to that of coal (Figure 3; Table 3). However, the footprint for LNG is greater than that of coal, diesel oil, or natural gas even in the case of short cruises using tankers that are powered by LNG, where the LNG emissions are 25% larger than for coal (Figure 3). The LNG footprint is 2.7 times greater than that of coal for the case of long cruises powered by those older tankers that burn heavy fuel oil (Figure 3).

Also shown in Figure 3 are the greenhouse gas emissions for using a ground-source heat pump to heat a home or commercial building, with the pump powered by the average grid electricity for Europe in 2022, as described in the "methods" section. Emissions are very low, less than 10% of those from burning natural gas, since heat pumps are extremely efficient and gain most of their heat from the environment, not from the electricity. These heat-pump emissions would be zero if the electricity were from 100% renewable sources. Even if the electricity came completely from burning coal, rather than the average European grid, emissions would be relatively low for the heat pump: 55 g $CO_2$-eq/MJ, assuming the coal power plant had an efficiency of 45%. Clearly heat pumps are far better than heating with LNG from the standpoint of greenhouse gas emissions.

### Comparison with prior studies:

Both Abrahams et al. (2015) and NETL (2019) assess the direct emissions from the final combustion of LNG and coal in terms of KWh of electricity produced, rather than per MJ of thermal energy. Converting their estimates to the thermal energy produced, their estimates for this direct combustion of fuels are very comparable to the values presented in my analysis. Both Abrahams et al. (2015) and NETL (2019) also have similar estimates for the other emissions associated with producing and using LNG compared to the most efficient tankers in my analysis. Abrahams et al. (2015) conclude that total pre-combustion emissions are 86 g $CO_2$-equivalent/MJ when using $GWP_{20}$ (their Table S-7), while the information in NETL (2019) provides an estimate of 95 g $CO_2$-equivalent/MJ when expressed per net calorific value and using $GWP_{20}$. For comparison, for LNG transported by the most modern 2-stroke engines, my analysis finds pre-combustion emissions of 98 g $CO_2$-equivalent/MJ when using $GWP_{20}$ (Table 3). For the case of old tankers burning fuel oil, which was not considered by either Abrahams et al. (2015) or NETL (2019), total pre-combustion emissions are almost twice as much at 187 g $CO_2$-equivalent/MJ (Table 3). All three studies show that the pre-combustion emissions are greater for LNG than the combustion emissions to produce thermal energy, when using $GWP_{20}$, but the difference is particularly stark for the old tankers in my analysis. For coal, on the other hand, all three studies show a dominance of the direct combustion emissions, with relatively low pre-combustion emissions: 7.6 g $CO_2$-equivalent/MJ (NETL 2019), 20.7 g $CO_2$-equivalent/MJ (this study, Table 3), and 26 g $CO_2$-equivalent/MJ (Abrahams et al. 2015, Table S-7), using $GWP_{20}$.

Sensitivity to GWP time frame:

My analysis is sensitive to the global warming potential that is used, as seen in the on-line only Supplemental Figures A and B. Using $GWP_{100}$ instead of $GWP_{20}$, as was used in Figures 2 and 3, decreases the methane emissions expressed as carbon-dioxide equivalents by a factor of 2.77. While methane emissions are larger than direct or indirect carbon dioxide emissions when considered through the $GWP_{20}$ lens for all four scenarios (Figure 2), the direct emissions of carbon dioxide from the final combustion of LNG are larger than methane emissions across three of the scenarios and equal to them in the fourth one when using $GWP_{100}$ (Supplemental Figure A). Similarly, the greenhouse gas footprint of LNG and natural gas relative to coal decreases when viewed through the lens of $GWP_{100}$ (Supplemental Figure B; Figure 3) since methane emissions from coal are less than from natural gas and LNG. Using $GWP_{100}$ total greenhouse gas emissions from LNG approach are roughly equivalent to those for coal in the scenario with short voyages and tankers burning LNG, are larger for these modern tankers on the longest cruises, and are considerably worse than coal for the scenario of long voyages by older tankers burning heavy fuel oil (Supplemental Figure B).

While the 100-year time frame of $GWP_{100}$ is widely used in lifecycle assessments and greenhouse gas inventories, it understates the extent of global warming that is caused by methane, particularly on the time frame of the next several decades. The use of $GWP_{100}$ dates back to the Kyoto Protocol in the 1990s, and was an arbitrary choice made at a time when few were paying much attention to the role of methane as an agent of global warming. As the Intergovernmental Panel on Climate Change stated in their AR5 synthesis report, “there is no scientific argument for selecting 100 years compared with other choices” (IPCC 2013). The latest IPCC AR6 synthesis reports that methane has contributed 0.5° C of the total global warming to date since the late 1800s, compared to 0.75° C for carbon dioxide (IPCC 2021). The rate of global warming over the next few decades is critical, with the rate of warming important in the context of potential tipping points in the climate system (Ritchie et al. 2023). Reducing methane emissions rapidly is increasingly viewed as critical to reaching climate targets (Collins et al. 2018; Nzotungicimpaye et al. 2023). In this context, many researchers call for using the 20-year time frame of $GWP_{20}$ instead of or in addition to $GWP_{100}$ (Howarth 2014, 2020; Ocko et al. 2017; Fesenfeld et al. 2018; Pavlenko et al. 2020; Howarth and Jacobson 2021; Balcombe et al. 2021, 2022). $GWP_{20}$ is the preferred approach in my analysis presented in this paper. Using $GWP_{20}$, LNG always has a larger greenhouse gas footprint than coal.

Concluding thoughts:

In many ways, my analysis may be conservative and underestimate emissions from the global tanker fleet on average, since I am relying on data available from facilities and ships which have allowed researchers access. These are likely to have better operations and lower emissions than average. Frank

(2023) notes the urgent need for using satellite data to better quantify methane emissions from LNG liquefaction facilities, without the need for cooperation by plant operators. Similarly Balcombe et al. (2022) have argued for the urgent need to expand emissions measurements to a much larger number of tankers that are more representative of the global fleet, and for independent researchers to conduct these measurements. My analysis assumes that those tankers that are capable of burning LNG for their propulsion do so, and that boil-off methane is effectively captured and used on these tankers with zero venting of unburned methane. The reality for many tankers may be quite different, with potentially significant venting of methane, as is the case for tankers that cannot burn LNG. Also, my analysis uses a rather low value for the emissions of methane from downstream gas pipeline delivery systems, only 0.32% (Alvarez et al. 2018). This is reasonable if the LNG is used to produce electricity, but the downstream emissions would almost certainly be higher for LNG used to heat homes, apartments, and commercial buildings (Defratyka et al. 2021; Howarth 2022-b).

My analysis leads to one strong recommendation: the venting of unburned methane from tanker boil off should be prohibited, and those older tankers that cannot capture and use boil-off methane should be retired within the near future. These older tankers that burn heavy fuel oil have a very large greenhouse gas footprint (Figure 3). Beyond this, even with modern tankers LNG has a large climate impact, significantly greater than using natural gas produced domestically because of the energy needed to power the super-cooling of natural gas to make LNG and because of the energy needed to transport LNG in tankers. Increasingly, leaders on global climate policy are recommending a rapid move away from all fossil fuels, including natural gas and not just coal (Gaventa and Patukhova 2021; Figueres 2021). With an even greater greenhouse gas footprint than natural gas, ending the use of LNG should be a global priority.

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**Data availability**

All data used in this paper are from publicly available sources that are identified in the manuscript.

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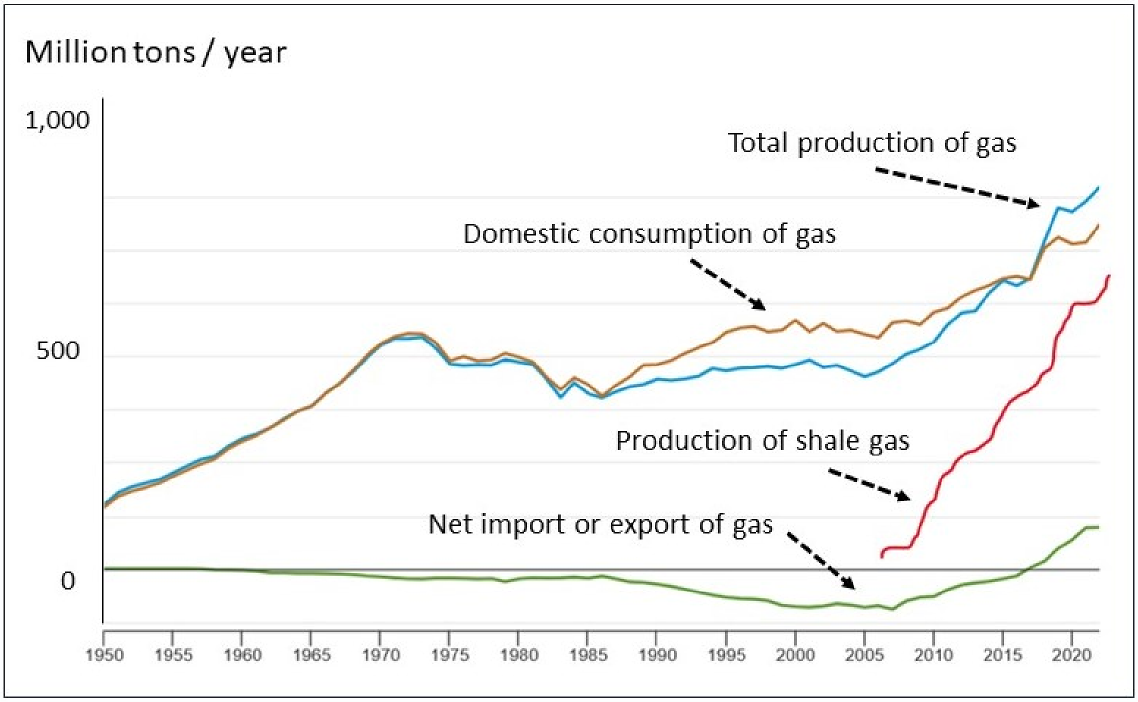


Figure 1. Trends in natural gas production in the United States from 1950 to 2022, showing total production of gas (conventional plus shale), production just of shale gas, domestic consumption, and the net import or export of gas. Almost all of the increase in natural gas production since 2005 has been shale gas. The United States was a net importer of natural gas from 1985 to 2015 but has been a net exporter since 2016.

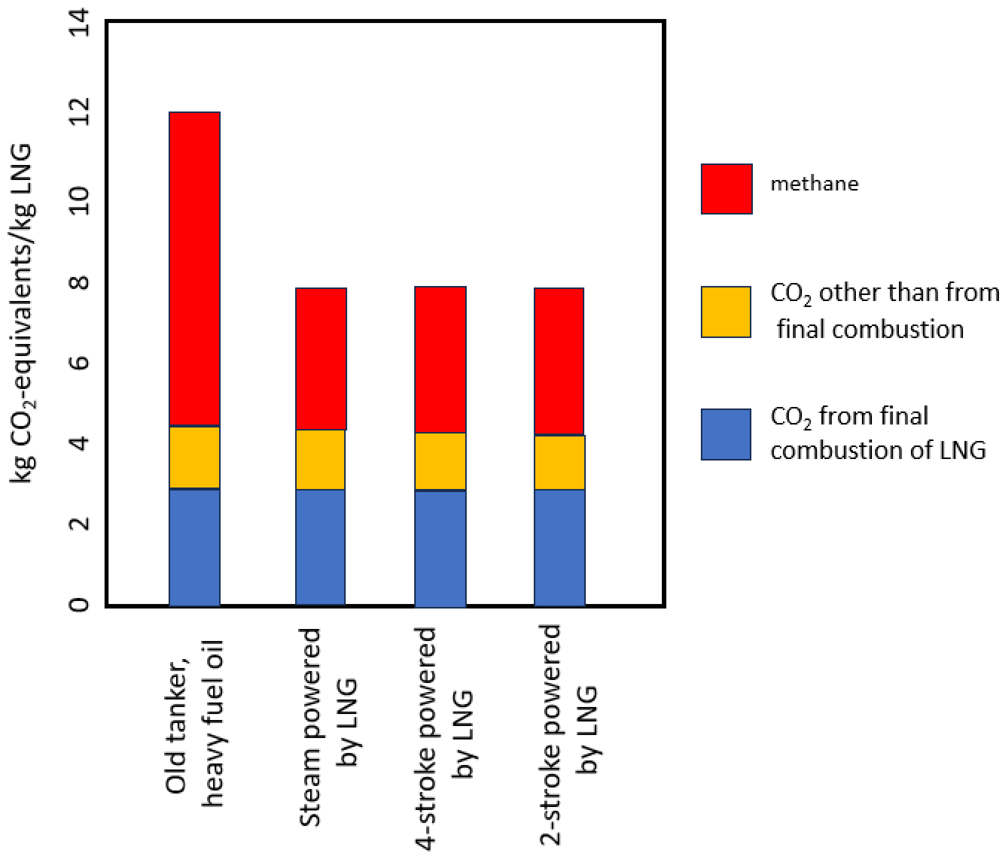


Figure 2. Full lifecycle greenhouse gas footprints for LNG expressed per mass of LNG burned by final consumer, comparing four scenarios where the LNG is transported by different types of tankers. Emissions of methane, the carbon dioxide emitted from the final combustion, and other carbon dioxide emissions are shown separately. Methane emissions are converted to carbon dioxide equivalents using $GWP_{20}$. See text.

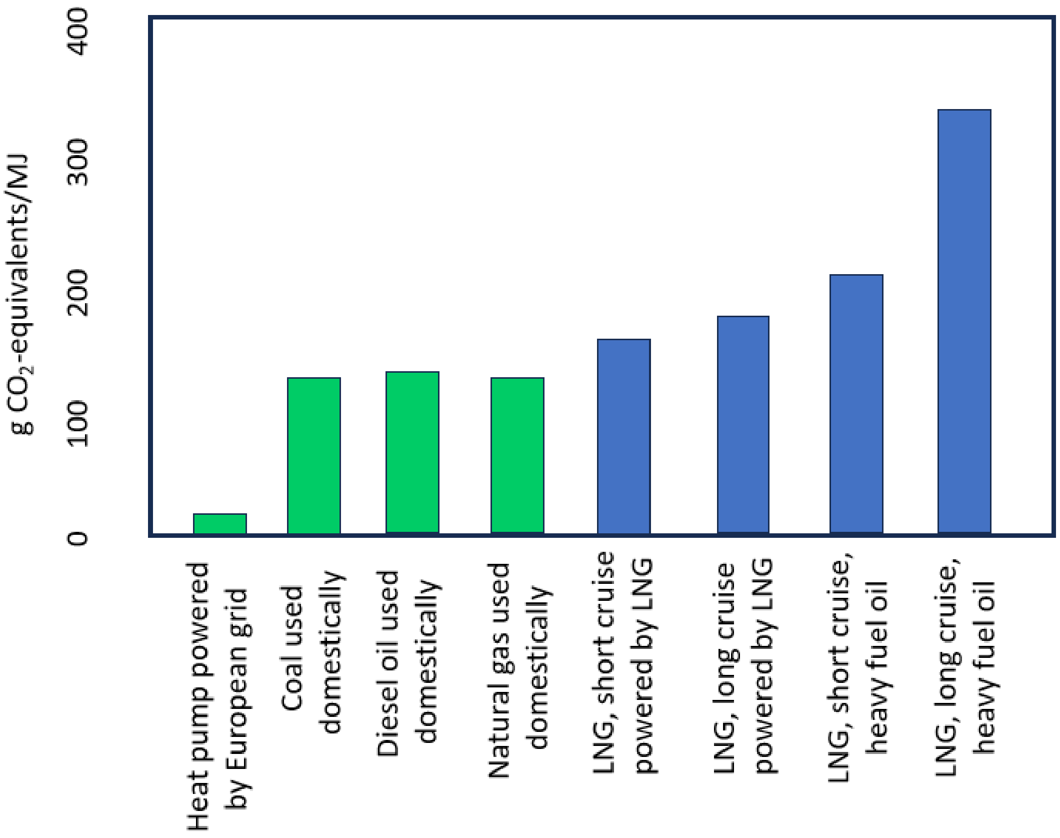


Figure 3. Full lifecycle greenhouse gas footprint for coal, diesel oil, natural gas, and electric-power ground source heat pump compared to four scenarios where LNG is transported by tankers that either burn LNG or heavy fuel oil for long or short voyages. Methane emissions are converted to carbon dioxide equivalents using $GWP_{20}$. See text.

Table 1. Comparison of rate of unforced boil off and fuel needs to power different types of LNG tankers.

| | Tons LNG per day |
|---|---|
| Unforced boil off, ambient temperature of 5° C | 67.5 [a] |
| Unforced boil off, ambient temperature of 25° C | 115 [a] |
| Boil off required for steam-powered tanker burning LNG | 175 |
| Boil off required for tanker powered by 4-stroke engines burning LNG | 130 |
| Boil off required for tanker powered by 2-stroke engines burning LNG | 108 |

a) Assumes tanker gross cargo capacity of 67,500 tons. Unforced boil off is that which occurs due to heat leakage to LNG storage tanks. Tankers can increase boil off rate to meet fuel demand.

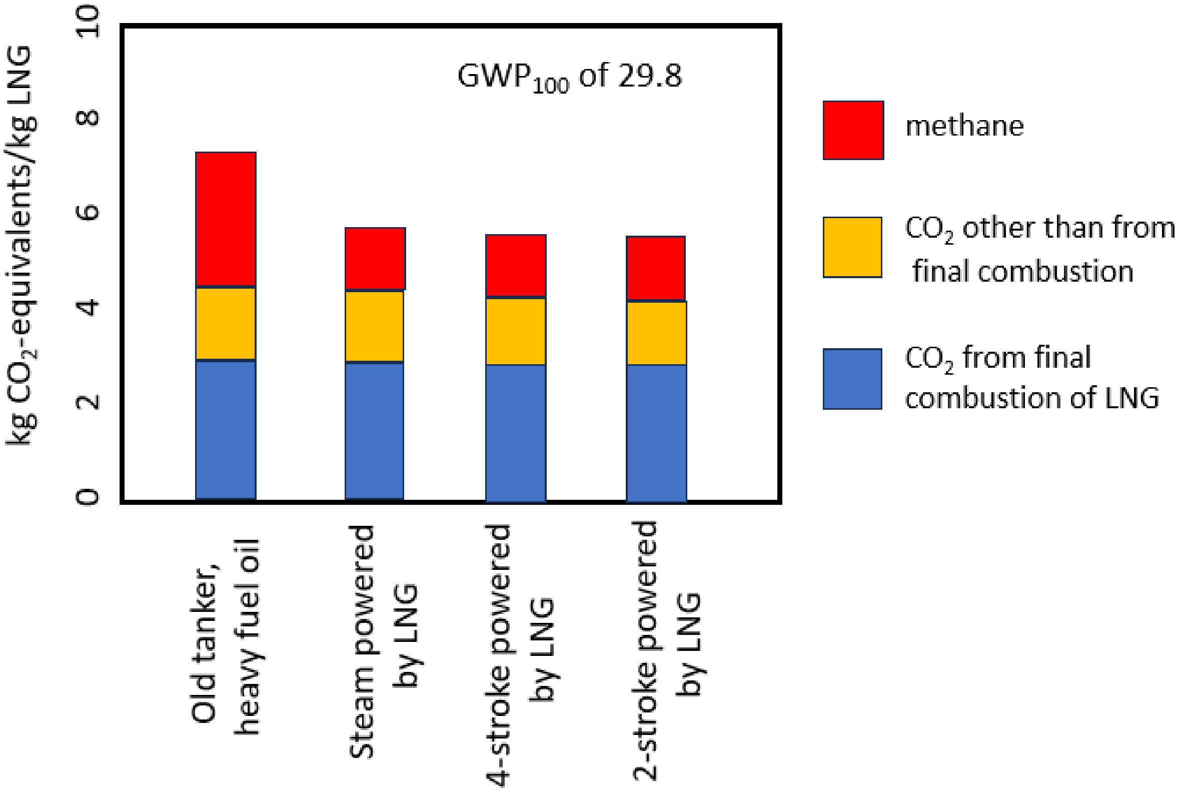
Table 2. Full lifecycle greenhouse gas emissions for LNG with four different scenarios for shipping by tanker, using world-average voyage times. Methane emissions are shown both as mass of methane and mass of carbon dioxide equivalents based on $GWO_{20}$. Values are per final mass of LNG consumed.

| | Carbon Dioxide | Methane | | Total combined |
|---|---|---|---|---|
| | g $CO_2$/kg | g $CH_4$/kg | g $CO_2$-eq/kg | g $CO_2$-eq/kg |
| Old tankers powered by heavy fuel oil | | | | |
| Upstream & midstream emissions | 793 | 35.1 | 2,898 | 3,691 |
| Liquefaction | 363 | 0.96 | 71 | 434 |
| Emissions from tanker | 326 | 51.3 | 4,232 | 4,558 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,232** | **90.6** | **7,465** | **11,697** |
| Steam tankers powered by LNG | | | | |
| Upstream & midstream emissions | 768 | 36.8 | 3,033 | 3,801 |
| Liquefaction | 383 | 0.98 | 81 | 464 |
| Emissions from tanker | 300 | --- | --- | 300 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,201** | **41.0** | **3,378** | **7,579** |
| 4-stroke engine tankers powered by LNG | | | | |
| Upstream & midstream emissions | 751 | 35.9 | 2,962 | 3,713 |
| Liquefaction | 374 | 0.96 | 79 | 453 |
| Emissions from tanker | 223 | 2.5 | 206 | 429 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,098** | **42.6** | **3,511** | **7,609** |
| 2-stroke engine tankers powered by LNG | | | | |
| Upstream & midstream emissions | 741 | 35.5 | 2,929 | 3,670 |
| Liquefaction | 369 | 0.93 | 77 | 446 |
| Emissions from tanker | 186 | 2.6 | 215 | 401 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,046** | **42.2** | **3,485** | **7,531** |

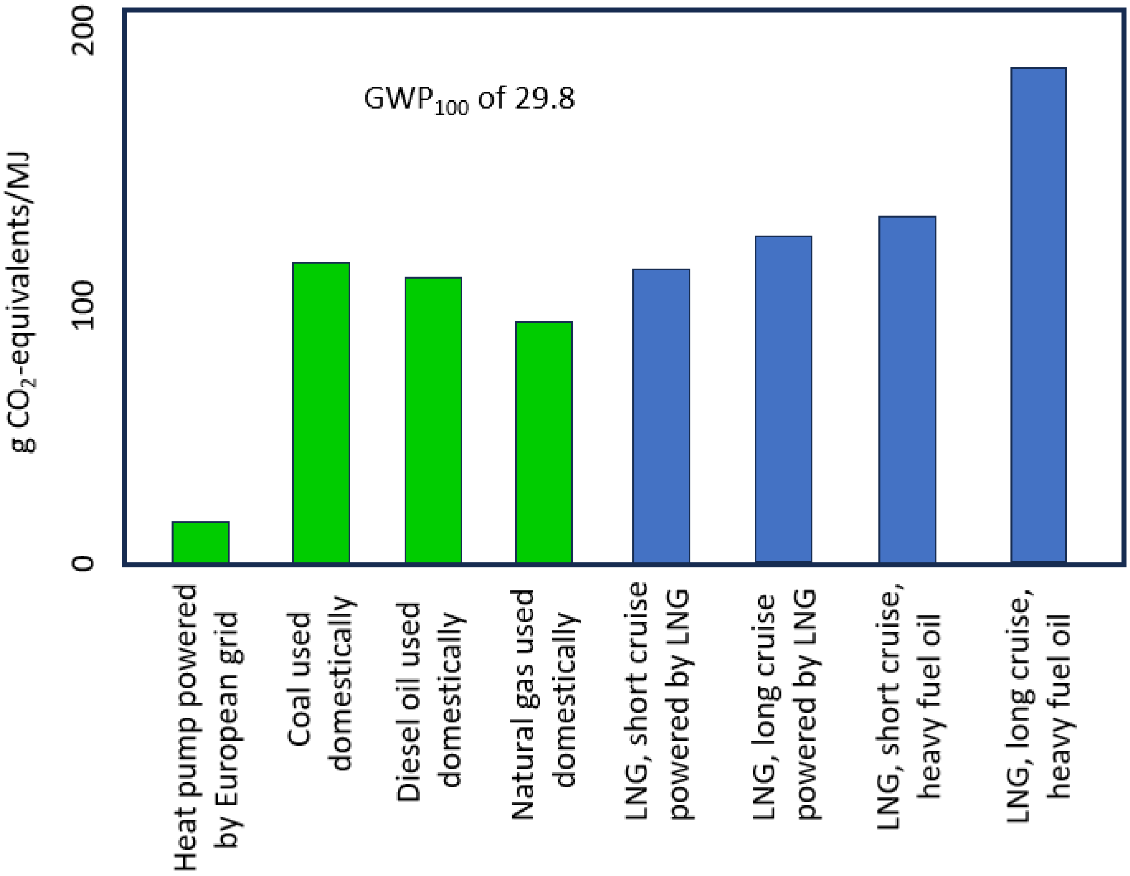
Table 3. Greenhouse gas emissions for LNG imported from the United States compared to those for diesel oil and for coal produced domestically near the final site of consumption. For LNG, emissions are shown for the two types of tankers that have the largest and smallest total emissions, using world-average voyage times. Methane emissions are shown both as mass of methane and mass of carbon dioxide equivalents based on $GWP_{20}$. Values expressed per quantity of energy available from the fuel.

| | Carbon Dioxide | Methane | | Total combined |
|---|---|---|---|---|
| | g $CO_2$/MJ | g $CH_4$/MJ | g $CO_2$-eq/MJ | g $CO_2$-eq/MJ |
| Old tankers powered by heavy fuel oil | | | | |
| Upstream & midstream emissions | 16.3 | 0.72 | 59.8 | 76.1 |
| Liquefaction | 7.5 | 0.047 | 3.9 | 11.4 |
| Emissions from tanker | 6.7 | 1.06 | 87.5 | 94.2 |
| Final transmission & distribution | --- | 0.066 | 5.4 | 5.4 |
| Combustion by final consumer | 55.0 | --- | --- | 55.0 |
| **Total** | **85.5** | **1.89** | **157** | **242** |
| 2-stroke engine tankers powered by LNG | | | | |
| Upstream & midstream emissions | 15.2 | 0.73 | 60.3 | 75.5 |
| Liquefaction | 7.6 | 0.019 | 1.6 | 9.2 |
| Emissions from tanker | 3.8 | 0.053 | 4.4 | 8.2 |
| Final transmission & distribution | --- | 0.066 | 5.4 | 5.4 |
| Combustion by final consumer | 55.0 | --- | --- | 55.0 |
| **Total** | **81.6** | **0.87** | **71.7** | **153** |
| Diesel oil | | | | |
| Upstream & transport emissions | 15.8 | 0.40 | 33.0 | 48.8 |
| Combustion by final consumer | 75.0 | --- | --- | 75.0 |
| **Total** | **90.8** | **0.40** | **33.0** | **123.8** |
| Coal used domestically | | | | |
| Upstream & transport emissions | 3.4 | 0.21 | 17.3 | 20.7 |
| Combustion by final consumer | 99.0 | --- | --- | 99.0 |
| **Total** | **102.4** | **0.21** | **17.3** | **119.7** |

# Supplemental Material for R. W. Howarth (2024) The Greenhouse Gas Footprint of Liquefied Natural Gas (LNG) Exported from the United States



Supplemental Figure A. Full lifecycle greenhouse gas footprints for LNG expressed per mass of LNG burned by final consumer, comparing four scenarios where the LNG is transported by different types of tankers. Emissions of methane, the carbon dioxide emitted from the final combustion, and other carbon dioxide emissions are shown separately. Methane emissions are converted to carbon dioxide equivalents using $GWP_{100}$. See text for similar figure using $GWP_{20}$.



Supplemental Figure B. Full lifecycle greenhouse gas footprint for ground-source heat pump powered by average European grid electricity, coal, diesel oil, and natural gas used domestically, and four scenarios where LNG is transported by tankers that either burn LNG or heavy fuel oil for long or short voyages. Methane emissions are converted to carbon dioxide equivalents using GWP$_{100}$. See text for similar figure using GWP$_{20}$.

Supplemental Table A. Methane emissions from both upstream and downstream associated with natural gas production in the Permian Basin for 8 campaigns as presented in Sherwin et al. (2024).

| Campaign | upstream emissions (tons/hr) [a] | midstream emissions (tons/hr) [b] | total emissions (tons/hr) | production (tons/hr) [c] | percent emitted |
|---|---|---|---|---|---|
| Kairos NM Permian | 48.8 | 78.9 | 127.7 | 1,952 | 6.5 % |
| CM Permian/2019 | 119 | 250.5 | 369.5 | 10,527 | 3.5 % |
| CM Permian/202 | 25.7 | 76.7 | 102.4 | 4,767 | 2.2 % |
| CM Permian/summer 2021 | 28.0 | 65.5 | 93.5 | 5,950 | 1.6 % |
| CM Permian/fall 2021 | 28.0 | 65.4 | 93.4 | 6,228 | 1.5 % |
| CM Permian F2021, boundary/2019 | 54.2 | 92.7 | 146.9 | 4,756 | 3.1 % |
| CM Permian F2021, Delaware/2019 | 30.7 | 50.6 | 81.3 | 3,613 | 2.3 % |
| CM Permian F2021, Midland/2019 | 23.8 | 42.4 | 66.2 | 1,143 | 5.8 % |
| **Total** | | | **1,080.9** | **38,936** | **2.8 %** [d] |

a) Calculated from data in Table S10, Table S12, and Table S24 of supplemental material from Sherwin et al. (2024), with emissions weighted for natural gas vs oil considering energy basis.

b) Calculated from data in Table S10 and Table S12 of supplemental material from Sherwin et al. (2024).

c) From Table S10 of supplemental material from Sherwin et al. (2024)

d) Percent of production emitted as methane weighted by the production occurring during each campaign.

Supplemental Table B. Full lifecycle greenhouse gas emissions for LNG with four different scenarios for shipping by tanker, using shortest voyage times. Methane emissions are shown both as mass of methane and of carbon dioxide equivalents based on GWO$_{20}$. Values are per final LNG consumed.

| | Carbon Dioxide | Methane | | Total combined |
|---|---|---|---|---|
| | g $CO_2$/kg | g $CH_4$/kg | g $CO_2$-eq/kg | g $CO_2$-eq/kg |
| Old tankers powered by heavy fuel oil | | | | |
| Upstream & midstream emissions | 749 | 34.3 | 2,827 | 3,576 |
| Liquefaction | 355 | 0.91 | 75 | 430 |
| Emissions from tanker | 183 | 29.0 | 2,393 | 2,576 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,037** | **67.1** | **5,559** | **9,596** |
| Steam tankers powered by LNG | | | | |
| Upstream & midstream emissions | 735 | 36.0 | 2,970 | 3,705 |
| Liquefaction | 366 | 0.93 | 77 | 443 |
| Emissions from tanker | 169 | --- | --- | 169 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,020** | **40.1** | **3,311** | **7,331** |
| 4-stroke engine tankers powered by LNG | | | | |
| Upstream & midstream emissions | 725 | 34.7 | 2,862 | 3,587 |
| Liquefaction | 361 | 0.93 | 77 | 438 |
| Emissions from tanker | 126 | 1.4 | 116 | 242 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **3,962** | **40.2** | **3,319** | **7,281** |
| 2-stroke engine tankers powered by LNG | | | | |
| Upstream & midstream emissions | 720 | 34.5 | 2,842 | 3,562 |
| Liquefaction | 359 | 0.91 | 75 | 434 |
| Emissions from tanker | 104 | 1.4 | 116 | 220 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **3,933** | **40.0** | **3,297** | **7,230** |

Supplemental Table C. Full lifecycle greenhouse gas emissions for LNG with four different scenarios for shipping by tanker, using longest voyage times. Methane emissions are shown both as mass of methane and mass of carbon dioxide equivalents based on GWO$_{20}$. Values are per final mass of LNG consumed.

| | Carbon Dioxide | Methane | | Total combined |
|---|---|---|---|---|
| | g $CO_2$/kg | g $CH_4$/kg | g $CO_2$-eq/kg | g $CO_2$-eq/kg |
| Old tankers powered by heavy fuel oil | | | | |
| Upstream & midstream emissions | 877 | 36.8 | 3,033 | 3,910 |
| Liquefaction | 378 | 0.96 | 79 | 457 |
| Emissions from tanker | 600 | 94.5 | 7,796 | 8,396 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,605** | **135** | **11,172** | **15,777** |
| Steam tankers powered by LNG | | | | |
| Upstream & midstream emissions | 832 | 39.8 | 3,284 | 4,116 |
| Liquefaction | 415 | 1.1 | 87 | 502 |
| Emissions from tanker | 554 | --- | --- | 554 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,551** | **44.1** | **3,635** | **8,186** |
| 4-stroke engine tankers powered by LNG | | | | |
| Upstream & midstream emissions | 799 | 38.3 | 3,159 | 3,958 |
| Liquefaction | 398 | 1.0 | 83 | 481 |
| Emissions from tanker | 412 | 4.6 | 380 | 792 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,359** | **47.1** | **3,886** | **8,245** |
| 2-stroke engine tankers powered by LNG | | | | |
| Upstream & midstream emissions | 782 | 37.4 | 3,088 | 3,870 |
| Liquefaction | 390 | 1.0 | 83 | 473 |
| Emissions from tanker | 342 | 4.7 | 388 | 730 |
| Final transmission & distribution | --- | 3.2 | 264 | 264 |
| Combustion by final consumer | 2,750 | --- | --- | 2,750 |
| **Total** | **4,264** | **46.3** | **3,823** | **8,087** |